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Characteristics of PD under square wave voltages and their influence on motor insulation endurance

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ABSTRACT

This paper reviews results of partial discharge measurements and accelerated life tests performed on models of random and form wound insulation systems subjected to impulse voltage waveforms. The goal is to highlight how the features of the supply voltage affect the partial discharge activity and how this, eventually, reflects on the endurance of the insulation system. The most salient results are that, for both types of insulation systems, short rise times trigger PD of large magnitude, which are able to erode the insulation system faster than the partial discharges incepted using waveforms with longer rise times. In particular, failure times estimated by tests under sinusoidal voltages can be overly optimistic in assessing the long-term behavior of the insulation system subjected to impulse voltage waveforms. Frequency also is very important, as it controls the interplay between physical and chemical degradation rates. As a result, above partial discharge inception voltage the frequency acceleration rule does not hold, and can lead therefore to excessively optimistic results.

Index Terms — Partial discharges, motor drives, pulse width modulated inverters, rotating machines insulation, induction motors, square wave generators, antennas.

1 INTRODUCTION

SINCE their appearance in the seventies of the last century, power electronic drives have become a fundamental industrial tool. However, with the advent of self-commutating solid state switching devices (e.g., IGBTs), induction machine insulation issues been recorded. Investigation of such new failure mechanisms started in the early 90s (e.g., [1]- [5]).

The most important contribution to electrical stress enhancement is associated with to the reflection at the motor terminals of the voltage surges generated by the converter. Depending on the length of the cable connecting the inverter to the motor, the speed of the surges traveling on the cable, the winding/cable impedance mismatch, and the rise time of the surge, the peak voltage can be more than doubled. However, the large slew rate of the voltage surges also influence the insulation system in other ways, i.e., by inducing (a) uneven turn voltage distributions [4], (b) overheating of the stress grading region in medium voltage machines [6]-[7]. When electrical stress

becomes excessively high, partial discharges (PDs) are incepted. In LV motors using organic insulation (Type I insulation systems), the inception of PDs can lead to insulation failure in a very short time. In form-wound rotating machines, whose insulation is inorganic/organic (type II insulation), PDs can be withstood for long time, provided that PD magnitudes are not too large.

The International Electrotechnical Commission (IEC) has produced two documents dealing with these issues: the standard 60034-18-41 [8] and the technical specification 60034-18-42 [9]. The first one deals with motors with organic insulation, that should not experience PD activity throughout their service life. The second one deals with hybrid organic/inorganic insulation systems (Type II insulation).

The above summary provides an encouraging scenario: the degradation mechanisms have been identified, and "countermeasures" have been taken by the most important normative body. What else need be done?

The open points are still many. Some of them concern the long term performance of the insulation. For type I insulation, the synergistic action of electrical, thermal and mechanical stress has not been explored thoroughly. The rationale is that the thickness

of the insulation is dictated mostly by the mechanical stress experienced during manufacturing, and largely exceeds the minimum thickness needed to withstand the electrical stress [10]. This assumption has been verified by decades of experience for rotating machines fed by sinusoidal voltages. However, repetitive surges are a more heavy duty than sinusoidal ones, and specific investigation would be important.

For Type II insulation systems [9] assumes that the insulation can be qualified for use under inverter voltages by accelerated life tests performed under sinusoidal voltages. However, as we shall show in the following, PD mechanisms are significantly different under repetitive surges, which are considerably more harmful than sinusoidal waveforms.

Other points worth of investigation are PD monitoring and testing, since both tasks are made difficult by the inherent poor signal-to-noise ratio. For qualification and type tests performed by the manufacturer, it is possible to select the repetition frequency and, to a less extent, the surge rise time. As shown in this paper, these parameters can have a remarkable influence on PD magnitudes, and a correct selection can improve signal-to-noise ratios. The issue of monitoring is much more complex, as the reference voltage changes continuously as its modulating frequency and the voltage cannot be raised to verify whether a dependence exists between what measured by the PD detector and the voltage level (an indirect proof that PD are measured).

In this paper, we address a few of the points above, i.e., the issue of voltage endurance under repetitive voltage surges and the effect of surge parameters on PD features.

2 FEATURES OF PD PULSES UNDER SQUARE WAVE VOLTAGES

The physical mechanisms postulated to explain the statistical PD behavior under sinusoidal voltages are [11]:

1. Space charge field
2. Availability of starting electrons (expressed in terms of hazard rate)
3. Phenomena occurring at polarity reversal

Space charge field is due to the charges left by previous PD events, and directly influences the field at the defect size.

