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# PD Properties when Varying the Smoothness of Synthesized Waveforms

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## ABSTRACT

**The increased use of power electronic components in power systems makes it important to understand how rapidly rising voltages affect insulation systems. One vital aspect of this challenge is the measurement of partial discharges, PDs, which are considered as being a sign of weakness and can affect the life of insulation considerably. In this paper an approach is presented to measure PDs in a dielectrically insulated cavity when exposed to pulse width modulated (PWM) voltage shapes with different degree of smoothness. This is a continuation of our earlier investigations on the different behavior of PDs where voltages characterized by different rise times were applied. The present investigation shows that the PD amplitude decreases significantly already at a moderate level of PWM voltage smoothness to a magnitude that is about the same as for sinusoidal voltage shape. For the phase resolved PD (PRPD) pattern to become similar to the normal AC pattern it is required that the remains from PWM steps are lower than the extinction voltage. This work elucidates how PDs are affected by synthesized waveforms and limits for a sufficient smoothing level are found, which is of importance when designing insulation systems exposed to fast transients.**

Index Terms — **Partial discharges, PWM, square like voltages, measurements, cavities.**

## I. INTRODUCTION

Recently the need for a more efficient control of the energy sources has implied an increased use of power electronics. In particular a train of square shaped voltage pulses is applied to synthesize sinusoidal waveforms, a so called pulse width modulated voltage (PWM) pattern. Numerous investigations suggest however that such stresses affect insulation systems negatively, particularly as a result of an increased amount of generated partial discharges (PDs) when high frequency components are present in the applied voltage. This phenomenon is an important cause of degradation and early failures and is therefore important to monitor. For limiting the effect, filter techniques are utilized to smooth the PWM pulses to both increase the power quality and to reduce the stress, as the degree of smoothness influences the lifetime of insulation systems. Such techniques are, however, associated with additional costs.

The conventional PD measuring techniques are primarily utilizing the vast difference in frequency content between the applied voltage and the PD signal. A direct detection of partial discharges at a PWM voltage is therefore difficult since its frequency content is considerably higher than that of the power frequency. This difficulty has triggered an ongoing discussion about the most suitable ways to diagnose high voltage insulation systems exposed to higher frequency stresses and several approaches have been proposed [1, 2].

Different voltage patterns have been suggested [3, 4, 5] with the aim of creating similar PD characteristics as within an insulation system exposed to actual PWM voltage. An example is a sinusoidal voltage with superimposed high frequency pulses [6, 7], which altogether are supposed to resemble the stress appearing on inverter driven equipment due to contributions from steep voltage fronts. Similar combinations of high and low frequency components had been used to simulate the stress present in HVDC converter stations [8]. Other waveforms used are square shaped voltages with different rise times and frequencies but hitherto with 50 % duty cycles [9, 10].

It has been demonstrated [11, 12] that PDs occurring at rapidly rising square voltages can be measured by applying differential probes, UHF sensors and current transformer bridges. These methods are useful at lower voltage levels, while significant problems appear at increased voltages. To overcome the difficulties arising when using the conventional measuring circuits, a time domain technique has recently been developed, which utilizes the stochastic nature of PDs to separate them from the applied voltage [13, 14]. It allows for exploration of the properties of PDs at varying voltage rise times and in various PD sources, as demonstrated in [15, 16] by applying semi square voltage pulses. The same approach can, in theory, be utilized to measure PDs at PWM voltage shapes. However some characteristics of PWM sources make

the technique less suitable. It is possible, for example, to relate position of PDs with respect to specific polarity reversals, but it is not possible to relate these events to the phase position within the modulated waveform. Thus it becomes impossible to create a phase resolved PD (PRPD) pattern, which makes a direct comparison with sinusoidal conditions difficult. The way to overcome this issue is discussed in this paper and a solution is presented. Also the degree of PWM waveform smoothness yielding the same level of PD activity as for sinusoidal waveforms is defined.

## II. PWM-PD ANALYSIS

### A. Basics of the PD detection method

Time domain detection of PD at fast rising waveforms [14] makes use of moderately sharp frequency filters in a PD decoupler. This PD decoupler is capacitively connected to the test object and the PD signal is amplified by resonances inflicted by high impedance terminations of a coaxial cable connected between the electrical filters and the high resolution digitizer, see [15]. The duration of the resonances from each PD is about 0.5 µs.

