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A Contribution to Thermal Ageing Assessment of Glass Fibre Insulated Wire Based on Partial Discharges Activity

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ABSTRACT This paper aims to evaluate a Type-II insulated wire (i.e., Glass fibre insulated wire) as a function of thermal ageing time based on partial discharges (PD) activity. Partial discharge inception voltage (PDIV), partial discharge extinction voltage (PDEV), and repetitive partial discharge inception voltage (RPDIV) measurements have been performed on both unaged and thermally aged specimens. Each specimen modelled the turn-to-turn insulation; hence it was made by a pair of Glass fibre wires wrapped in PTFE tape for a mechanical purpose. The PD tests have been carried out under positive and negative unipolar square waveform excitations using different rise times: 80, 400 and 800 ns. The trend of PD quantities vs exposure time demonstrates that the effect of space charge accumulation under unipolar excitation must be taken into account when unaged and thermally aged specimens are compared. Results revealed that although sometimes thermally aged samples might show a temporary superiority in the short run, unaged ones always present a better performance after space charge accumulation, as expected. Following the statistic postprocessing of the collected data, shape/slope parameters of the Weibull distribution relevant to PDIV can be used as an ageing indicator for Glass fibre insulated wire. Finally, the permittivity evaluation vs thermal and electrical stresses have been performed, relying on the measured capacitance of each specimen just after every PD test. Such analysis revealed that thermal ageing increases permittivity in the long run. However, electrical stress has different impacts on permittivity depending on the rise time, polarity, and magnitude of the applied voltage.

INDEX TERMS Accelerated ageing, electric machines, partial discharges, pulse width modulation, reliability, space charge, variable speed drives.

I. INTRODUCTION

Electrical machines fed by power converters have been used extensively in aerospace and automotive applications due to better control, energy efficiency, power density, versatility, and improvement of AC motor performance [1]–[5]. The purpose of modern inverters (e.g., silicon carbide-based inverters) is to increase the power density while reducing losses. Because they provide shorter rise times, enabling higher switching frequencies, voltages, and temperatures. However, faster rise times pose higher stress levels on the insulation system (i.e., turn-to-turn insulation), reducing the reliability. A shorter rise time increases the non-linear partition of the jump voltage (potential difference between the line terminal and star point) between the turns, enhancing the risk of PD [6]. Once the partial discharges (PD) inception field corresponding to the turn-to-turn insulation is reached, PD can promote the accelerated insulation degradation affecting insulation reliability. The continuous PD activity can result in premature failure of the winding insulation and consequently electrical machine out of service [7], [8]. Thus, low voltage electrical machines should be designed according to the PD-free criterion, i.e., the minimum PDIV is greater than the peak voltage between two adjacent turns [8]. However, this criterion might not be ensured throughout the insulation system life due to the inevitable ageing (e.g., thermal ageing). Indeed, PD activity might degenerate consequent to thermal ageing, particularly if the insulation is subjected to a steep-fronted square waveform.

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IEC standards introduce two main types of insulation systems for motor winding, namely Type I and Type II [4], [9]. Type I insulations (i.e., organic insulating materials, e.g., polyamide-imide) are commonly used as winding insulation of low voltage electrical machines. Although PD is considered the end-of-life criterion for Type I and a PD-free insulation design is required [10], it is claimed that Type II (i.e., mixed organic-inorganic insulating materials, so-called corona-resistant materials) has a better ability to endure PD. Hence, using Type II instead of Type I insulation would be an alternative solution, introducing a paradigm shift. Therefore, Glass fibre insulated wire as a Type II insulation has been considered for this study.

Thermal ageing can change insulating materials characteristics such as chemical, electrical, and mechanical properties. These probably increase the degradation rate under PD. Moreover, the impact of very fast rise time on PD activity of the turn-to-turn insulation, particularly under thermal and electrical stresses, represents a critical topic due to the combination of conflicting effects as discussed in the following scenarios. In the first scenario, while shorter rise time can lead to higher PDIV, thermal ageing would decrease the PDIV. In this case, higher PDIV caused by fast rise time could be ascribed to the decrease of permittivity due to the high-frequency content of the fast rise time. In addition, there could be a lower possibility for the first electron availability to initiate the discharge avalanche [6]. As a result, higher PDIV would be plausible when the rise time is very fast. On the other hand, the thermal ageing byproducts are mostly polar components, resulting in higher permittivity, consequently, PDIV decrement would be possible as a result of an electric field increase in the air gap [11].

In the second scenario, uneven voltage distribution along the motor windings can cause a large overstress between the turns, enhancing the risk of incepting PD between adjacent turns. Therefore, lower PDIV would be expected [7]. Furthermore, when the rise time is fast, there is a higher PD charge amplitude and PD repetition rate [12], [13]. As a result, there would be more surface charge density/interface space charge accumulation resulting from the charge deposition after subsequent PD [13], [14]. It can increase the effective permittivity, leading to PDIV reduction caused by fast rise time [13]. On the other hand, the polar byproducts caused by thermal ageing can increase surface conductivity, exhibiting more dielectric losses [11]. In this case, the electric field can drop in the air gap, leading to higher PDIV (at least in the short run) [15]. To sum up, the interaction between the rise time and thermal ageing impacts on PDIV is a topic worthy of being experimentally investigated. Thus, this paper focuses its attention on evaluating the thermal ageing role of PDIV, PDEV and RPDIV.

The space charge accumulation under unipolar square waveform excitation (e.g., 3-level inverters) is inevitable even at high impulse repetition frequencies due to the presence of a DC component [14]. It can change the electric field intensity in the air gap between the two wires (i.e., adjacent turns), increasing or decreasing PDIV. Considering the significant role played by the space charge under unipolar excitation, appropriate focus is given in this investigation. Indeed, the PD quantities (i.e., PDIV, PDEV and RPDIV) are evaluated at different rise times on both unaged and thermally aged Glass fibre samples.

Under repetitive impulsive excitations, the electric field is ruled by the permittivity. Any information regarding the permittivity value of a stressed specimen/insulation with a specific voltage rise time and polarity at each thermal ageing period can be helpful. Indeed, the higher permittivity can imply the higher electric field concentration in the air rather than the insulation, thus lower PDIV. Therefore, permittivity evaluation was performed relying on insulation capacitance and dissipation factor measurements carried out just after finishing the PD test for each specimen (i.e., after RPDIV measurements).

The test samples preparation, the PD measurement setup and measurement procedure are explained in section II. The experimental results and discussions are presented in sections III and IV. The PD activity under thermal ageing is reported and discussed in section III. The effect of space charge accumulation on PD activity comparing unaged and thermally aged samples is presented and discussed in section IV. Finally, the conclusions of the study are summarized in section V.

II. METHODOLOGY

A. TEST SAMPLES

Fig. 1 illustrates the samples preparation process. PD measurements have been performed on unaged and thermally aged polytetrafluoroethylene (PTFE)-wrapped pairs of Glass fibre insulated wire, which mirrors the turn-to-turn insulation system (Fig. 2a). The manufacturer of the insulated wires (2 Silix VSI) is Von Roll, and the bare wire diameter is 0.9 mm.

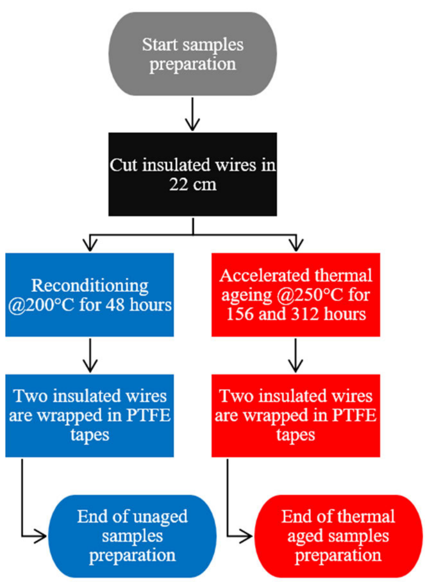


FIGURE 1. A flowchart to visualize the samples preparation process.

