CHANGES IN PD PROPERTIES WITH DECREASING VOLTAGE RISE TIME IN DIELECTRICALLY INSULATED CAVITIES

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Abstract: The increased use of power electronic components in power systems requires understanding of how rapidly rising voltages affect insulation systems. One important aspect of this challenge is to measure partial discharges, PDs, which are considered as being a sign of insulation weakness and can affect its life considerably. This paper presents a continuation of our earlier investigations on the difference in PD behaviour when voltages characterized by different rise times are applied. The results indicate that the effect on the insulation system is indeed dependent on the voltage wave shape. Applying square-like voltages to a cavity with dielectric insulated electrodes significantly affects the discharge amplitude, its rise time, the inception voltage and the distribution shape. It is further examined how the dimensions of the cavity affect the PD characteristics and the investigation shows that PD amplitude increases while its duration decreases for shorter voltage rise times, being indications of a possible change in the discharge mechanism. This in turn can lead to faster deterioration and reduction of insulation service life. To illustrate the degradation process, microscopic images show how shorter rise times affect differently the cavity surface deterioration, which is consistent with the other observations.

1 INTRODUCTION

The occurrences of partial discharges, PDs, are often considered as a sign of weakness when appearing in an insulation system and may cause severe degradation. Many investigations of this phenomenon have been done for 50 and 60 Hz sinusoidal voltages using conventional and unconventional measurement methods. Presently there is an increased use of pulse width modulated voltage signals to synthesize sinusoidal voltages by power electronics. Several investigations show that this yields an increased electrical stress in diverse types of electrical insulation.

A number of time-to-breakdown studies for sinusoidal voltages have indicated that the most important parameter is the frequency of the applied voltage [1, 2]. This is basically because a higher frequency also means an increased amount of PDs occurring at a given time period, assuming that the PD properties in each period are similar. Thus the service life of the insulation system would depend inversely on the frequency and, as to our knowledge no exception to this rule has been reported.

The conventional PD measuring techniques [3, 4] are primarily utilizing the vast difference in frequency content of the applied voltage and of the PD signal itself. Direct detection of PDs at steeply rising voltages is therefore difficult as the frequency contents of the applied voltage is much higher than that of power frequency. An IEC task force has studied this issue [5], in particular for voltage impulses with 50 µs rise time or less. Additionally, a number of non-conventional techniques have been employed for these types of applications [6, 7].

To overcome the difficulties arising when using the conventional circuits, a time domain technique has recently been developed, utilizing the stochastic nature of PDs for separating them from the applied voltage [8]. To explore the feasibility of this approach and to investigate properties of PDs at varying voltage rise times, a number of different PD sources were studied [9, 10]. The PD extinction voltages at a short (~2 µs) and a long (~100 µs) rise times were compared. For dielectric cavities in particular [10], a significant reduction of the extinction voltage was observed for shorter rise times. Moreover, the number of discharges per cycle showed clearly different voltage dependence at the short rise times for the dielectric cavity, whereas this behavior remained quite similar for other sources.

A deeper study of the differences in PD characteristics (extinction voltage, number of PDs per period, duration and amplitude) for cavity sources is therefore motivated and this is the subject of this contribution.

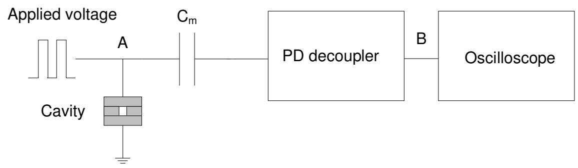

Figure 1 The measurement set-up including the PD signal decoupling circuit [11].

2 STUDY OUTLINE

Due to the stochastic nature of pPDs it is often a non-trivial task to reproduce results of similar measurements. The initial task in this investigation was therefore to reproduce the results published earlier in [10]. To measure PDs, an electrical measurement method was employed, as described in [11] in order to study the extinction voltage. The main component of the circuit included a PD decoupler to facilitate measurement of discharge duration, are illustrated in Fig.1. The same approach was applied in [10]. The test objects, in form of artificial cavity, were made out of three 0.75 mm thick polycarbonate discs pressed together. Before the assembly, the cavity was made by drilling a circular hole in the middle plate. A bipolar voltage source was applied, which offered a possibility to vary the rise times as well as voltage levels. The applied semi-square shaped voltage signals had a fundamental frequency of 313 Hz in all measurements. Data from 200 positive voltage changes were collected during each of the measurements, since the earlier investigations had shown that the changes in PD characteristics due to different rise times for the negative voltages were similar to the changes at positive polarity.