The availability (or hazard rate) of starting electrons keeps into account the stochastic nature of free electrons. These can be created by background radiation, or can be provided by the charge left on the defect surface by previous PD events. Often, availability of starting electrons is specified in terms of the average stochastic delay between two consecutive electrons.

Polarity reversal is a complex set of phenomena that have been empirically observed when the total field at the defect site and space charge field have equal sign [11]. Under these special conditions (at maximum two PD per cycle occur at polarity reversal), the delay between the moment the field is large enough to trigger a PD and the moment a starting electron is extracted from defect surfaces becomes statistically longer than those observed under normal conditions. This phenomenon gives rise to PD pattern characterized by "rabbit ear" structures. By considering (1)-(3), a general framework

can be obtained to explain PD under sinusoidal and square wave conditions.

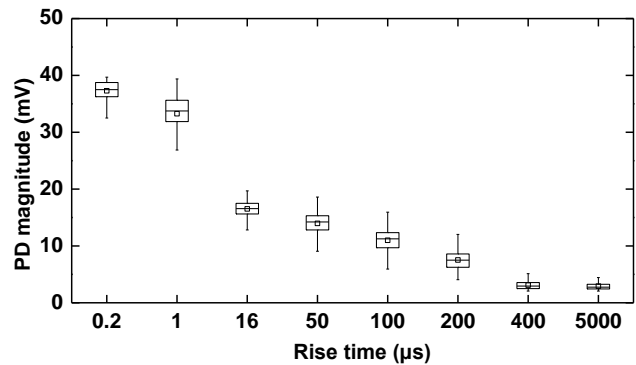


Figure 1. PD magnitude as a function of rise time in Type I crossed pair samples. Note: the 5000 μ s rise time corresponds to a sinusoidal voltage waveform.

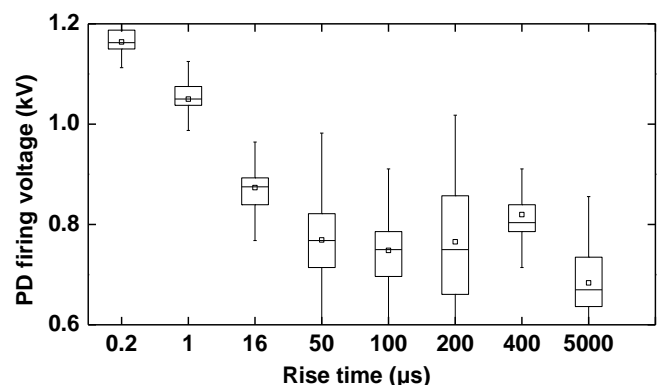


Figure 2. Firing voltage as a function of rise time in Type I crossed pair samples. Note: the 5000 μ s rise time corresponds to a sinusoidal voltage waveform.

2.1 TYPE I INSULATION SYSTEMS

A great deal of work was made in the last years to characterize phenomena in Type I insulation systems under square wave voltages. We shall discuss here some of the results obtained focusing on crossed pair samples (i.e., a couple of wires laid forming a cross, thus touching in a single point) [12]. The wires were insulated by polyamide-imide enamel in the overcoat, and had a radius of 0.7 mm. In all tests, the applied voltage was kept equal to 2.5 kV peak-to-peak.

The experiments were carried out using different generators to ensure different rise times (or slew rates) and supply frequencies. The PD signals were coupled using an antenna having a gain profile from 1 GHz to 3 GHz [12]. The PDs were recorded using a 2 GHz bandwidth, 16 GS/s digital sampling oscilloscope (Lecroy Wavepro 960).

The first conclusions gathered from the experiments were that PD magnitudes were consistently dependent on the rise time of the applied voltage, see Figure 1. By recording the applied voltage and the PD signal simultaneously, it was possible to observe that, with shorter rise times, PD with large magnitude tend to occur at higher voltage levels (here defined as, firing voltages), as shown in Figures 2 and 3. It was also

observed that, during the rising flanks (or, symmetrically, during the falling flanks) a single PD could be observed with rise times shorter than more than 1 μs . With longer rise times, more PD could be detected, as emphasized in Figure 3 [6].

These findings can be explained considering that a PD can be incepted under the conditions: (a) the electric field is sufficiently high, and (b) a free electron is available to start the discharge avalanche. Due to the stochastic nature of starting electrons, the PD process starts with some delay with respect to the time the field becomes sufficiently high. Therefore, the faster the rate of raise of the applied voltage (the shorter the rise time), the larger will be the overvoltage at which PDs will occur. Inspecting Figure 2, one can observe that, with a rise time of 200 ns, PD occur at voltages comparable with the peak voltage of the source (1.25 kV).