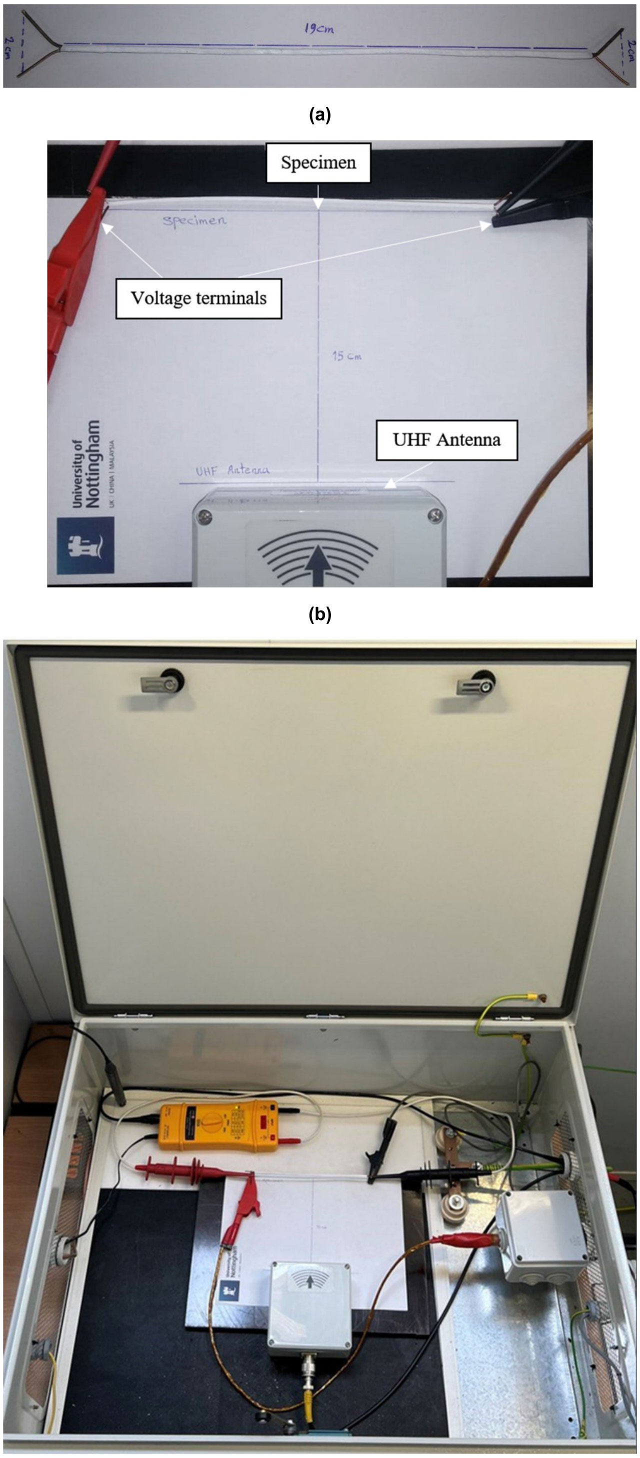


FIGURE 2. **(a) Test sample and (b) PD detection arrangement, and (c) test cell.**

The insulation is characterized by a thermal class of 200°C. It features a thickness of 100 μm impregnated with silicone-based varnish. The wires composing the sample were not twisted to avoid/prevent the cracking of the Glass fibre coating during the twisting process. Thus, instead of twisted pairs, PTFE-wrapped pairs of Glass fibre insulated wires were used to model the turn-to-turn insulation system. The two wires have been kept next to each other by a binding tape [4] (i.e., PTFE tapes) to provide complete contact between their insulation surfaces. Therefore, the PTFE tape has a purely mechanical function in the specimen assembly and does not play any electrical insulation role.

The unaged samples have been dried and reconditioned at 200°C for 48 hours (at the thermal index of insulation). Indeed, preconditioning was performed to reduce the possible effect of absorbed humidity from the atmosphere on PDIV drop. The accelerated thermal ageing process has been carried out at 250°C (i.e., 50°C higher than the thermal index) for two different time durations: 156 and 312 hours. These two thermal exposure time values have been considered to assess the PD quantities at different thermal ageing levels. After finishing both reconditioning and thermal ageing processes, the two portions of insulated wire, each with a length of about 22 cm, has been wrapped in PTFE tapes. Five specimens have been tested for each considered case study (i.e., each specified voltage rise time, polarity, and thermal ageing period).

B. PD MEASUREMENT SETUP

The PD sensor is an ultra-high frequency (UHF) antenna that features a bandwidth of 100 MHz–3 GHz acquiring the electromagnetic wave emissions produced by PD in the sample under test. The UHF antenna is placed at a distance of 15 cm from the specimen using the layout illustrated in Fig. 2b. The whole test cell is depicted in Fig. 2c.

The acquired PD signals are processed through IEC 60270-compliant instrumentation (i.e., Techimp PDBaseII) characterized with a bandwidth of 40 MHz and a sampling rate of 200 MSa/s [15]. A frequency shifter is used to mitigate the frequency content of the UHF signals. Indeed, it is necessary to provide the required frequency range for both the PD detection unit and the impulsive test synchronization module (ITSM). The ITSM generates a digital synchronization pulse synchronized to the pulse generator fundamental frequency through low pass filtering. A high-pass filter can be connected between the UHF antenna and frequency shifter to improve the signal to noise ratio (SNR) employed for PDIV and PDEV tests [17]. The schematic diagram of the PD measurement setup is illustrated in Fig. 3.

C. MEASUREMENT PROCEDURE

A commercial variable pulse generator system (RUP6-18bip) has been used to produce positive and negative unipolar square voltage waveform excitations. The rise time is defined as the time interval the voltage rises from 0.1 to 0.9 of the peak value [18]. Therefore, three different rise times such as 80, 400 and 800 ns have been selected for the test campaign. RUP6-18bip was set to produce a square waveform with a switching frequency of 2.5 kHz and a duty cycle of 50%. Thus, the impulse voltage width duration was constant equal to 100 μs. Fig. 4 indicates a typical voltage waveform of applied positive excitation.

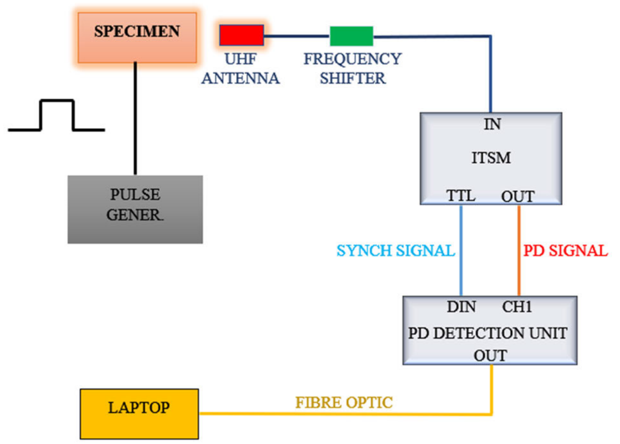


FIGURE 3. Circuit and connections layout for PD measurements setup.

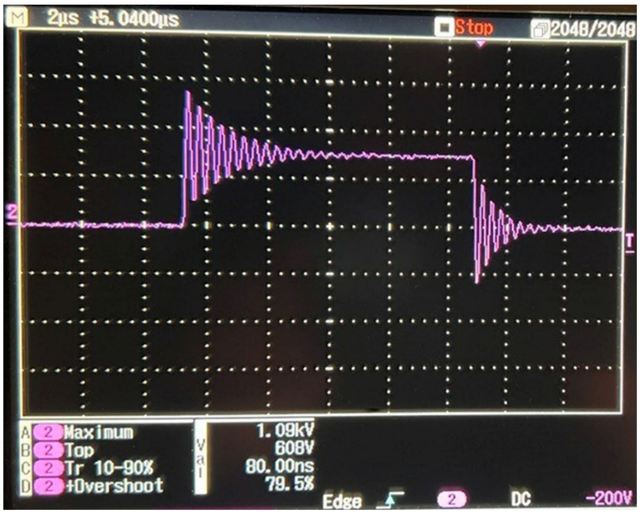


FIGURE 4. A typical voltage waveform of applied positive excitation.

The PD tests have been carried out at room temperature (21°C), atmospheric pressure (1013 mbar) and relative humidity of 28±5%. Regarding PDIV measurement, the voltage magnitude was increased in steps of 25 V peak every 30 seconds [19], and its waveform was monitored through a Lecroy WaveJet Touch 334 oscilloscope that featured 350 MHz bandwidth, 2 GS/s sampling rate. The excitation voltage waveforms were collected by a CT4079-NA differential probe (50 MHz bandwidth, 2000:1 voltage ratio, 50 Ω impendence). The peak value of the voltage was recorded as PDIV once the PD activity was incepted with the PD repetition rate of at least two PD per minute. The voltage step (25 V) and the stop duration (30 seconds) have been selected to provide a reasonable test duration and accuracy of the collected data. Indeed, a high voltage increasing rate might deliver a substantial (positive) error in the measured PDIV [19]. In addition, the PDIV definition based on the proposed PD repetition rate criteria allows collecting more meaningful and repeatable PDIV values for the comparative analysis against the PDEV measurements.

After detecting PDIV, the voltage was decreased in steps of 25 V peak each one minute. When PD activity was extinguished, the peak value of the voltage was recorded as PDEV. Finally, RPDIV was measured as the voltage peak at which the probability of incepting a PD per voltage impulse is 50% [9]. Starting from the recorded peak value of PDIV, the voltage was increased (with the same voltage step and stop duration as considered for the PDIV). When RPDIV was triggered, the peak value of the voltage was registered.

Each sample has been tested only once to avoid the possibility of PDIV falls due to the damage of previous PD activity. The statistical post-processing of the collected measurements was performed relying on the two-parameter Weibull distribution. The Weibull distribution of the five measured peak values is calculated for each data group. A selected percentile in the tail of the distribution is employed to realize the comparison between the unaged and thermally aged samples since the weakest link of the chain determines the reliability of the whole system in the insulation systems [6]. In this work, the 10^{th} percentile of the non-exceedance probability of Weibull distribution fitting to each data set has been selected to achieve the reported PDIV, PDEV, and RPDIV values.