Since PDs occur randomly, the contribution from the applied voltage after filtering can be removed by subtracting a calculated average value of the acquired signal, leaving random events like PD in the remnant. Thus, PDs can be detected in cases when the shape of the applied voltage is sufficiently stable. This technique is applicable to most PD sensors [17] and is thus not limited only to the decoupler utilized in the present paper.

Moreover, PDs are detected when the remnant signal exceeds a threshold where both the maximum amplitude and the time of occurrence are identified. With adequate time resolution, individual PDs can be identified accurately. The measurement data were collected by means of an acquisition card (NI PCI 5122) with sampling rate of 100 MS/s. This sample rate is high enough to resolve the amplitude of
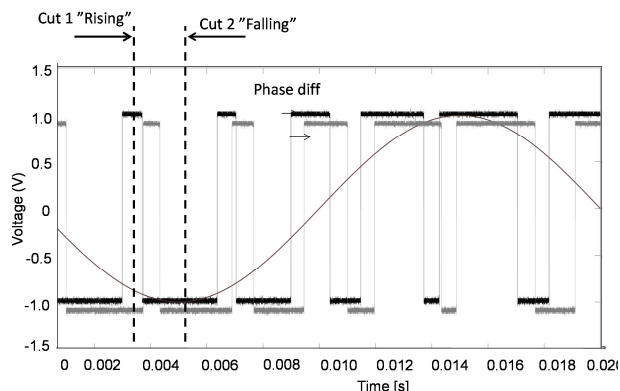
individual PDs as was verified in previous investigations on the same test object [15]. As the used detection circuit does not involve integration, the risk for over-estimating the amplitude of individual discharges due to superposition is decreased considerably.

### B. Impact of PWM waveform

In a PWM voltage pulse train the pulse width changes in relation to the phase position on the modulated waveform, as illustrated in Figure 1. The generated sinusoidal form defines the modulation or fundamental frequency, whereas the pulse repetition rate is denoted the carrier frequency. PWM waveforms are further characterized by a modulation depth that reflects how much of the available pulse width is used for the modulation, less modulation means that pulse width variation is reduced. It is necessary to consider the phase drift between the carrier and modulation frequency, as indicated in the figure. This is obvious in cases when the ratio between the carrier and modulation frequencies is not an integer, as the switching events do not appear at the same phase positions in different voltage periods. There may also appear jitter in the firing of the steps in addition to the phase drift, which altogether cause that pulses may vary by several µs in length at the same phase position. If the PWM carrier waveform and the modulated waveform were in perfectly stable phase match, it would be straightforward to make PRPD analysis for the individual steps and the entire generated period by applying the stochastic PD detection presented in [14]. As this is often not the case, the approach has to be modified substantially for taking the drift and the jitter into account.

### C. Signal processing algorithm

The two most important issues when creating a suitable algorithm of PD analysis is enabling a possibility to detect PDs versus the closest voltage step and the relative time position within the modulated frequency. This implicates that at least two time scales are necessary, which can be accomplished by first analyzing each PD in relation to the step event and then relating this time to the position within the period of the modulated signal. The first necessary action to



**Figure 1** A sinusoidal voltage shape synthesized by a bipolar two level PWM converter with carrier frequency 300 Hz. Two PWM waves recorded at different times are shown. The phase drift between the carrier and modulation is indicated, whereas the timing jitter is invisible in the scale of the figure. The PWM waves are displaced in amplitude to facilitate the readability and the indicated cuts refer to the black PWM wave.
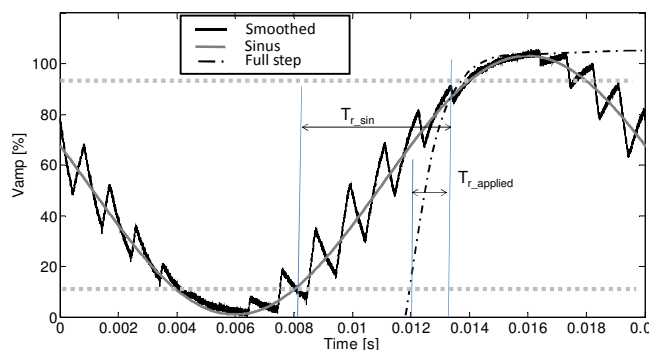


**Figure 2** The definition of smoothness applied relates the rise time of the smoothed and the ideal sinusoidal voltage waveform. Note that the rise time is defined between 10 and 90 % of the magnitude.