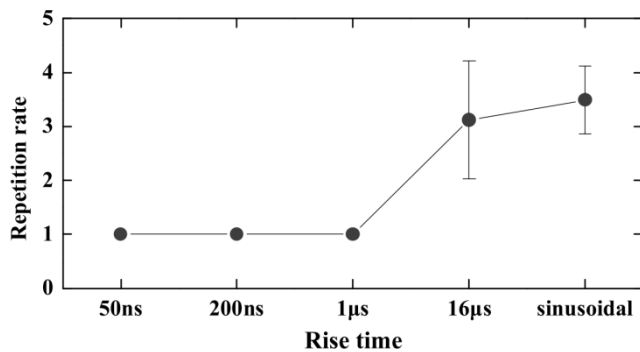


Figure 3. Mean values of PD repetition rate as a function of rise time in Type I crossed pair samples. The 95% confidence intervals are also reported in the figure.

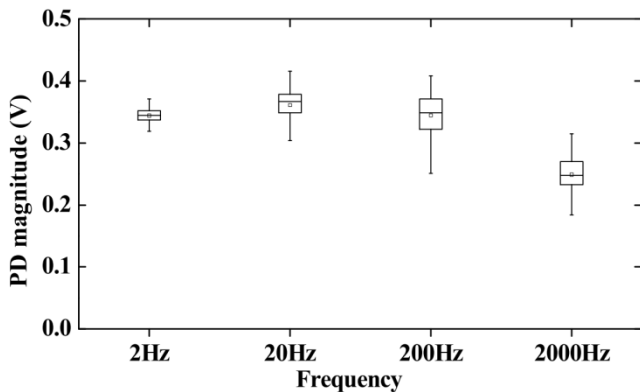


Figure 4. PD magnitude as a function of impulse voltage frequency in Type I crossed pair samples.

It is worth observing that spectral analysis of the PD pulses (reported in [12]), shows that, with shorter rise time (i.e., at higher overvoltages), PD pulses tend to have a larger frequency content. This could favor PD detection when resorting to ultra-high frequency (UHF) technologies, since at higher frequency PD tend to have more energy. When design antenna for PD tests at impulsive voltages, the influence of rise time on PD frequency features should be carefully considered in order to design UHF sensor with appropriate frequency response.

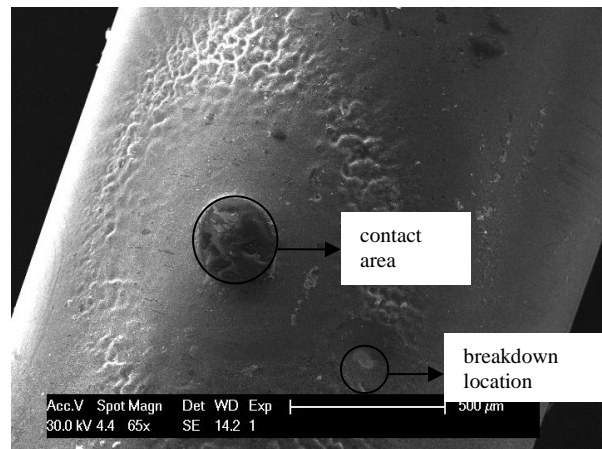
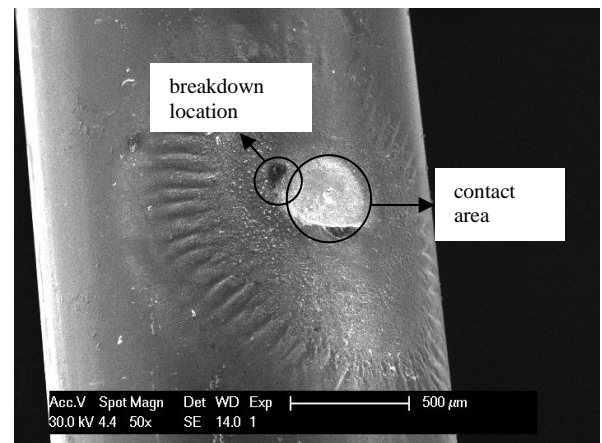


Figure 5. Breakdown SEM photos (the peak-to-peak voltage and frequency are kept at 3.5kV and 5kHz, respectively). Above: Square wave voltage with 50ns rise time. Below: sinusoidal voltage

It is interesting to observe that also frequency has a role in determining the discharge magnitude level. Figure 4 shows that, with increasing frequency, PD magnitude tends to decrease. This can be explained bearing in mind that, the larger the frequency, the shorter the period thus, the stronger will be the influence of charges left at the defect site by previous discharges (since less time is available for recombination). These could favor the extraction of electrons from the defect surfaces, thus will enable discharges to occur at lower overvoltages.