III. PD ACTIVITY UNDER THERMAL AGEING

The experimental results corresponding to the PD activity as a function of thermal ageing duration are discussed in this section. Firstly, the measured capacitance and dissipation factor of the unaged and thermally aged samples before starting the PD tests are reported in section A. These results are helpful to describe and explain the PD measurement results. The measurement results of PDIV, PDEV and RPDIV are discussed in sections B, C and D, respectively. Finally, the capacitance of the thermally aged samples just after finishing the PD test are reported in section E. These measurements are performed to illustrate the impact of PD activity on the capacitance of the specimens at each thermal ageing duration.

A. CAPACITANCE AND DISSIPATION FACTOR AS A FUNCTION OF THERMAL AGEING

The insulation capacitance and dissipation factor variations consequent to thermal ageing are investigated in this section. This investigation is conducted here due to the direct relationship between capacitance and permittivity. Indeed, when capacitance/permittivity increases, the electric field amplification factor in the air gap between the two adjacent insulated wires can increase. Consequently, the chance of PD inception would be higher. Thus, knowledge about permittivity variations through thermal ageing can be helpful to explain the PD activity variations as a function of the thermal ageing period. In addition, the dissipation factor measurement results can provide excessive data regarding the loss index (i.e., the imaginary part of permittivity) consequent to thermal ageing.

The capacitance and dissipation factor tip-up (i.e., ΔC and $\Delta \tan\delta$) is measured adopting a Megger Delta4000 [20].

Figs. 5 and 6 report the measured capacitance and dissipation factor (i.e., $\mathrm{Tan}\delta$), respectively, for different thermal

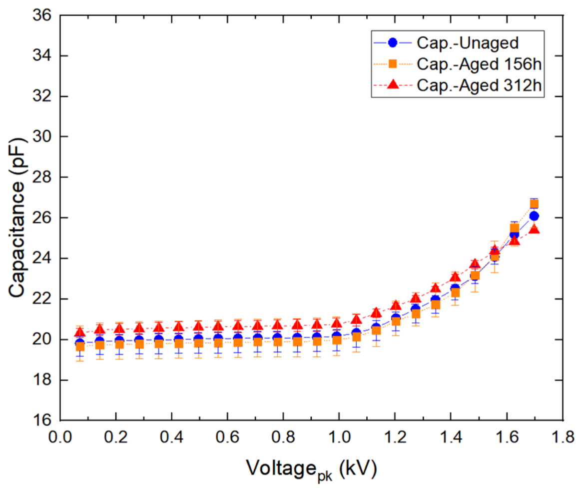


FIGURE 5. Capacitance variations consequent to thermal ageing versus the peak of applied sinusoidal voltage at 50 Hz. Confidence intervals with a probability of 95% are also indicated. (Each plot reports the mean value of thirty measured samples).

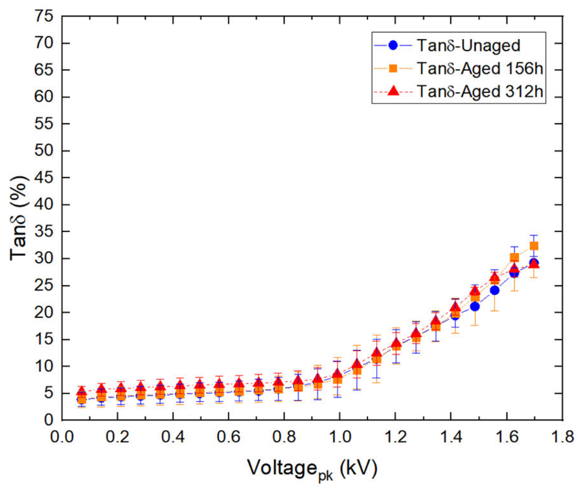


FIGURE 6. Dissipation factor variations consequent to thermal ageing versus the peak of applied sinusoidal voltage at 50 Hz. Confidence intervals with a probability of 95% are also indicated. (Each plot reports the mean value of thirty measured samples).

ageing intervals. This figure shows the measurement results for different peak values of the applied sinusoidal voltage at 50 Hz. Each plot reports the mean value of thirty measured samples. The measurements were performed up to 1.7 kV peak since the maximum dielectric strength of the thermally aged specimens for 312 hours was observed up to this voltage level.

Fig. 5 illustrates that overall thermal aged samples (i.e., 312 hours) deliver higher capacitance/permittivity than unaged ones. Therefore, there is more possibility to measure lower PDIV for the thermally aged specimens. It is noteworthy to mention that thermal ageing leads to a low variation of capacitance (Fig. 5) and dielectric dissipation factor (Fig. 6). However, as will be demonstrated later, the variations of capacitance (Figs. 12 and 16) and dielectric dissipation factor (Fig. 17) caused by the PD activity under repetitive steep-fronted waveform excitation would be more significant.

The de-polymerization and oxidation byproducts consequent to thermal ageing can increase the permittivity [21]–[23]. It can be more significant at higher frequencies such as 2.5 kHz as used for PDIV measurement and even higher under very fast steep-fronted square waveform excitation due to the non-negligible spectral energy of the voltage waveform.

Interestingly, while thermally aged specimens for the longer duration (i.e., 312 hours) give larger capacitance (Fig. 5) and dissipation factor (Fig. 6) than those aged for the shorter interval (i.e., 156 hours), the reverse holds at the highest voltage level (e.g., 1.7 kV peak). There are probably higher polar ageing byproducts for the aged specimens for 312 hours at lower voltage levels delivering higher permittivity. However, some polar compounds of the thermally aged samples can change to non-polar ones at a certain level of the applied voltage resulting in lower permittivity. Furthermore, it is also possible to have some available ageing byproducts at 156 hours which can be converted to polar compounds at the highest voltage level. However, these byproducts might be vaporized from 156 to 312 hours. As a result, lower permittivity at the highest voltage level can be observed after 312 hours. Thus, different polarization mechanisms would be plausible for each case at different voltage levels. Indeed, various polarization mechanisms can occur at different magnitudes, polarities, and frequencies of the applied voltage.

B. PDIV ANALYSIS IN TERMS OF THERMAL AGEING, RISE TIME, AND POLARITY

In this section, the PDIV measurement results are reported and discussed. The measurements were performed according to the procedure explained in section II.C. Fig. 7 shows the PDIV variation detected on unaged and thermally aged samples for both 156 and 312 hours exposure time. The PDIV was measured under positive and negative unipolar square waveform excitation considering three different rise time values (i.e., 80, 400 and 800 ns). The impulse voltage repetition frequency and pulse width duration were constant at 2.5 kHz and 100 μs, respectively.

In Fig. 7, a PDIV decrement as a function of the thermally ageing period (except for negative polarity with the rise time of 80 ns) is observable. The overall reduction of PDIV can be attributed to the increase of dielectric permittivity against ageing time. This permittivity increase can be due to de-polymerization and oxidation byproducts in particular polar compounds (e.g., moisture, carboxylic acids) which are inevitable due to the presence of organic compounds even in Type II wire insulations [24]. As a result of permittivity increment, the electric field concentrates more in the air than the dielectric. Hence, a higher chance to initiate PD in the air gap would be plausible. Considering the direct relationship between capacitance and permittivity, the higher measured capacitance for the thermally aged specimens after 312 hours than unaged ones (indicated in Fig. 5) can support

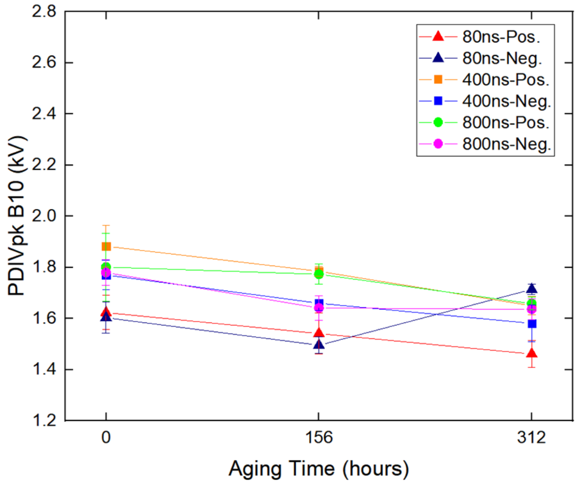


FIGURE 7. **PDIV trend consequent to thermal ageing under positive and negative unipolar square waveform excitations using three different rise times, relying on the tenth percentile of the Weibull distribution. Confidence intervals with a probability of 95% are also indicated.**

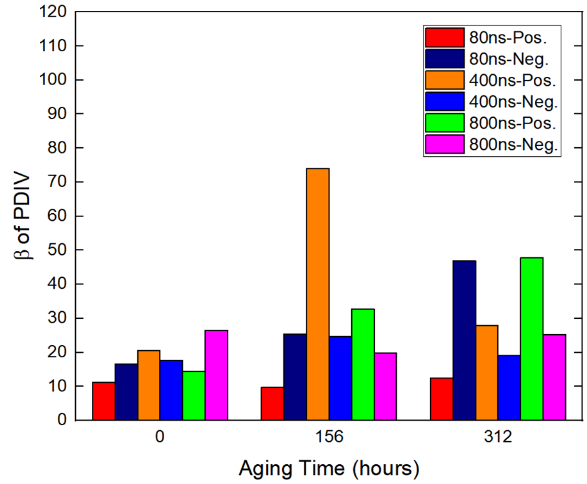


FIGURE 8. **The dispersion level of measured peak values of PDIV as a function of ageing time, using the shape/slope parameter of the Weibull distribution.**

this explanation. Regarding the exceptional case of PDIV increment at 80 ns and negative polarity from the ageing period of 156 to 312 hours, it can be ascribed to space charge accumulation (i.e., heterocharge) which is reasonable under unipolar square waveform excitation. This concept will be analyzed and discussed in section IV.