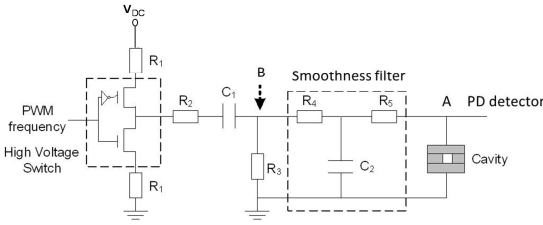| $R_1$(kΩ) | $R_2$(kΩ) | $R_3$(MΩ) | $C_1$(nF) |
|---|---|---|---|
| 3 | 1 | 100 | 68 |



**Figure 3** Test setup including a 2 level bipolar PWM generation circuit. The high voltage switch is a Behlke HTS 301-03-GSM.

accomplish this task is to identify the position of each step and classify the steps in a suitable number of classes. For a two level inverter these classes are respectively associated with the "Rising" and the "Falling" pulse flanks or edges.

In a case of multilevel inverter, a larger number of classes may be required, but otherwise the same principle can be applied. Several approaches can be utilized in order to find the position of each step. However, to allow PD detection at voltage shapes with a high level of smoothing or at sinusoidal waveform, information about the original steps is needed. Here a non-smoothed PWM voltage can be used as a separate synchronization channel to relate the smoothed signal to the non-filtered one. Based on this synchronization, the position between each of the "Rising" and the "Falling" flanks within the modulated period are detected as indicated in Figure 1 for the first two voltage steps. These positions are then utilized to divide the captured waveform into separate traces, each stored according to class. In Figure 1 the PWM waveform contains eleven flanks, thus this would implicate a total of eleven traces where six are classified as "Falling" and five as "Rising". Within each of the classes the starting position is adjusted to make the voltage step appearing at the same time in every trace. This implies a time correction factor for each step in relation to the original starting point of the trace. This parameter is necessary in order to calculate the initial position of PDs within the time period of the modulated voltage. When each new trace within a class is adjusted to the previous flanks of the same class, the average value of the traces can be calculated and used to eliminate voltage remnants, which enables detection of the PDs within the captured trace. The

**Table 1:** Different electric filter components and their characteristics

| Level | $R_5$ (kΩ) | $R_4$ (kΩ) | $C_2$ (pF) | Smoothness | $T_r$ (µs) |
|---|---|---|---|---|---|
| 1 | 2 | - | - | 0.0003 | 2 |
| 2 | 12 | - | - | 0.0018 | 12 |
| 3 | 100 | 100 | - | 0.006 | 40 |
| 4 | 300 | 100 | - | 0.028 | 160 |
| 5 | 1300 | 100 | - | 0.11 | 730 |
| 6 | 1300 | 100 | 100 | 0.18 | 1200 |
| 7 | 2300 | 100 | 100 | 0.29 | 1900 |

detected PDs can then be related to two time frames: the first in relation to the nearest voltage flank and the second to the phase position within the modulated frequency. One additional advantage with classifying the PWM signal into the "Rising" and the "Falling" flanks is that non-symmetrical behavior of PD characteristics can easily be analyzed.

### D. Quantification of smoothness

The harmonic spectrum of the applied PWM pulse train can be utilized to classify the level of smoothness by taking the ratio between the amount of harmonic distortion and the modulated frequency [18]. Thus lower smoothness implies a higher degree of harmonic content on the applied waveform. However a different approach is chosen in this investigation, both to enable a more intuitive correlation between the different levels of smoothness investigated but also with the possibility to clearly include the influence of the rise time of the applied PWM pulse train maintaining the same peak- to peak ratio. To quantify the level of smoothness, the relation between the rise time of the applied voltage and a sinusoidal voltage at power frequency was used, as shown in Equation 1. Note that Equation 1 assumes that the rise times for both signals are measured between 10 and 90 % of the peak- to peak value, thus the rise time of a 50 Hz sinus is 6.7 ms. This is illustrated in Figure 2, for both the rise time of a full step, representative for the PWM pulse train, and a sinusoidal wave used as reference. With this approach the smoothness value reflects not only the peak-to-peak value of the individual steps but also the rise time of the applied voltage. Thus, it enables a quantification of the full range of waveforms investigated in this paper.

$$S = \frac{T_{r\_applied}}{T_{r\_sin}} \tag{1}$$

### III. MEASUREMENT SYSTEM SETUP &TEST RESULTS

### A. Voltage generation and test object

To imitate an insulation defect, a cylindrical cavity (diameter of 4 mm) in a system of three 1.00 mm thick polycarbonate discs pressed together was used, as indicated in Figure 3. The test object was connected between point "A" of the measuring set-up and ground. A two level bipolar PWM source was connected to point "B", offering a possibility to use different rise times, modulation and carrier frequencies as well as voltage levels. Parameters of the circuit (Figure 3) were selected according to data in Table 1 to smooth the PWM signals. To enable a comparison of the measured PD characteristics arising at the various PWM voltage shapes, a sinusoidal wave form was utilized as a reference. This voltage was obtained from a regulated 40 kV$_{pp}$ voltage transformer.