In the following, four different measurement series, elucidating various aspects, are reported. The study of the critical rise time for a lowered extinction voltage is presented in section 3 and study on the duration of the PD event in section 4. Amplitude characteristics are reported for a number of cavity sizes in section 5 and the surface degradation effects in section 6.

3 PD EXTINCTION VOLTAGE

Measurement of extinction voltage is a relevant test to find the voltage level below which no PDs should be present in the insulation system. The test is done by increasing the applied voltage until a significant amount of PD occurs and then gradually decreasing it until not a single PD could be detected.

The extinction voltage for a 3.5 mm diameter cavity was measured at rise times of 4, 7, 16, 20 and 40 µs. To measure the extinction voltage level, amplitudes changing between 4.0 and 8.5 kV were applied, and this was repeated for all the rise times investigated.

The measured numbers of PDs per period for the investigated rise times are shown in Fig. 2, from which the extinction voltages can be

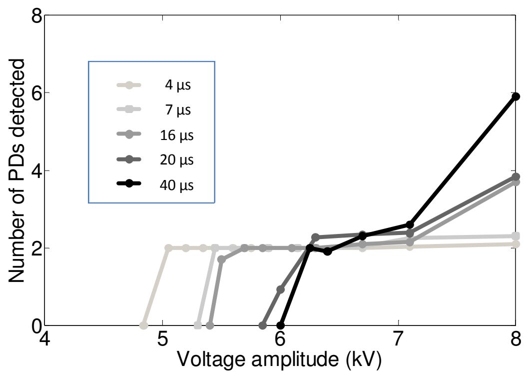

Figure 2 Number of PDs detected per period at different rise times for a cavity of 3.5 mm in diameter; note that shorter rise times yield almost a constant number of PD's per period.

estimated. Based on this approach it is clear that the short rise times result in an almost constant number of PDs at all investigated voltages above the extinction, whereas the longer rise times yield a progressively increasing number of discharges and a higher extinction voltage. The critical rise time between these extremes seem to be roughly between 16 and 20 µs. This type of behaviour has not been observed for other types of PD sources, where similar investigations of extinction voltage have been performed [9]. Thus the cavity source might be the first observation indicating a possible change of PD character with varying voltage rise time.

The position of occurrence of individual PDs on the voltage waveform has been found to be quite informative in many respects. From Fig. 2 it becomes clear that the voltage range between 7.1 and 8.0 kV is important to consider since the detected number of PDs increases significantly for the longer rise times (16 to 40 µs). In Fig. 3 the PD occurrences during the voltage rise until 7.1 kV are illustrated for the rise times of 4 and 40 µs. It is apparent to note that the spread in time and number of PDs decreases significantly for shorter rise times. Accordingly, as can be found from Fig. 2 , only two PDs per period can be detected for the 4 µs voltage pulse.

Yet another important observation from Fig. 3 is that the voltage over the cavity must be significantly different from the applied voltage since the first PDs occur close to 0 kV, indicating that the cavity must be pre-charged for making a PD event possible. Other PD sources investigated, such as needles and twisted pairs [8], have not exhibited any influence of rise time on the PD distribution.

4 PD DURATION

The duration of the actual PD event is a sensitive indicator of the physical discharge mechanism according to [12, 13]. Due to the resonant character of the PD decoupling, PD duration is

Table 1 Comparison of PD duration.

Voltage rise time (µs)	2.5	40
Average PD duration (ns)	4.3	7.0
Standard deviation (ns)	0.8	2.3

here reflected in the acquired signal by the initial rise time in the PD event, shown in Fig. 4.

To investigate possible differences in the duration of the PDs, resolving transient signals in the range of ns is necessary. To enable the use of a fast digitizer with low resolution, a special PD decoupler circuit had to be employed. The basic principle of this measurement device is described in [12]. An oscilloscope with sampling rate of 2.5 GS/s and 8 bits resolution could therefore be used. An example of measured PD signals is shown in Fig. 4 for two different rise times (2.5 and 40 µs) occurring in the cavity of 3.5 mm in diameter.