Fig. 7 indicates that the intensity of PDIV decrement consequent to thermal ageing differs for the longer rise time (i.e., 800 ns, under both positive and negative polarity) compared to faster rise times. The PDIV reduction is almost negligible under positive polarity till 156 hours. The same stands for the negative polarity from 156 to 312 hours. This stabilization of PDIV is probably due to the slight permittivity change in these periods. Indeed, two factors can impact permittivity: thermal ageing and surface charge density caused by electrical stress with a steep-fronted waveform. The former can increase the permittivity in the long run [21]–[23] (Fig. 5). It is probably due to the increased oxidation byproducts, especially polar compounds. However, the latter can reduce or increase the permittivity, depending on the rise time. For instance, it can mitigate the permittivity, particularly at a longer rise time, likely due to lower surface charge density (Fig. 12). However, it is not the case for faster rise times (e.g., 400 ns and 80 ns, except for negative polarity). In these cases, higher permittivity can be associated with more surface charge density [13]. The permittivity rise is likely due to the double impact of both thermal ageing and electrical stress with a faster rise time.

Referring to Fig. 7, PDIV can be compared at different rise times at each ageing stage. It illustrates lower PDIV for the fastest rise time (i.e., 80 ns) with only one exception (i.e., 80 ns under negative polarity after 312 hours). This lower PDIV can be associated with permittivity escalation. The higher measured capacitance for the stressed specimens by 80 ns can support this description. An increase of the effective permittivity can occur through more surface charge density caused by higher PD charge amplitude and PD repetition rate when the rise time is the shortest [12], [13]. It is noteworthy to highlight that the higher capacitance for the stressed specimens by the fastest rise time (i.e., 80 ns) would be less evident if the test samples rest for a long time after the PD test, thus allowance to reach the charge equilibrium. In addition, more surface discharges (i.e., tripping of the pulse generator) were observed when the rise time was the longest (i.e., 800 ns). It is probably due to higher surface conductivity, thus lower surface charge density when the rise time is longer. Consequently, these observations can support the possible impact of surface charge density on effective permittivity.

The comparison between positive and negative polarities at longer rise time shows that lower PDIV is measured under negative polarity, especially at 400 ns. It can be attributed to different interface space charge accumulation under different polarities of the unipolar square waveform excitation [14]. The higher permittivity of the dielectric under negative polarity can deliver lower PDIV.

Fig. 8 indicates the dispersion level of the measured PDIV values consequent to thermal ageing resorting to the shape/slope parameter of the Weibull distribution (i.e., β). The dispersion level of the results decreases/β increases versus ageing time. It is more evident for 80 ns under negative excitation and 800 ns under positive one, where β increases monotone as a function of ageing time. As a result of this finding, β of PDIV can be a potential ageing indicator.

C. PDEV ANALYSIS IN TERMS OF THERMAL AGEING, RISE TIME, AND POLARITY

In this section, the PDEV measurement results as a function of thermal ageing time, rise time and excitation polarity are reported and discussed. The PDEV measurements were performed after the PDIV test (not RPDIV) according to the procedure described in section II.C. Fig. 9 illustrates the

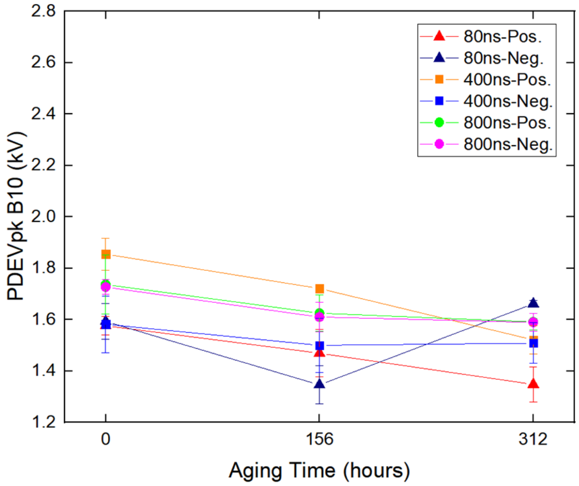


FIGURE 9. PDEV trend due to thermal ageing under positive and negative unipolar square waveform excitations using three different rise times, relying on the tenth percentile of the Weibull distribution. Confidence intervals with a probability of 95% are also indicated.

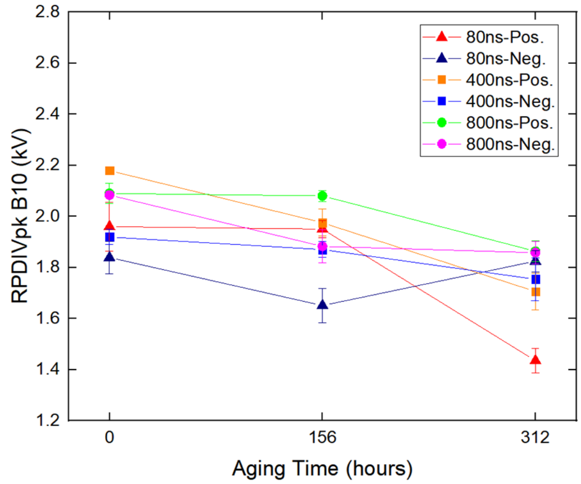


FIGURE 10. RPDIV trend caused by thermal ageing under positive and negative unipolar square waveform excitations using three different rise times, relying on the tenth percentile of the Weibull distribution. Confidence intervals with a probability of 95% are also indicated.

PDEV trend for different thermal ageing durations. PDEV decreases as a function of thermal ageing for all cases up to the ageing period of 156 hours. These trends are almost the same as PDIV, which can be associated with permittivity increase due to thermal ageing. The de-polymerization and oxidation process resulting from thermal ageing might increase the dielectric permittivity more at higher frequencies (e.g., 2.5 kHz) than at 50 Hz used to obtain the results shown in Fig. 5 [6].

However, there are different PDEV trends for thermally aged samples. It remains almost stable for the longer rise times in this time interval. For example, it is almost constant at 800 ns under positive and negative polarity (i.e., the same as PDIV) and 400 ns under negative polarity. It is probably due to permittivity stability from 156 to 312 hours, especially for the stressed specimens with longer rise time. It can occur because of the interaction between thermal ageing and electrical stress under a longer rise time. While the former can increase the permittivity, the latter can reduce it. The same as PDIV, the opposite PDEV trend is observed for positive and negative excitation at the fastest rise time (i.e., 80 ns) from 156 to 312 hours. The PDEV decrement at positive polarity might be associated with permittivity rise, likely due to the double effect of thermal ageing and polarization at the fastest rise time (Fig. 12). As a result, the permittivity increase leads to electric field enhancement in the air gap. Hence, lower applied voltage (i.e., PDEV) would be required to extinguish PD activity. However, the considerable PDIV and PDEV increment under negative excitation and rise time of 80 ns cannot be attributed to the permittivity since its increase is observed rather than its reduction for this case (Fig. 12). This increment is probably due to the charge accumulation in insulation bulk (i.e., heterocharge) prevailing the effect of permittivity.

Considering the PDIV (Fig. 7) and PDEV (Fig. 9) results under different polarities, unaged specimens show polarity independence. However, the polarity dependence is more observed for the thermally aged samples.

D. RPDIV ANALYSIS IN TERMS OF THERMAL AGEING, RISE TIME, AND POLARITY

In this section, the measured values for RPDIV consequent to thermal ageing duration, rise time and excitation polarity are reported and discussed. The RPDIV measurements were carried out after the PDEV test according to the explained procedure in section II.C. Fig. 10 indicates the behaviour of RPDIV as a function of thermal ageing. Like PDIV and PDEV, there is the lowest RPDIV at the fastest rise time (i.e., 80 ns) and positive polarity after the thermal ageing duration of 312 hours.

However, the lowest RPDIV at 156 hours is observed for the shortest rise time and negative polarity as PDIV. Interestingly, only the impulse voltage waveform with the rise time of 400 ns and positive polarity gives a monotone decreasing trend for PDIV, PDEV and RPDIV consequent to thermal ageing. Moreover, the highest PDIV, PDEV and RPDIV values for the unaged samples are obtained for this voltage waveform.