When measuring PDs, the peak- to peak voltage level was adjusted to about 17 kV$_{pp}$ for all rise times investigated, since the main objective was to study the PD pattern for a gradually increased smoothness of the PWM voltage waveform.

Before each test, the specimen was conditioned so stable PD characteristics were obtained. To further ensure reliable
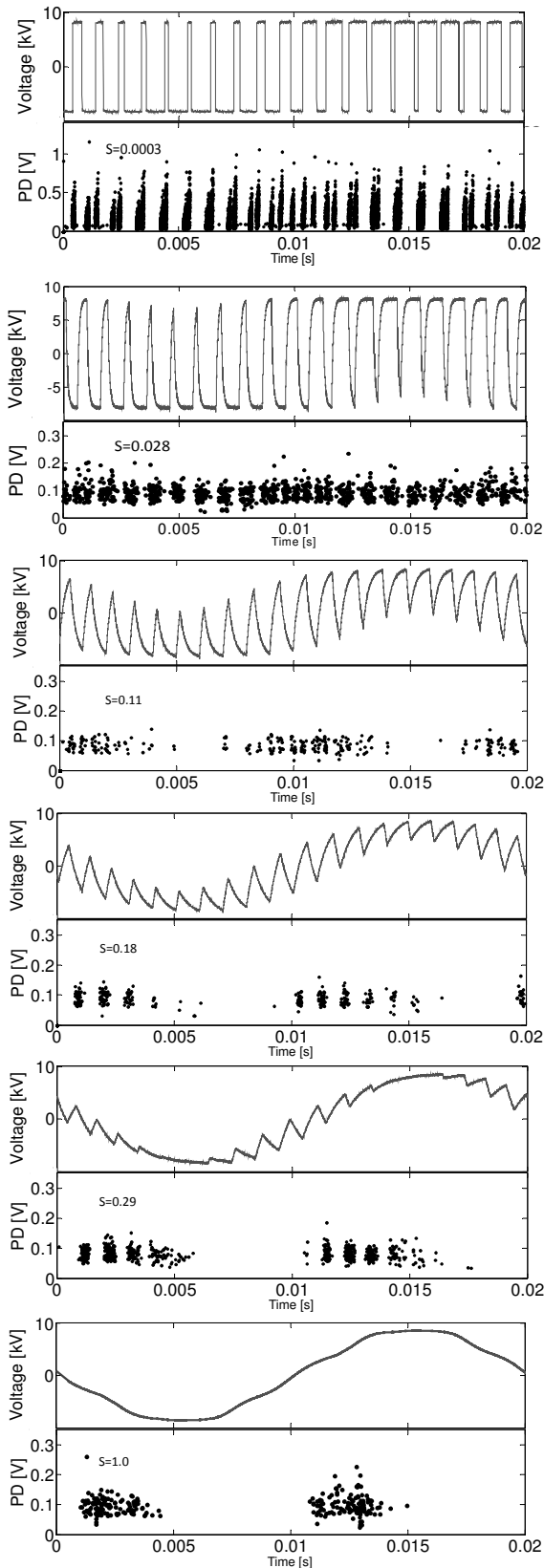
**Figure 4** PD patterns at different levels of PWM smoothness and for a sinusoidal waveform. In each figure, the applied voltage is shown in the top panel and the observed PD pattern in the lower. Note that the PD amplitude scale is larger for the lowest level of smoothness.

test results, repeated investigations have been performed on the same test specimen for different levels of smoothness showing that the observations are consistent; this suggests that degradation of the cavity endplates does not influence the presented results.

The applied carrier frequency was 1 kHz and the modulation frequency was 50 Hz. Thus the relation between the two frequencies was an even multiplier, which facilitated the interpretation of PD patterns in relation to the modulation frequency. This is, however, not a necessary condition to enable the measurement and analysis of PDs.

The PWM wave form was generated by an Agilent 33220A, set at 34 % duty cycle variation. For additional details regarding the measurement procedure, see [12].