Eventually, we observed that the PD site conditions differ depending on the voltage surge rise time. In fact, as shown in Figure 5, failures tend to occur in close proximity of the contact area for short rise times, at a distance from the contact area under long rise times and sinusoidal voltages.

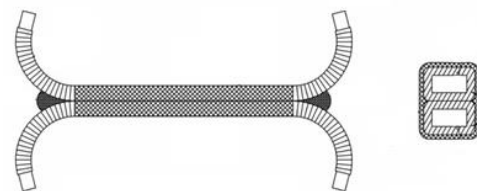


Figure 6. Specimen for testing turn/turn insulation for form wound motors

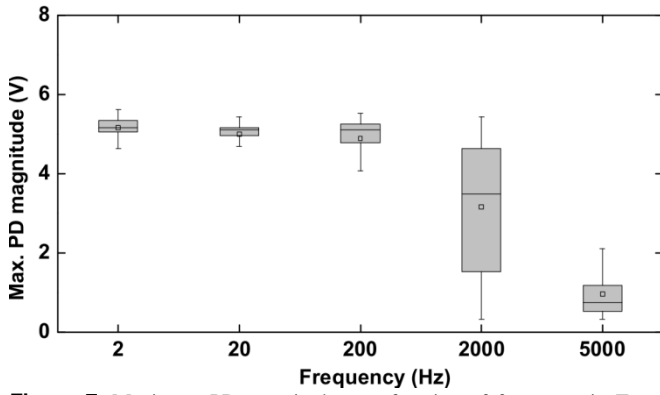


Figure 7. Maximum PD magnitude as a function of frequency in Type II turn/turn samples.

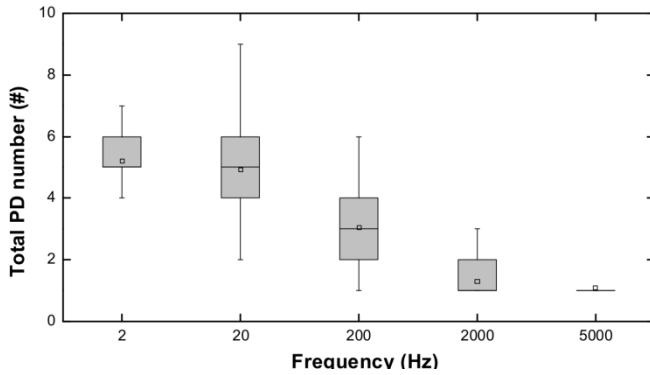


Figure 8. Boxplot of total PD number in one voltage cycle as a function of frequency in Type II turn/turn samples.

2.2 TYPE II INSULATION SYSTEMS

Resorting to the Ultra-High Frequency (UHF) PD detection method, tests were carried out on turn/turn insulation mockups (see Figure 6). In order to adapt the bandwidth of the sensor to that of the detector, we used a 40 dB UHF amplifier in series with an envelope demodulator.

The turn/turn insulation mockups were made up of two conductors with the size of 10.50 mm x 3.40 mm. The insulation consisted of polyester-mica tape with a 50% overlap. The tape was 0.09 mm thick, the total thickness of the insulation 0.17 mm. The specimens were impregnated with a solventless epoxy resin using the Vacuum Pressure Impregnation (VPI) technique.

It is also important to observe that impregnation through the VPI technique of these small objects is almost perfect, i.e., voids within the insulation are extremely small and PD can be incepted only at very high voltages. Therefore, accelerated aging under thermal cycling was carried out as a preliminary step to create voids large enough to become site of PDs. Indeed, it is likely that the IEC will discontinue the use of these specimens in favor of more complex, but more realistic, formettes.

Due to the large contact area, these specimens have a large capacitance, which prevents the surge generator to operate with rise times below 150 ns (while twisted pairs were tested with rise times down to 50 ns).

The investigation was focused on the dependence of PD magnitudes on frequency. Figure 7 confirms the data shown in Figure 4, i.e., independently of the type of insulation system, increasing the frequency reduces the PD magnitudes (here the boxplot showing the distribution of the maximum PD magnitude in different cycles are presented). Also, following a trend similar to that observed for Type I insulation, less PD events (per cycle) are obtained at higher frequencies (see Figure 8).