The comparison between the decreasing trend of RPDIV and that of PDIV as a function of thermal ageing duration shows that this trend is more evident for PDIV than RPDIV. It can be associated with more surface insulation damage during RPDIV measurements due to the higher PD repetition rate under RPDIV. The damage density can be more severe when the rise time is faster due to the higher PD repetition rate and PD charge amplitude than those under longer rise time [12], [13]. As a result, it can influence the charge depletion time constant of the deposited charge caused by subsequent PD, consequently affecting PD repetition rate and RPDIV

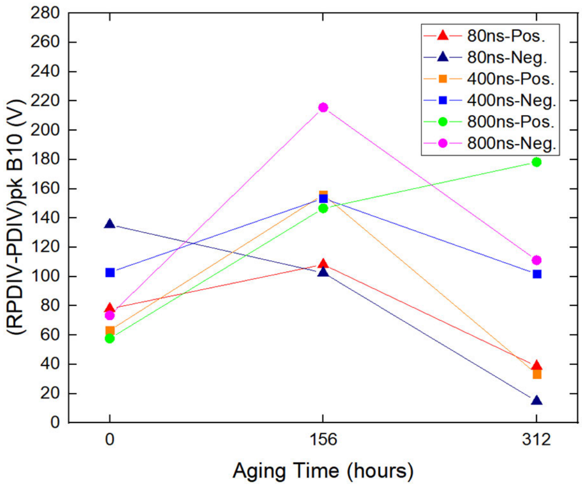


FIGURE 11. The over-voltage against PDIV to trigger RPDIV consequent to thermal ageing under positive and negative unipolar square waveform excitations using three different rise times, relying on the tenth percentile of the Weibull distribution.

measurement. It can be a reason to observe more intensity of RPDIV decrement from 156 to 312 hours than PDIV at 80 ns and positive polarity. Also, bulk and interface space charge accumulation can play a role under unipolar excitation. In this way, homocharge space accumulation under positive polarity can increase the electric field in the air gap and mitigate the RPDIV. However, the opposite effect (i.e., heterocharge space charge accumulation) can reduce the electric field and increase the RPDIV (e.g., at 80 ns and negative polarity from 156 to 312 hours of the thermal ageing period).

Fig. 11 depicts the required over-voltage against PDIV to trigger RPDIV as a function of thermal ageing time. It shows that this over-voltage declines after 312 hours at a faster rise time (i.e., 80 ns), particularly under negative excitation. Under negative polarity, it falls steady from the highest value for pristine samples to the lowest value after 312 hours.

However, this decreasing trend against thermal ageing is not evident, considering only RPDIV at 80 ns and negative polarity (Fig. 10). The opposite stands for a longer rise time (i.e., 800 ns). In this case, the required over-voltage to trigger RPDIV is higher after 312 hours than unaged samples, especially under positive polarity.

There is not always a linear trend consequent to thermal ageing, such as a peak value observed for 156 hours at 80 ns-Pos., 400 ns-Pos., 400 ns-Neg., and 800 ns-Neg.

Several parameters can impact the intensity of the electric field in the air gap between the two wires and consequently the required over-voltage against PDIV to trigger RPDIV. The permittivity rules the electric field distribution under repetitive impulsive voltage. Electrical stress with steep-fronted waveform, de-polymerization, and chemical reactions (e.g., oxidation) through the ageing process can change the permittivity. The electrical stress can increase or decrease the permittivity depending on the rise time, voltage magnitude, excitation polarity, exposure duration, and impulse voltage repetition frequency. Apart from the electrical stress, the oxidation byproducts through the thermal ageing campaign can change during different ageing periods (i.e., not necessarily with a monotone increasing trend, at least in the short run).

Type II insulation is a mixed organic-inorganic insulating material. When organic compounds are present (even a low percentage), the creation of moisture and carboxylic acids consequent to oxidation phenomena (i.e., thermal ageing) is inevitable [24]. The excess of these polar compounds can raise the permittivity. However, they might decrease due to vaporization through further thermal ageing, thus mitigating the permittivity. Moreover, different ageing byproducts can lead to an increase or decrease of permittivity under electrical stress. As a practical example, Fig. 12 reports the capacitance of each specimen (i.e., thermally aged for 156 and 312 hours) measured just after finishing the PD measurements.

E. CAPACITANCE VARIATIONS AS A FUNCTION OF EXCITATION RISE TIME AND POLARITY AT EACH THERMAL AGEING PERIOD

In this section, the impacts of the rise time and polarity of voltage excitation on the capacitance of the tested specimens at each thermal ageing duration are reported (Fig. 12).

Insulating materials properties can change consequent to thermal ageing. It is due to the inevitable ageing byproducts. Therefore, the insulation can behave differently after being stressed electrically. For instance, permittivity and insulation capability to store electrical charges can change due to thermal ageing. These factors play roles in determining the electric field distribution. Thus, their evaluation as a function of thermal ageing would be interesting. Hence, the capacitance measurements tip-up (i.e., ΔC) were carried out for each specimen in each thermal ageing period, just after finishing the PD test (i.e., RPDIV test) using a Megger Delta4000 [20]. The peak of applied sinusoidal voltage at 50 Hz was raised from zero to 1.7 kV with an increasing step of 50 V. Fig. 12 reports the mean value of five capacitance measurements for each case study (i.e., each specified voltage rise time, polarity, and thermal ageing period).

Fig. 12 substantiates that different impulse voltage characteristics can result in various capacitance versus the applied voltage at each thermal ageing period (particularly for the thermally aged samples after 312 hours).

It is noteworthy to mention measured values for PDIV, PDEV, RPDIV and the over-voltage against PDIV to trigger RPDIV, which cannot be justified/explained only, resorting to the capacitance/permittivity variations. For instance, considering Fig. 12a (i.e., thermal ageing period 156 hours), while the highest permittivity is observed for 800ns under negative polarity, the measured PD quantities are not the lowest. In addition, the lowest permittivity value at 80ns under positive excitation does not imply the highest PDIV.

Considering Fig. 12b (i.e., thermal ageing period 312 hours), the higher permittivity at 80ns under negative polarity, and 400ns, and 80ns under positive polarity, can only be referred to explain/justify the lowest required

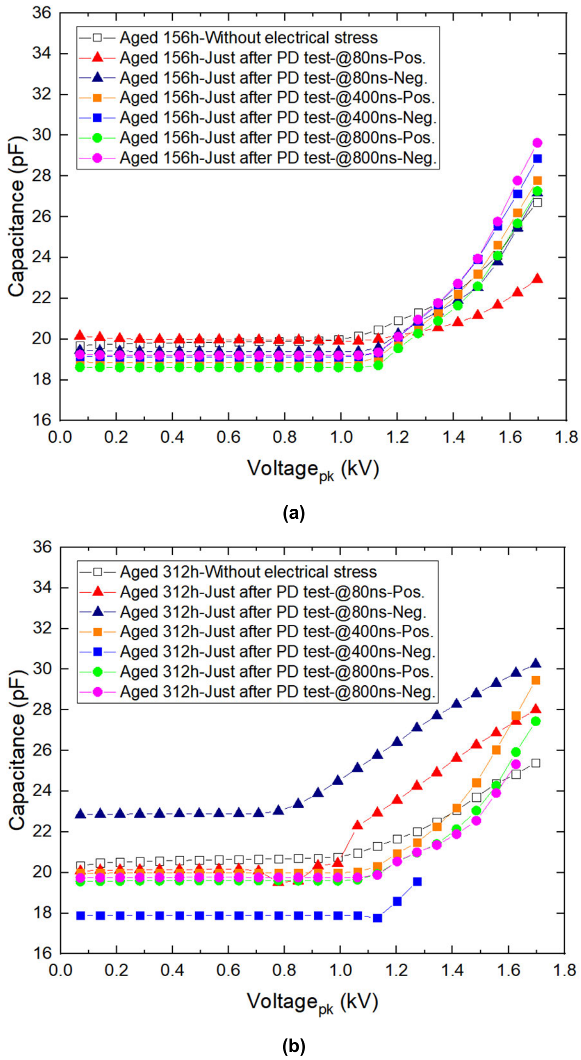


FIGURE 12. Capacitance variations of the specimens versus the peak of applied sinusoidal voltage at 50 Hz just after finishing the PD tests (this figure reports the mean value of five measurements for each point).

over-voltage against PDIV to trigger RPDIV, but not other PD quantities. Furthermore, higher permittivity at 800ns under positive polarity than negative one does not reflect lower PD quantities under positive excitation. Regarding the results at 400ns under negative excitation, since the specimen could not withstand the voltage peak higher than 1.3 kV peak, the averaged values up to this level of voltage is reported in Fig. 12b. While the capacitance/permittivity at 400 ns and negative polarity is the lowest (Fig. 12b), it does not result in the highest PD quantities for this voltage waveform. It is probably due to the higher frequency used for the PD test and different interfacial/dipole orientation polarizations at 2.5 kHz. Therefore, it is perceived that the trend of PD quantities cannot be ascribed only to the permittivity variations.

It is noteworthy to highlight that the polarization processes, which rule the 50 Hz measurements, might not be developed in the frequency range associated with the rise time of the pulses in the range of tens of nanoseconds. Therefore, it might not be easy to explain the PDIV and PDEV behaviour based on the field distribution change considering the results of capacitance and dielectric dissipation factor measurements at 50 Hz. Interestingly, the influence of electrical stress can be still evaluated and compared for different cases using a sinusoidal power supply at 50 Hz. It is likely due to the durability of the orientated dipoles of the dielectric and various surface charge densities caused by different rise times after stressing under unipolar steep-fronted waveform excitation.

In addition, the space charge accumulation in insulation (bulk and interfaces) can influence the intensity of the electric field in the air gap between two wires affecting the PD activity. It is plausible under unipolar square waveform excitation even at high frequencies. There is homocharge and heterocharge space charge accumulation. While the former can increase the electric field in the air gap, the latter can decrease it [14]. Each one can prevail over the other one during the ageing campaign stages.