### B. PD characteristics at varying PWM smoothness

The investigations concentrated on analyzing the amplitude and the number of PDs. In Figure 4, the shape of the applied voltage as well as the corresponding PD pattern is shown for an increasing level of smoothness, until sinusoidal conditions are reached. It is apparent that PDs occur on each voltage flank at the low smoothness levels. It further appears that the PD pattern is clearly influenced by the phase shift and jitter in the PWM signal. If the PDs were occurring only on the voltage flank, the pattern would consist of thin vertical lines for a stable PWM waveform, however in the presented results this is not the case. The width of the pattern reveals the presence of phase shift and jitter. Despite of it is still possible to clearly distinguish the positions of the PWM train edges, as the modulation and carrier frequency are almost synchronized.

For increasing smoothness degree the PD pattern gradually transforms in number, amplitude and phase position. This is particularly obvious when the smoothness level increases above 0.03, for which the PDs occur only at some of the edges. Although the spread in PDs is increased, the presence of the edges is still clearly visible. This increase in width is partly affected by the rise time of the applied voltage, as it becomes longer than for the cases of lower smoothness. Figure 4 also shows an additional behavior apparent for the higher smoothness levels, e.g. appearance of distinct areas where no PDs occur. These areas are presumably reflecting the negative amplitude contributions from the smoothed voltage steps on the modulated waveform which reduces the externally applied electric field. In relation to the space and surface charges in the cavity this presumably lowers the total electric field level in the cavity and thus diminishes the amount of generated PDs.

For smoothness around 0.1, one can notice that the PDs roughly concentrate where the peak-to-peak values of the remaining PWM steps are largest. Further, no PDs occur at the peak voltage of the modulated sinusoidal shape. Both the modulation and the carrier frequency thus influence the PD pattern in this region of smoothness. At yet increasing smoothness, the most significant change is in the phase distribution. To increase the understanding of the observed changes in the PD pattern, a comparison of the PD distribution relative to the non-filtered voltage flanks can give important information, particularly at higher smoothness degree. A
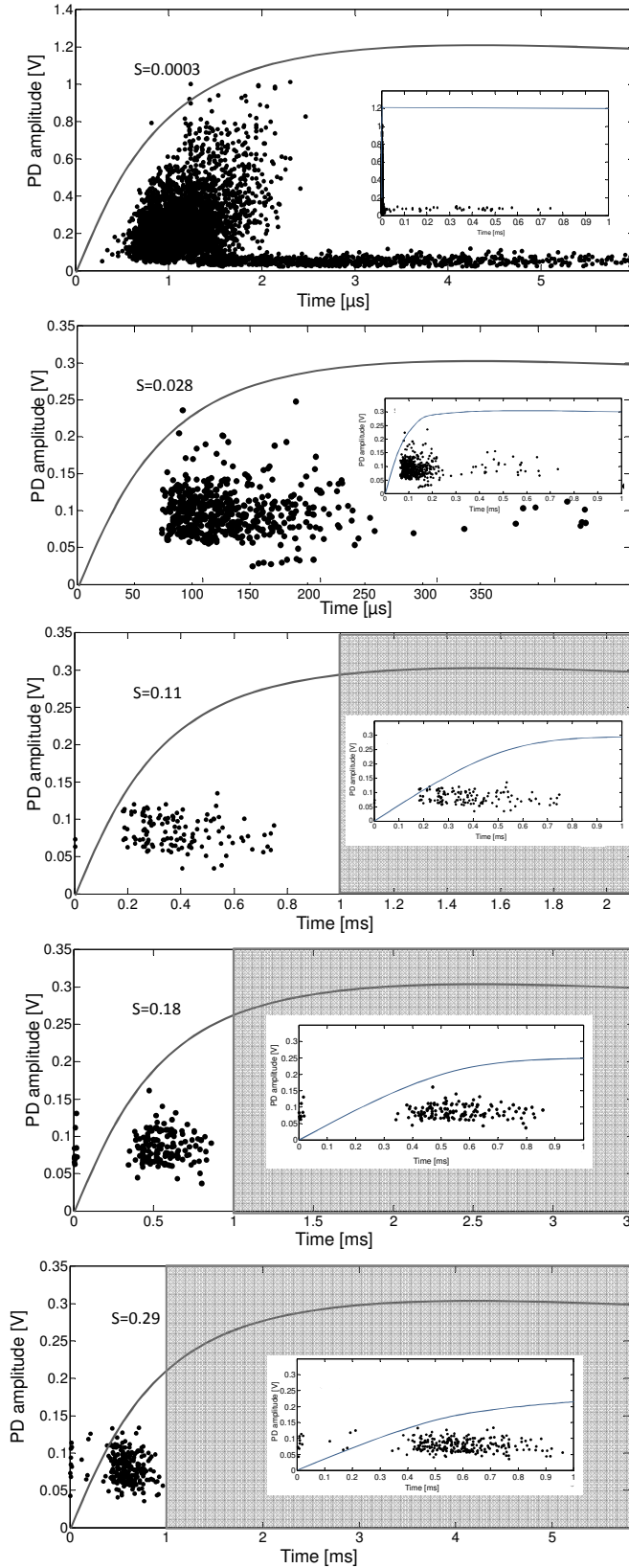
**Figure 5** The PD pattern in relation to the flank of the voltage at different level of smoothness. For each smoothness level the time scale is adjusted to show the same portion of a flank, as a guidance the approximate shape of a rising flank is indicated. In the inserts, the same data is shown with the same time scale for all rise times. Note that no PD can be detected after 1 ms so only part of the flank is indicated for higher smoothness level. Further note that the PD amplitude is approximately constant for all but the smallest smoothness.