From the measurement data, it is possible to derive a PD pattern, similar to that obtained using ac sinusoidal voltages. In this case, instead of the phase angle, PD can be reported as a function of the delay time, i.e., the time elapsed from the zero crossing of the supply waveform to the PD event. The results of this procedure are reported in Figure 9 for a rise time of 16 μ s and for voltage impulse frequency of 200, 2000 and 5000 Hz.

Interestingly, at the lowest frequencies it is possible to observe multiple vertical structures, which tend to disappear with increasing frequency. These structures seems to be equivalent to the so-called "rabbit-ear" structures, and signal the strong analogy between what observed using 50/60 Hz ac waveforms and what measured using square wave voltages.

2.3 FINAL REMARKS

Summarizing, voltage waveforms with shorter rise times give rise to highly energetic phenomena, more harmful to insulation reliability. On the other hand, less PD events take place, and this could help insulation to withstand longer times. In order to understand which phenomenon is predominant, accelerated life test were carried out, the results of which are discussed in the next section.

3 ENDURANCE (LIFE)

In the following, we shall report results of accelerated life tests carried out on both crossed pairs and type II turn/turn insulation mockups. In light of the results reported in the following, it is important to highlight that degradation proceeds through two competing phenomena:

1. Physical degradation due to electron bombardment. This mechanisms involves C-H and C-C bond breaking through the Dissociative Electron Attachment processes [14][15].
2. Chemical degradation. This phenomenon is strongly dependent on the availability of oxygen and on the chemistry of the insulation surface. As an example, Hudon *et alia* found that corona bombardment of epoxy slabs in free air created a mixture of weak acids on the epoxy surface [16].

3.1 TYPE I INSULATION SYSTEMS

Since IEC 60034-18-41 requires that PD phenomena are absent in new machines, endurance of Type I insulation system will depend on thermal, electrical, ambient and

mechanical (TEAM) stresses and their synergistic interaction. Accordingly, endurance depends on the time that is necessary to develop cracks or cavities or surface defects within the insulation system, and allow them to grow up to a size that permits PDs to be incepted. When this happens, degradation rate becomes much larger, and failure occurs within a short time.

In the following, we shall analyze results obtained incepting partial discharge in crossed pair samples using both unipolar and bipolar waveforms. According to the previous discussion, these results cannot provide indications concerning the endurance of Type I machine. However, they are interesting as they highlight how PD interacts with the insulation system leading to breakdown. The PDIV of the crossed pair samples is around 2.0 kV. We decided to use a voltage well above PDIV, i.e. 3.5 kV, to perform accelerated endurance test.

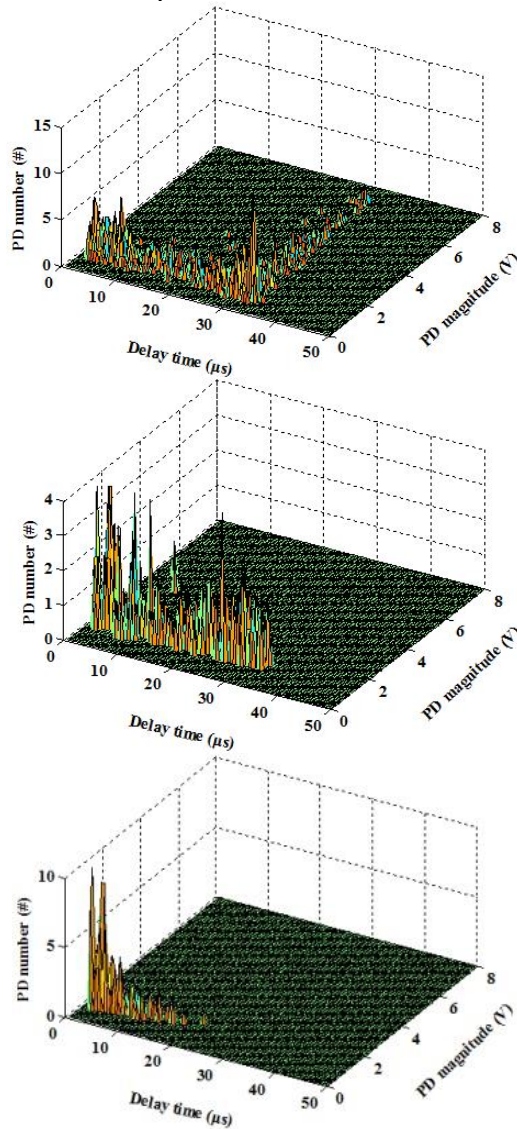


Figure 9. PD patterns recorded with supply frequencies of (top) 200 Hz, (middle) 2000 Hz, (bottom) 5000 Hz.