Another parameter that can influence the electric field in the air gap is the surface conductivity of the insulation, where its increment consequent to thermal ageing can decrease the electric field in the air gap or vice versa [16]. Indeed, when surface conductivity decreases, the charge depletion time constant decreases. As a result, the level of surface charge density can increase, leading to an increase in effective permittivity [13]. Consequently, the electric field in the air gap between two adjacent insulated wires might increase, resulting in a PDIV drop. The opposite process can occur due to surface conductivity increasing [16]. Moreover, a faster rise time can lead to higher damage imposed on the insulation under RPDIV. It is due to the higher PD repetition rate and PD charge amplitude when the rise time is shorter. As a result, it can affect the surface conductivity and electric field intensity in the air gap [12], [13]. There is also a possibility to measure higher PDIV at significant fast rise times. It is due to the inevitable delay for the first electron availability [6]. However, this reason does not set up a reasonable description to justify the obtained results in our test campaign, probably due to a slower employed rise time here.

In addition, change of sample geometry (e.g., shrinking of insulation) and hygroscopicity increment consequent to thermal ageing have been reported in the literature [25], [26]. Apart from all the above influential factors on the electric field in the air gap, extreme ambient conditions (e.g., high/low temperature, humidity, and partial vacuum) will affect the electric field and the PDIV. Consequently, the ageing process consequent to thermal and electrical stress is a multiphysics concept. Furthermore, ageing is the result of several chemical reactions. The values of chemical ageing byproducts (i.e., polar and non-polar compounds) can change consequent to different levels of electrical stress. Hence, all the influential parameters must be understood empirically for each insulating material and considered in the Design of Experiments (DoE).

IV. EFFECT OF SPACE CHARGE ACCUMULATION ON PD ACTIVITY (UNAGED VS THERMALLY AGED SAMPLES)

The impact of space charge accumulation caused by unipolar excitation on the PD activity is investigated and discussed in this section. The comparison is performed between the unaged and the thermally aged specimens (i.e., aged at 250°C for 312 hours). The investigation shows how the rise time and polarity of the unipolar steep-fronted voltage waveform can affect the unaged and thermally aged specimens differently.

In this test campaign, the PD measurements were performed for unaged and thermally aged samples under positive and negative unipolar square waveform excitations with two rise times (i.e., 80 and 800 ns). The environmental conditions were the same as in the previous section. First, PDIV was measured for each sample. Then, the voltage magnitude was declined to 0.85 as a fixed poling voltage for three different exposure periods: zero (without poling), half an hour, and one hour. Eventually, PDIV, PDEV and RPDIV tests were performed at the end of each exposure time duration. For each case, five specimens were used to collect the data set. Furthermore, each sample was tested only one time to prevent the effect of previous discharge activities [27]. With this approach, the influence of bulk and interface space charge accumulation on PD activity can be compared for unaged and thermally aged specimens.

The measurement results of PDIV as a function of poling time comparing the unaged and thermally aged specimens are presented and discussed in section A. Considering the measured PDIV as a reference, the required under-voltage to extinguish PD and the over-voltage to trigger RPDIV as a function of poling time for unaged and thermally aged specimens are discussed in section B and C, respectively. Finally, the measured capacitance and dissipation factor as a function of poling time comparing unaged and thermally aged specimens are reported in section D.

It is noteworthy to highlight that only the results under negative excitations are presented for the thermally aged samples. The reason for this is that those specimens could not withstand the electrical stress/poling under positive polarity excitation even at a lower voltage level than PDIV (i.e., 0.85 PDIV). Indeed, the breakdown was observed less than half an hour, especially at a faster rise time. It can be concluded that the thermally aged Glass fibre insulated wires might be more vulnerable against positive excitation than a negative one.

A. PDIV AS A FUNCTION OF POLING TIME

The space charge accumulation can occur under unipolar square waveform excitation even at high impulse repetition frequencies (e.g., 2.5 kHz) through the presence of a DC component [14]. It can mitigate and enhance the electric field intensity in the air gap between the two wires (i.e., adjacent turns), leading to an increase and decrease of PDIV, respectively. An electric field drop can happen in the air gap due to heterocharge space charge accumulation (i.e., the polarity of the space charge is opposite to that of the neighbouring electrode). The opposite can stand for the homocharge space charge accumulation (i.e., the polarity of the space charge is the same as that of the neighbouring electrode).

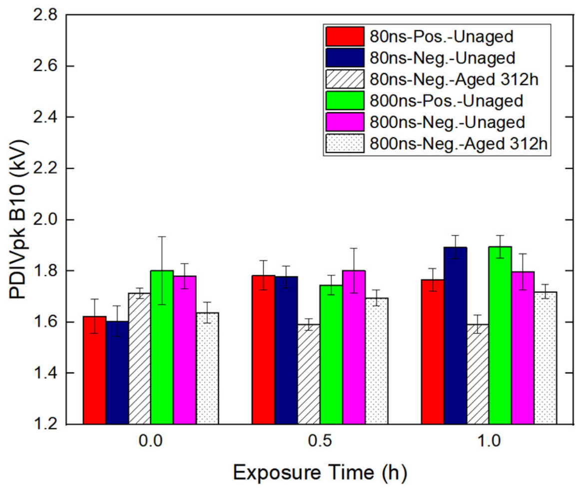
Figs. 13a and 13b illustrate, respectively, the PDIV trend and the relevant shape/slope parameter of the Weibull distribution (i.e., β) for unaged and thermally aged specimens subjected to the electrical stress under unipolar square waveform excitations. Considering the obtained results at a faster rise time (i.e., 80 ns), the measured PDIV for the thermally aged specimens is higher than unaged ones under both positive and negative polarities before poling. However, the opposite holds after half an hour. The PDIV reaches stability for the unaged specimens under positive excitation after an initial increase after half an hour. There is a monotone growing trend for the pristine samples as a function of poling time under negative excitation.

The initial PDIV increment during the first half an hour for both polarities are likely due to the permittivity reduction as observed by the capacitance measurement (Fig. 12a at 1.7 kV peak). The PDIV stabilization during the second half an hour under positive polarity can be associated with the opposite contribution of heterocharge space charge accumulation, neutralizing the impact of permittivity rise (Fig. 16a). However, more significant heterocharge space charge accumulation under negative polarity prevails over increasing permittivity delivering PDIV increment during the second half an hour. The electric field in the air gap can be mitigated by heterocharge accumulation as a function of exposure time, leading to PDIV increment about 1.2 times after one hour under negative polarity.

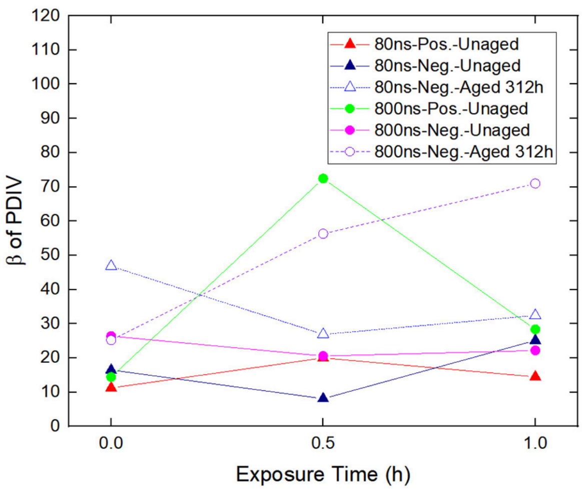
The effect of interfacial polarization has probably shorter time constant than the heterocharge space charge accumulation when poling voltage is applied with faster rise time on the unaged specimens [14]. Hence, the initial PDIV increment is ruled by permittivity rather than space charge accumulation. However, there is a reducing trend for PDIV of the thermally aged samples at 80 ns up to half an hour, reaching a saturation level afterwards. This PDIV reduction might be due to homocharge space charge accumulation prevailing the influence of interfacial polarization (i.e., permittivity reduction) (Fig. 16b). Consequently, the field in the air gap increases as a function of poling time resulting in PDIV decrement about 0.9 times just after half an hour. The effect of homocharge space charge accumulation has likely shorter time constant than the interfacial polarization for the thermally aged specimens, while the reverse is observed for the unaged ones.

Regarding the results at longer rise time (i.e., 800 ns), the unaged specimens give higher PDIV than the thermally aged ones for any exposure times. However, this superiority is observed after space charge stability (i.e., after half an hour) for the faster rise time (i.e., 80 ns). Overall, the lowest variation of PDIV can be ascribed to the obtained results at a longer rise time.

The PDIV results can be compared at a shorter and longer rise time for the thermally aged samples. It substantiates that



(a)



(b)

FIGURE 13. (a) PDIV trend consequent to poling time for unaged samples (under positive and negative polarities) vs. thermally aged ones (under negative polarity) using two different rise times, relying on the tenth percentile of the Weibull distribution. Confidence intervals with a probability of 95% are also indicated. (b) The dispersion level of measured peak values of PDIV as a function of poling time, using the shape/slope parameter of the Weibull distribution.