The duration of the PD signals in Fig. 4 were measured to be approximately 8 and 4 ns, respectively for the 40 and 2.5 µs voltage pulses. The average rise times and standard deviations for both pulses, based on data from 100 recorded periods, are presented in Tab. 1. The standard deviation values indicate that the difference seen in Fig. 4 has some statistical significance, even for a reasonably large number of discharges. It is apparent from Tab. 1 that the PD duration is shorter for the shorter rise time but the difference is not large enough to firmly conclude that it is due to a change of the actual PD mechanism.

A significant decrease in rise time to about 1 ns or less is expected for a change from a Townsend to a streamer discharge [13]. When measuring the rise time of the PD it is however important to realize that both parasitic components and the electric circuit cause delays and disturb the shape of the actual PD pulse. An approximate mathematical model of the measurement circuit according to [11] was therefore used in order to compare the calculated PD signal at the oscilloscope input with the signal introduced at the coupling capacitor, marked ‘B’ and ‘A’ respectively

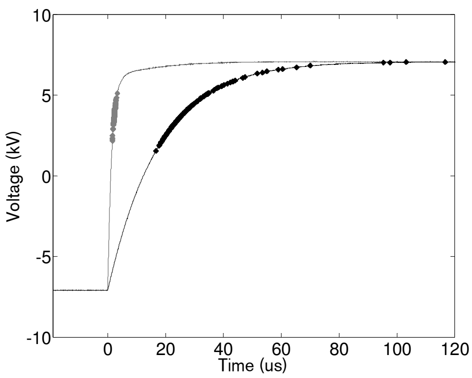

Figure 3 Occurrence of PDs on 7.1 kV voltage signal for different rise times, at 4 and 40 µs in a 3.5 mm cavity; note that for the longer rise time PDs occur even after the voltage reaches a stable level.

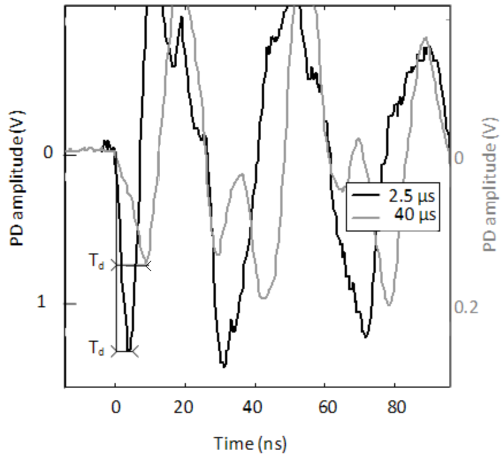

Figure 4 PD signals duration measured at two different voltage rise times in a 3.5 mm cavity indicated as T_d. Note the different y-scales for the two signals.

in Fig. 1. The steepness of the simulated PD pulse at the input was then compared to the corresponding pulse at the decoupling capacitor and the result indicated that a PD occurring with 1 ns rise time will be measured as about 4 ns long due to the influences from the electric circuit. This means that for the shorter rise time the duration of measured PD should correspond to about 1 ns and for the longer rise time to about 7 ns, as for the latter the circuit responds with approximately the right rise time. This means that the PD duration for the shorter rise time could be in the range of what it expected of a streamer type of discharge.

5 PD AMPLITUDE AND CHARACTERISTICS

To better understand the discharge process in the cavity, more indications for a change of its mechanism are needed. Indeed the most common quantity associated with PDs is their amplitude (or apparent charge). The measurement set up was calibrated using a calibrator unit with 100 pF capacitor and 200 pC charge, which provided a relation between the measured PD signal voltage and the apparent charge. According to the calibrator, 200 pC corresponded to about 35 mV signal in this set up. However, the relation between

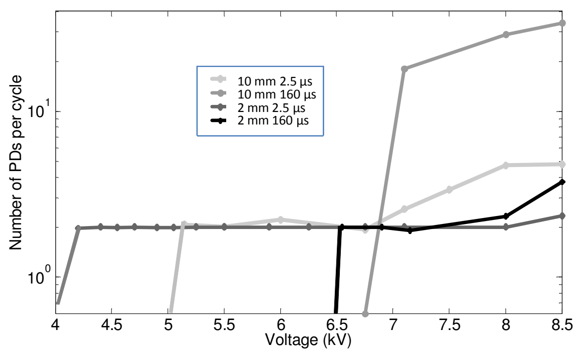

Figure 5 Extinction voltage plot for 2 and 10 mm diameter cavities. Note that the difference in PD characteristics discussed in chapter 2.1 prevails.