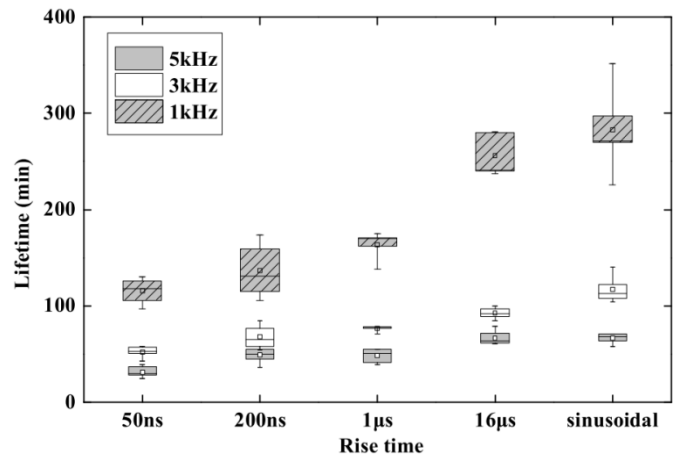


Figure 10. Time to failure of Type I crossed pair specimens subjected to bipolar square wave voltages having different rise times and frequencies.

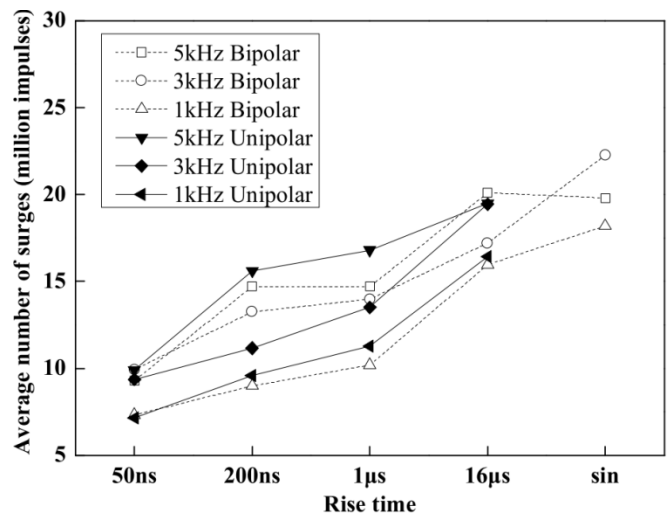


Figure 11. Average number of surges to failure of Type I crossed pair specimens subjected to square wave voltages having different rise times and frequencies.

Figure 10 shows that, the shorter the rise time, the shorter the lifetime of the insulation samples. Since PDs are generally incepted at each voltage impulse, it is not surprising to observe that failure times are longer with lower frequencies. Thus, to get more information about the interaction of PD with the insulation system, it is more enlightening to consider the number of magnitudes to breakdown. Figure 11 shows the average (evaluated over 5 specimens) number of surges to breakdown as a function of rise time and for different frequency values. The figure shows that, the shorter the rise time, the lower the number of surges to breakdown. Interestingly enough, it is also clear that the number of surges to breakdown decreases with the impulse voltage frequency.

To explain these findings, Figure 12 shows the correlation between the average number of surges to breakdown and the average value of PD magnitudes. As one could expect, the highest PD magnitudes (obtained using the shortest rise times, as explained in the previous section), correspond to the lower number of surges to breakdown. Considering the findings discussed in the previous section, this means that a single PD

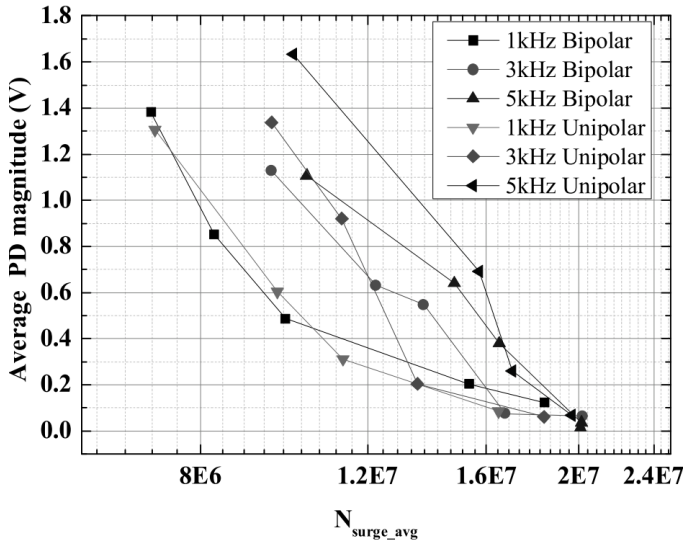


Figure 12. Correlation between number of surges to failure and PD magnitude for Type I crossed pair specimens subjected to square wave voltages having different rise times and frequencies.