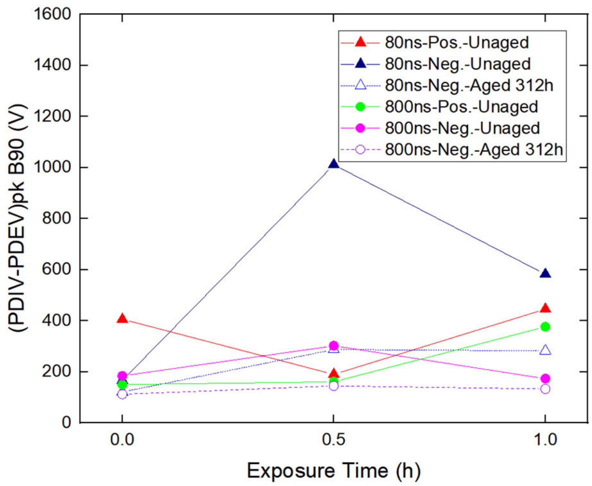


FIGURE 14. The under-voltage against PDIV to extinguish PD as a function of poling time for unaged samples (under positive and negative polarities) vs. thermally aged ones (under negative polarity) using two different rise times, relying on the 90th percentile of the Weibull distribution.

while PDIV at faster rise time is higher than slower one before poling, the opposite holds after space charge stability (i.e., half an hour).

Consequently, the impact of bulk and interface space charge accumulation under unipolar square waveform excitation would be crucial. It can affect the meaningfulness of the test data. Thus, it must be considered to design the ageing campaign to provide a reasonable evaluation of the thermally aged samples against pristine ones.

As shown in Fig. 13b, the aged samples deliver higher β/lower dispersion after space charge stability (i.e., one hour) for both rise time values. In addition, there is a monotone increasing trend for β as a function of exposure time at longer rise time and negative polarity. Therefore, these findings can be considered as ageing indicators. In addition, higher β/lower dispersion of the measured PDIV values for the aged specimens is observed at longer rise time after space charge stability (i.e., half an hour and afterwards), while the opposite holds before poling.

B. (PDIV-PDEV) AS A FUNCTION OF POLING TIME

The required under-voltage against PDIV to extinguish PD (i.e., PDEV) as a function of poling time is shown in Fig. 14. The 90th percentile (B90) of the non-exceedance probability of Weibull distribution (i.e., reliability 90%) fitting to each data set has been used to drive the trends illustrated in Fig. 14.

As shown in Fig. 14, the required under-voltage for unaged specimen excited under negative polarity with faster rise time (i.e., 80 ns) increases significantly during the first half an hour (about six times). Afterwards, it declines about 1.7 times during the second half an hour.

The growing trend is due to the electric field increase in the air gap. It is probably due to increasing either or both homocharge space charge accumulation and permittivity. Here, the former might be more plausible since the increase of permittivity was not observed through the capacitance measurements (i.e., at least at 50 Hz) for the unaged specimens subjected to the electrical stress for half an hour (Fig. 16a).

The reducing trend from 0.5 to 1 h at 80 ns and negative polarity is due to the field decrease in the air gap. It is possibly because of either or both: increasing heterocharge space charge accumulation and permittivity drop. Here, the former would be more probable because the permittivity rise was noticed for the unaged specimens subjected to the electrical stress for one hour rather than decrease (Fig. 16a). In addition, the heterocharge space charge accumulation was already speculated through the growing trend of PDIV for this case. There is an increasing trend from 0.5 h to 1 h

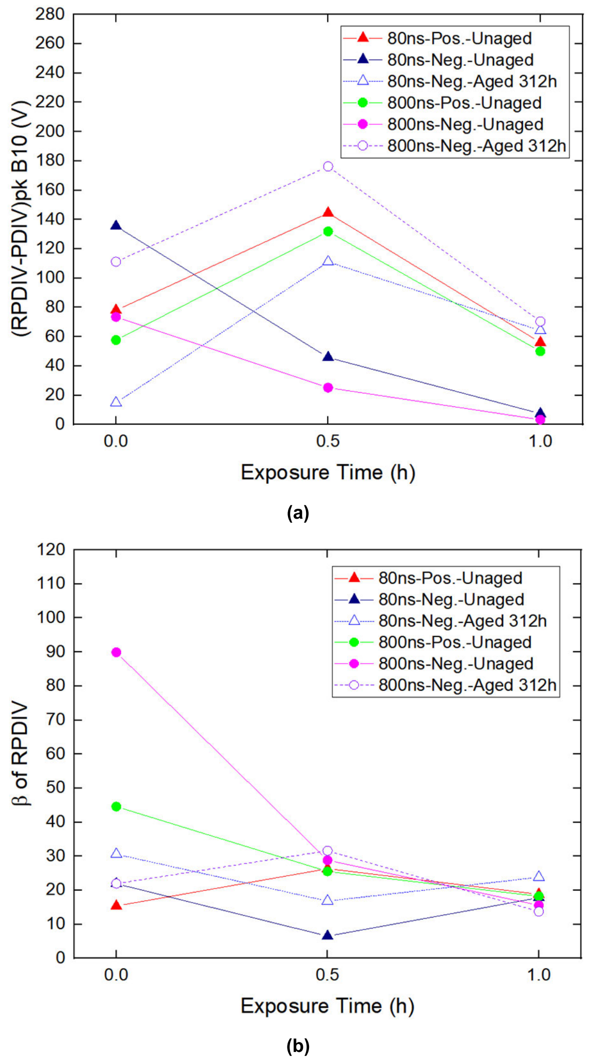


FIGURE 15. **(a) The over-voltage against PDIV to trigger RPDIV consequent to poling time for unaged samples (under positive and negative polarities) vs. thermally aged ones (under negative polarity) using two different rise times, relying on the 10th percentile of the Weibull distribution. (b) The dispersion level of measured peak values of RPDIV as a function of poling time, using the shape/slope parameter of the Weibull distribution.**

for the unaged specimens under positive polarity at 80 ns caused by electric field increase in the air gap probably due to permittivity rise (Fig. 16a). The highest variations can be ascribed to the unaged specimens excited with faster rise time, especially under negative polarity.

This under-voltage remains constant for the aged specimens after space charge stability (i.e., half an hour and afterwards) at both short and large rise times. It is noteworthy to mention that this under-voltage is stable and the lowest for all exposure intervals at the longer rise time for the aged specimens.

The impact of permittivity does not set up a valid description for the results after one hour exposure time and space charge stability for the unaged specimens. Because at faster rise time (i.e., 80 ns), although permittivity is higher under positive polarity than a negative one (Fig. 16a), the required under-voltage at negative excitation is higher. The same description can be presented for the longer rise time comparing positive and negative polarities. Hence, the influence of space charge accumulation on the required under-voltage to extinguish PD dominates as time increases (e.g., after one hour of exposure time). As illustrated in Fig. 14, it is noteworthy to mention that the almost (overlapping) convergence of the required under-voltage to extinguish PD before poling changes to distinctive values for each case after one hour exposure time.

C. (RPDIV-PDIV) AS A FUNCTION OF POLING TIME

The required over-voltage against PDIV to trigger RPDIV and the dispersion level of the measured peak values for RPDIV resorting to the shape/slope parameter of the Weibull distribution as a function of poling time is shown in Figs. 15a and 15b, respectively.

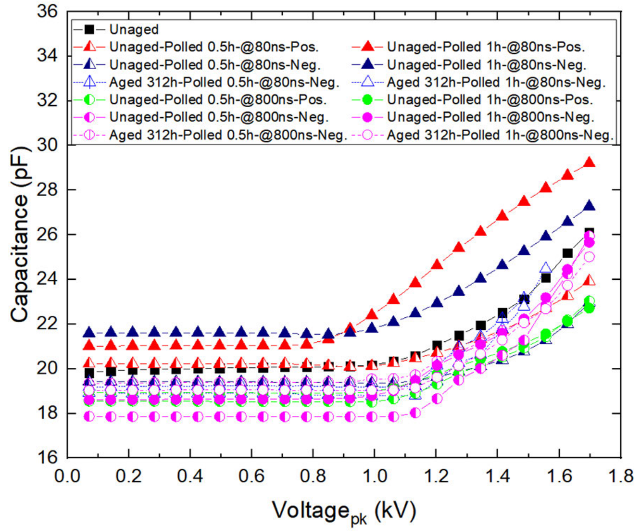
Interestingly, the required over-voltage to trigger RPDIV tends to be independent of the rise time after space charge stability (i.e., one hour). It means that it becomes almost constant for one type of specimen stressed with the same polarity. Moreover, the same trend is observed for a sample excited under the same polarity independent of the rise time.

The required over-voltage is higher for the aged specimens after one hour. It is probably also due to their lower permittivity after one hour of exposure (Fig. 16b). However, there is lower over-voltage for unaged ones after one hour. Also, probably due to higher permittivity for the unaged specimens, especially at faster rise time (Fig. 16a). Indeed, the lowest over-voltage is attributed to the pristine samples excited under negative polarity after one hour. Although for new ones, lower over-voltage is required at longer rise time, particularly before one hour, the opposite stands for the aged samples where lower over-voltage is observed at faster rise time.