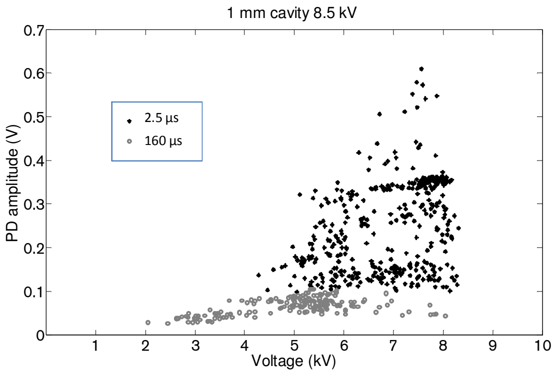

Figure 6 Amplitude of PDs occurring in a cavity of 1 mm in diameter as function of the applied voltage. The PDs occur at significantly higher voltage levels for the shorter rise time and have considerably higher amplitude.

voltage and charge becomes less accurate if different discharge mechanisms are involved that significantly differ in their own rise times and duration. Therefore the PD amplitude is here presented in volts.

To investigate how different cavity dimensions affect the discharges, several cavity diameters were tested: 1, 2, 4 and 10 mm. Here one short and one long rise time, 2.5 and 160 µs respectively, were applied to limit the amount of data. The extinction voltage plots for 2 and 10 mm cavities are shown in Fig. 5, further confirming that the observations presented in Fig. 2 and in [10] remain at least quantitatively valid for vastly different cavity diameters.

By plotting the PD amplitudes as a function of the applied voltage one could observe differences in both the amplitude and the voltage level at which PDs occur for all the dimensions investigated, as respectively shown in Figs. 6 – 9 for 1 to 10 mm cavities. Two rise times were used, 2.5 and 160 µs, and these were intentionally chosen shorter and longer than those from Fig. 2 for elucidating the fact that changes in the PD

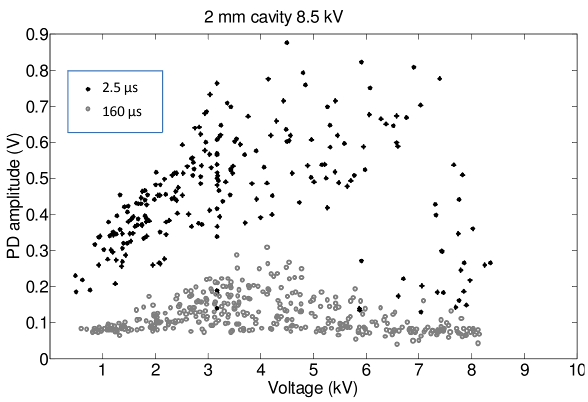

Figure 7 Amplitude of PDs occurring in a cavity of 2 mm in diameter as function of the applied voltage. At this size there is no significant difference in PD occurrence voltage in contrast to all the other cavity sizes. This could be a statistical effect.

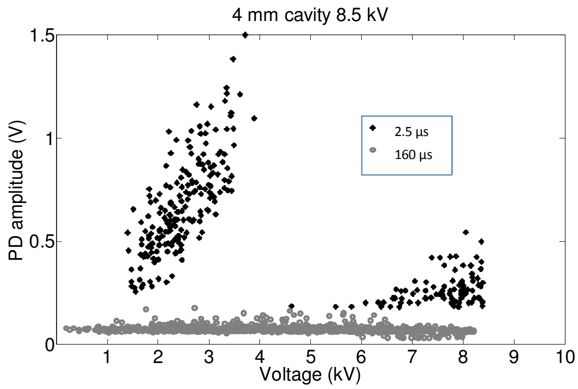

Figure 8 Amplitude of PDs occurring in a cavity of 4 mm in diameter as function of the applied voltage. In this figure two generations of PD are visible for the short rise time. Note that the amplitude scale is about twice as large as in Figs. 6-7.

characteristics are significant also for different cavity geometries. At the shorter rise time (2.5 µs) PDs are on average displaced to higher voltage levels by about 10% of the peak value in all the cavities tested, as compared to the longer ones, which again indicates that the shape of the applied voltage has here a significant influence. The PD amplitude for the long rise time (160 µs) remained about the same in all cavity dimensions whereas it increases with cavity diameter for the short rise time.