event of large magnitude is more harmful than several discharges of lower magnitude. Indeed, Figure 12 highlights that, for a specified average PD magnitude level, the lowest frequencies give rise to the lowest number of surges to breakdown. The only way to explain this is by considering that as the frequency decreases, the period increases. Therefore, more time elapses between two consecutive PD events. During this time, chemical degradation due to acids and free radicals created on the dielectric surface by PD bombardment continues to erode the dielectric. An indirect proof of this statement comes from the two photographs reported in Figure 13. Both represent discharge sites in crossed pairs subjected to sinusoidal AC voltage waveforms. Differently from the site depicted in Figure 13a, which was under ordinary environmental conditions during the test, the site reported in Figure 13b was in proximity of a fan, thus subjected to an unidirectional air flow (the direction of the air flow is indicated by the white arrow in the picture). As can be seen, under normal condition (Figure 13a) the degradation site is a circular halo surrounding the contact point, and the discharge tends to occur close to the contact point itself. Due to wind induced by the fan, the halo tends to elongate in the direction of the air flow, signaling that contaminants drift under the action of the fan. Moreover, the discharge site is shifted in the direction of the wind.

The above phenomena have an impact on accelerated life tests under PD (although they are not of interest for Type I insulation system, as explained above). In fact, it is often assumed that the number of surges to breakdown, i.e., the product of the voltage impulse frequency, f , times the time to failure, t_f , is independent of frequency, thus:

$$f_1 \cdot t_{f_1} = f_2 \cdot t_{f_2} \quad (1)$$

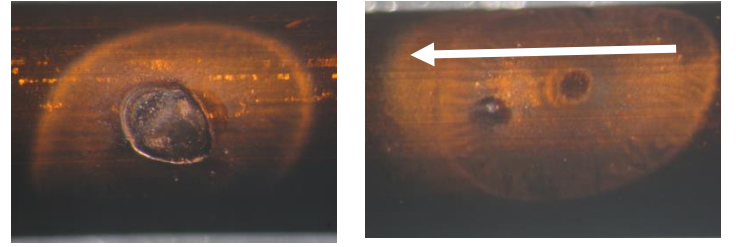


Figure 13. Discharge and erosion site in crossed pair under (a) ordinary environmental conditions, (b) unidirectional air flow (the direction is indicated by the white arrow)

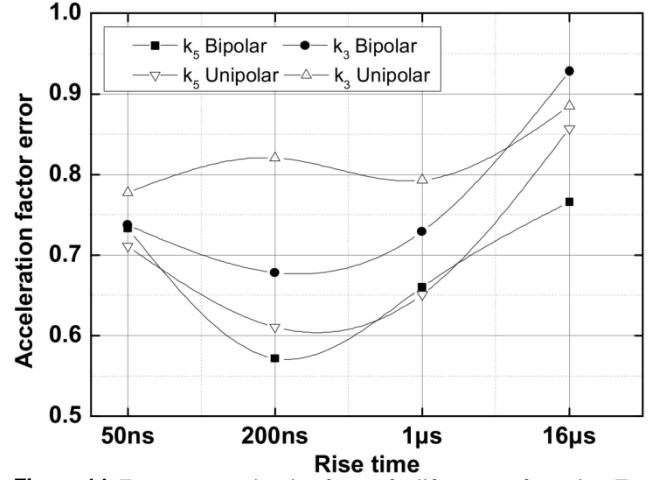


Figure 14. Frequency acceleration factors for life tests performed on Type I insulation systems.