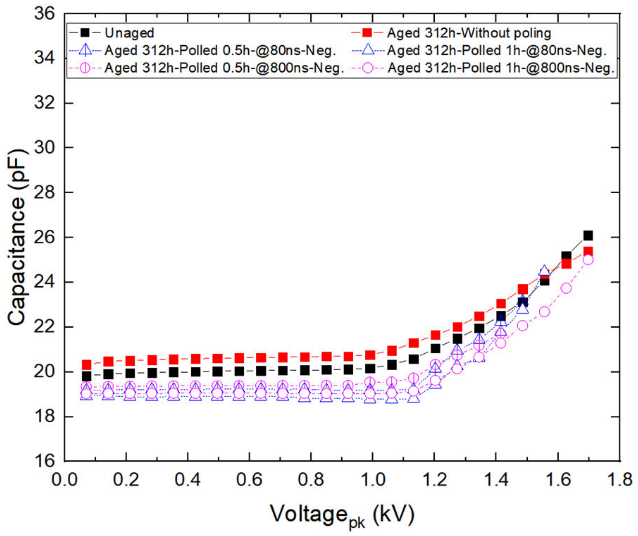
Regarding the RPDIV dispersion level quantified in Fig. 15b, it is interesting that there is a convergence trend for β as a function of exposure time, providing almost the same level of dispersion after one hour. The aged samples excited under negative polarity at 80 ns give higher β than the new ones for different exposure durations. It can be an ageing indicator for Glass fibre insulated wire.

D. CAPACITANCE AND DISSIPATION FACTOR AS A FUNCTION OF POLING TIME

The capacitance measurement tip-up (i.e., ΔC) of each specimen was performed at 50 Hz using a sinusoidal voltage waveform just after finishing the PD tests (i.e., RPDIV test) adopting a Megger Delta4000 [20]. The peak of applied sinusoidal voltage at 50 Hz was raised from zero to 1.7 kV with a step of 50 V. Fig. 16 reports the mean value of five capacitance measurements for unaged and thermally aged samples (i.e., each specified voltage rise time, polarity, and poling period).



(a)



(b)

FIGURE 16. (a) Capacitance variations of (a) all the specimens and (b) only thermally aged specimens vs the peak of applied sinusoidal voltage at 50 Hz, measured just after finishing the PD tests consequent to different exposure durations, using two different rise times. The value of the unaged specimen is shown as a reference (the mean value of five measurements for each point is reported).

The capacitance variations can be associated with the permittivity directly. As shown in Fig. 16a, the impact of the rise time on the capacitance/permittivity against the unaged specimen as a reference is interesting. In this view, stressing the unaged samples with faster rise time under both positive and negative excitations can lead to higher capacitance/permittivity of the specimen. The opposite stands for the excitation at longer rise time where lower permittivity is observed. This different effect of the rise time is still measurable at 50 Hz. Different rise times deliver different spectral energy levels and surface charge densities affecting the permittivity. In addition, other features of the voltage waveform, such as polarity, magnitude, and frequency, can play their role. Moreover, the exposure duration can affect the polarization mechanism, thus the permittivity (Fig. 16).

Fig. 16a can clarify the influence of voltage magnitude and polarity on permittivity. It shows that the one hour stressed specimens with faster rise time (i.e., 80 ns) under negative polarity deliver slightly higher permittivity than stressed ones with positive polarity up to 800 V. While for higher voltage magnitudes than 1 kV, stressed specimens with positive polarity gives a higher permittivity. The opposite holds for a longer rise time. Here, one hour stressed samples at 800 ns under negative polarity deliver higher permittivity than the stressed ones under positive polarity for the voltage levels higher than 1.2 kV. Therefore, evaluating the impact of excitation polarity on permittivity must be done at a pertinent voltage magnitude the same as used in practice.

The capacitance of the specimens stressed with different exposure time durations can be compared. Interestingly, longer exposure time durations deliver higher capacitance/permittivity for unaged samples. However, the opposite stands for the aged ones, where longer poling periods give lower permittivity (Fig. 16b).

Fig. 16b indicates that the thermally aged specimens without electrical stress deliver higher permittivity than unaged ones except for voltage magnitudes higher than 1.6 kV. Overall, the higher permittivity of the thermally aged samples can be because of the de-polymerization or ageing byproducts (i.e., polar compounds). The permittivity reduction is observed for thermally aged samples after electrical stress, interestingly for faster and longer rise times (Fig. 16b). While for the pristine specimens, the permittivity decrement is observed only after being stressed with a longer rise time (Fig. 16a). However, this permittivity reduction after electrical stress could not deliver higher PDIV for the thermally aged specimens than the new specimens after poling (Fig. 13a). It is probably due to homocharge space charge accumulation dominating the impact of permittivity for the aged samples.

Fig. 17 depicts the dissipation factor measurements tip-up (i.e., $\Delta \tan\delta$) of each specimen corresponding to Fig. 16a. This figure presents the mean value of five dissipation factor measurements for unaged and thermally aged samples (i.e., each specified voltage rise time, polarity, and poling period).

The dissipation factor is the highest for the unaged samples stressed with a faster rise time for a longer exposure duration under negative polarity. Interestingly, the dissipation factor is higher under positive excitation than a negative one for the pristine specimens considering a faster rise time (i.e., 80 ns) at a shorter exposure time (i.e., 0.5 h). It is probably due to the higher damage resulting from higher PD repetition rate and PD charge amplitude under positive polarity. It might be another reason to substantiate that positive excitation is more harmful and detrimental than the negative one for Glass fibre insulated wire. Also, a breakdown occurred for less than half an hour under positive polarity for the thermally aged

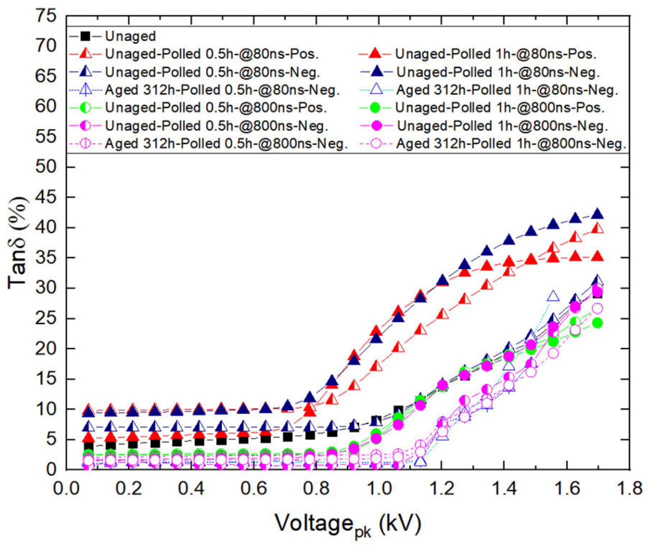


FIGURE 17. Dissipation factor as a function of the peak of applied sinusoidal voltage at 50 Hz measured just after finishing the PD tests consequent to different poling times for unaged samples (under positive and negative polarities) vs thermally aged ones (under negative polarity) using two rise times. The unaged specimen is shown as a reference (the mean value of five measurements for each point is reported).

specimens at 0.85 PDIV. However, electrical stress with a longer rise time can lead to a lower dissipation factor, even lower than unaged samples, the same as capacitance results. Finally, the dissipation factor is higher for a longer exposure time for both unaged and aged specimens under negative excitation. However, for pristine ones under positive polarity, the dissipation factor tends to be lower for a longer electrical stress duration.

The comparison of the specimens at the same condition (50 Hz), while they were already stressed by RPDIV at different rise times, shows that the stressed specimens by RPDIV with a faster rise time can indicate a higher measured value for the capacitance and dissipation factor. These findings reveal that the capacitance and in particular the dissipation factor measurements at 50 Hz can be considered as diagnostic markers for the PD activity of the winding insulation stressed by power electronic converters.

V. CONCLUSION

According to the experimental data presented and discussed in this paper, it was proven that thermally aged specimens might show temporary superiority in the short-run (i.e., before space charge stability) under unipolar excitation in a particular rise time and polarity. However, pristine specimens present better performance after longer exposure time, thus space charge stability. It was substantiated that the insulation capacitance/permittivity can be influenced by:

- The rise time of steep-fronted voltage waveform
- The polarity of voltage excitation
- The magnitude of voltage excitation
- Exposure time

It was shown that capacitance/permittivity variations are not necessarily monotone as a function of thermal ageing. Hence, the PDIV decrement trend consequent to thermal ageing cannot always be explained, resorting to the permittivity variations. The space charge accumulation under unipolar excitation (i.e., homocharge) would be more plausible for the thermally aged Glass fibre insulated wires, delivering lower PDIV after a further exposure duration.

It was substantiated that the shape/slope parameter (i.e., β) of Weibull distribution relevant to PDIV can be considered as an ageing indicator. In addition, it was found that the required over-voltage against PDIV to trigger RPDIV after space charge stability would be independent of the rise time, becoming almost stable for one type of specimen stressed with the same polarity.

Consequently, the results of the present investigation would be beneficial to researchers to define the test procedures to obtain more meaningful data when the evaluation of the thermally aged insulated wires with unaged ones is accomplished under unipolar steep-fronted square waveform excitation. In addition, this study can be fruitful for technological advancement, helping to design and manufacture insulating materials used in converter-fed motors.

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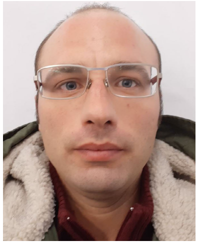

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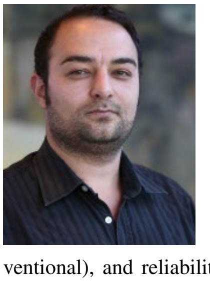

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