As the number of discharges for long and short rise times is different, it is interesting to also compare the total charge, i.e the summarizing the PD amplitude during each cycle. Fig. 10 shows the average single PD amplitude and the total summarized PD amplitude per cycle for all the cavity dimensions. It is apparent that although the total number of PDs increases at longer rise times, the total summed amplitude remains considerably lower. The PD amplitudes are on average 3 - 4 times higher for the short rise time than the long one, which should certainly influence the charge distribution in the cavity and thus contribute to the large difference in extinction and inception voltage,

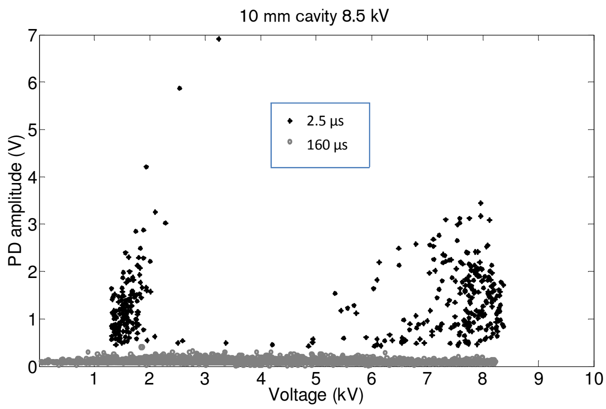

Figure 9 Amplitude of PDs occurring in a cavity of 10 mm in diameter as function of the applied voltage. The PD amplitudes have increased considerably as compared to those in Fig. 8.

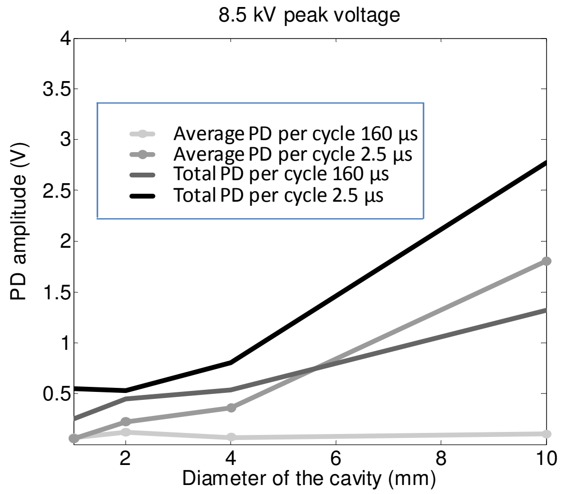

Figure 10 Total and average PD amplitudes in cavities of different diameters. Note that the average PD increases significantly with increased diameter.

as seen in Fig. 2 for different rise times. As expected [13], the voltage level required for breakdown in a dielectrically insulated cavity is approximately 5% higher for a streamer than for a Townsend discharge, the fact that PDs starts to occur at a higher instantaneous voltage for the short rise time as compared to the long one motivates a possibility that we here perhaps deal with discharges of different nature. This hypothesis is further strengthen by the fact that discharge amplitudes also differ significantly, as it is known that Townsend and streamer mechanisms show large differences both in amplitude and rise time of the discharge signal [12, 13].

6 DEGRADATION TEST

It has been concluded in the previous sections that the rise time of the applied voltage has significant influence of the characteristics of PDs occurring in a cavity. Particularly the average PD amplitude as well as the total charge increase at shorter voltage rise times, which leads to the

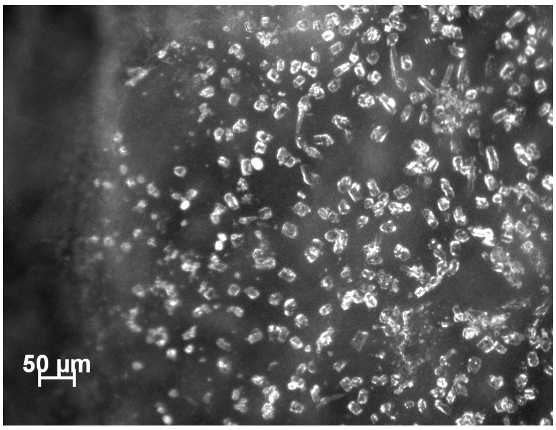

Figure 11 Microscopic view of one (of two surface plates of the cavity) exposed to 2 million cycles at 40 µs rise time - appearance of a large number of small pits, approximately similar in size.