Accordingly, if tests have been performed at f_1 but the failure time at f_2 is of practical interest, it is possible to write:

$$t_{f_2} = f_1 / f_2 \cdot t_{f_1} = AF^* \cdot t_{f_1} \quad (2)$$

where AF^* is the theoretical frequency acceleration factor. Indeed, by estimating the empirical acceleration coefficients, t_{f_2} / t_{f_1} , and comparing them with AF^* it is possible to evaluate how equation (2) is able to model the actual physics of PD induced degradation. In Figure 14, we report the acceleration factor error:

$$r = AF_{0.63} / AF^* \quad (3)$$

which is defined as the ratio between the Weibull scale parameter (63.2% percentile) of empirical acceleration coefficients, t_{f_2} / t_{f_1} , and the theoretical acceleration coefficient, AF^* . Specifically, tests at 3 kHz and 5 kHz were made to estimate the breakdown time at 1 kHz. Thus, considering for instance a test frequency of 5 kHz, the target is to evaluate how well the breakdown time at 1 kHz can be predicted by:

$$t_{1\text{kHz}} = AF^* \cdot t_{5\text{kHz}} = \frac{5\text{kHz}}{1\text{kHz}} \cdot t_{5\text{kHz}} \quad (4)$$

Since the empirical acceleration factor is always below 1, this means that breakdown times at 1 kHz are overestimated using results obtained at 5 kHz and the theoretical acceleration factor. This may be due to the synergistic action of two degradation mechanisms associated with PD, that is, electron bombardment (which might cause bond breakdown for energies above a few eV) and chemical degradation. With higher frequencies, the effect of chemical degradation might become negligible compared to electron bombardment. On the contrary, for lower frequencies, the two competing degradation modes may have comparable rates. Thus, extrapolation at different frequency may involve different degradation modes, thus it could provide non-accurate results.

3. 2 TYPE II INSULATION SYSTEMS

Endurance of Type II insulation system under square wave voltages is a debated topic, in that few data have been published. IEC 60034-18-42 supports a qualification procedure that is based on sinusoidal voltages having a frequency comparable to that of the inverter modulation frequency. Indeed, the results reported here cast some doubts on this procedure as (a) the different voltage waveforms give rise to PDs of different harmfulness, (b) if frequency-accelerated tests are carried out, chemical degradation processes might play a role which is difficult to predict.

At present we have started experiments to single out the dependence of Type II insulation system (using the same models employed to measure PD, described in the previous section) on square voltage waveform rise time and compare it with results obtained using sinusoidal voltage waveforms of the same frequency. To do that, tests were carried out using a supply frequency of 5 kHz, with a peak voltage of 6 kV. The square voltage waveforms had rise time of 150 ns and 2000 ns, respectively.

To date, only a small number of specimens broke down (4 under sinusoidal conditions, 3 and 4 under square waves having rise time of 2000 and 150 ns, respectively). The results are therefore affected by a large uncertainty, and should be considered with great care. In any case, Figure 15 hints that sinusoidal waveforms will not provide results comparable with those obtained using square wave voltages. Particularly for square waveforms having short rise times, breakdown times will likely be shorter compared with those obtained with sinusoidal waveforms.

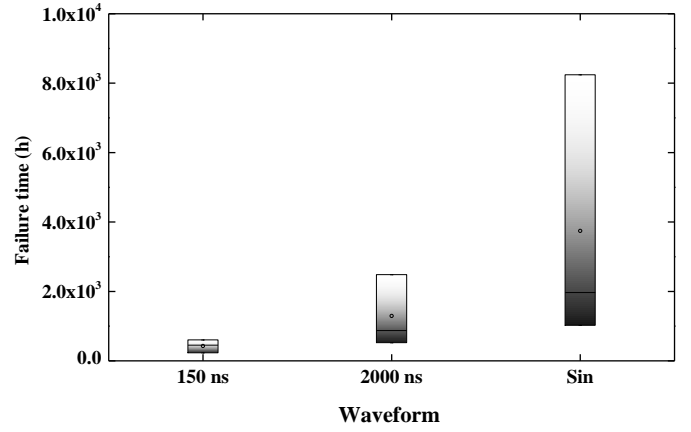


Figure 15. Breakdown times for Type II insulation models subjected to waveforms of different types.

7 CONCLUSION

The features of impulse voltage waveforms have a deep impact on PD behavior, and this turns out to affect the endurance of insulation systems. These considerations are of little importance for Type I insulation systems. In fact, the std. IEC 60034-18-41 was devised to ensure that, by design, a Type I insulation system is not affected by PD activity for a time long enough to ensure a satisfactory reliability.

For Type II insulation systems, the picture is far more complex. In fact, for both technical and economical reasons, these insulation systems are designed to withstand PDs long enough to ensure reliability. IEC 60034-18-42 allows manufacturers to test using sinusoidal voltages, and supports the theoretical frequency acceleration factor. From the results presented in this paper, this can lead to overestimates of insulation endurance (even if, the standard notes that using sinusoidal voltages "ignores the fact that the occurrence of PD and thus its effect on the ageing rate is influenced by the rise time of the impulses").

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