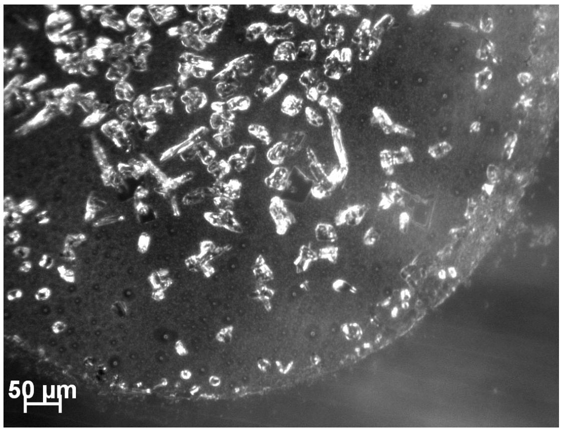

Figure 12 Microscopic view of one (of two surface plates of the cavity) exposed to 2 million cycles at 2.5 µs rise time - larger but fewer pits.

expectations that the difference in the discharge mechanism should affect the degradation of the surface material of the cavity.

Thus two cavities in a polycarbonate material, each with 1 mm diameter, were exposed to 9.5 kV voltage pulses with 2.5 and 40 µs rise times. The voltage amplitude was selected to be well above the inception level. Results of a microscopic study of the defects appearing on the surfaces of the cavity are shown in Figs. 11 and 12. The pictures reveal that for the longer rise time considerably smaller pits occur on the surface of polycarbonate as compared to the one exposed to shorter pulses. Additionally the number of defects is increased on the surface exposed to the longer voltage pulses. This agrees well with the observations presented in the previous sections, for shorter rise times the number of PDs decreases but the amplitude increases considerably.

7 CONCLUSIONS AND OUTLOOK

The studies presented above have shown that the number of PDs per period under exposure to short voltage pulses possess a very different dependence as compared to the exposure to longer ones. Further, PDs at the shorter rise times occur at a higher voltage level and thus the relative time delay relative the polarity reversal increases. This effect appears to be reproducible in cavities of different dimensions while exposed to voltages of several rise times. For the studied cavity in polycarbonate (diameter 3.5 mm, height 0.75 mm), the critical rise time at which the behavior changes lies between 10 and 20 µs. It has additionally been observed that PDs appearing in all the studied cases have larger amplitudes at shorter rise times, which, on average, also increases with voltage level and cavity diameter. For the longer rise times the PD amplitude remains approximately constant and at a lower level, though more PDs are generated per period. For the increasing cavity diameters, the average PD amplitude also increases, however not at the same pace as for the short rise times. In addition, the duration of PD event is significantly shorter at shorter voltage rise times than at longer ones.

Taken together, these conclusions suggest a possible change of the PD discharge mechanism as the voltage rise time decreases. At the present stage, one may only speculate on the nature and cause of this change but a transition from a Townsend to a streamer-like discharge seems to be a possible scenario. It has been considered in [12] that the evolving PD degradation in gas filled cavities do cause changes in the discharge mechanism, so that streamer, Townsend and pitting phenomena occur as the degradation proceeds. This affects the number of PDs occurring in each period. However, the differences described in this paper reflect behavior attributed to the influence of rise time influence and not the degradation, as in [12].

It is rather difficult at the present stage to estimate the effect of mechanism change on the insulation system life time. Considering the shorter duration and larger amplitude of the streamer-like discharges, it seems probable that the deteriorating effects may be stronger. The degradation tests performed suggest indeed that this effect can potentially have an impact on the service lifetime of insulation systems exposed to rapidly changing voltages, and therefore deserve further studies.

While considering the dominating belief within the electrical insulation community that only the frequency of applied voltage affects the service lifetime, while the voltage rise time has only a minor influence, it seems important to investigate any possible exceptions from this rule. Our previous investigations [10] have indicated that the rule seems valid in some insulation systems, but not in all. If and when such exceptions are established, the result will have an impact on design and production of electrical apparatuses.

8 ACKNOWLEDGMENTS

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