natural assumption is that the occurrence of PDs is less dependent on the initial voltage steps when the smoothness level becomes high enough. To elucidate this in detail the PD position and amplitude relative to the voltage flanks are indicated for some different rise times in Figure 5. Only the positive flanks are displayed as the PD pattern is symmetrical. Since the carrier frequency is 1000 Hz, no PDs can appear later than 1 ms after the step. Naturally, this limits the interval for PDs appearance, particularly for higher smoothness levels.

The PD distribution relative to the flanks experiences only minor changes despite the rise times increases considerably for larger smoothness levels. However some PDs start to appear close to the polarity reversals. Based on this observation it seems likely that these PDs become less dependent on the position of the smoothed voltage step. However, as all the appearing PDs are not evenly distributed across the pulse width, the result is not clear enough to definitely conclude on how the characteristics are dependent on the smoothness level.

To properly quantify the dependence between PD characteristics and smoothness, additional examinations of the measured data are needed, involving determinations of the number of PDs occurring and the average PD amplitude per cycle. The investigated cases reveal that the number of PDs changes, particularly for the lower smoothness levels. This is particularly obvious when studying Figure 6 where the total number of PDs per cycle is displayed for the different levels of smoothness. As it is evident from Figure 4 that the filters applied in the first three cases do not yield sufficient smoothness for reducing the peak value of the voltage steps, only the applied rise time affects the PD characteristics. At the lowest smoothness level, the average total number of PDs per cycle is equal to the number of voltage flanks appearing in each modulated cycle. With increasing PWM voltage smoothness, the number of PDs initially increases. This agrees with our previous observations [15]. However, at still increasing smoothness level the detected number of PDs starts decaying rapidly. The smoothness level required to reach about the same number of PDs as for the sinusoidal waveform is between 0.006 and 0.028. The center of this interval is marked as the knee position in figure.

The dependence of the average PD amplitude as a function of smoothness level is illustrated in Figure 7. It can be noticed that the amplitudes become strongly reduced with increasing smoothness. When the PWM waveform is smoothened to between 0.0018 and 0.006, a constant PD amplitude of about 70 mV on average per 50 Hz period is reached. For yet higher smoothness levels only minor differences can be observed. This suggests that possibly different phenomena may be influencing the change in PDs amplitude and number.

## IV. TRANSITION OF PD PATTERN

At smoothness level where the voltage step sizes remains constant and at the same level as the amplitude of sinusoidal waveform (s < 0.028) the total number of PDs per cycle is

**Figure 6** Number of PDs detected for exposure of PWM voltage shapes as a function of PWM smoothness. Here a 1000 Hz carrier frequency and 17 kV$_{pp}$ are applied. The standard deviation is indicated for each measured value.

larger than that for sinusoidal excitation. Above it, PD characteristics start to shift in phase and form groups. Already at s = 0.028, when the magnitude of the remaining voltage steps vary between 8 and 14 kV$_{pp}$, the number of PDs are reduced. Incidentally, here the lowest voltage steps are less than the extinction voltage threshold. With further increased smoothness level, it can be observed (see Figure 4) that at s = 0.29 the PD pattern becomes similar in its character to the one measured under sinusoidal condition, which corresponds to the voltage step interval of 0.5 to 6 kV$_{pp}$. In this case the magnitude of the maximum remaining voltage steps is lower than the extinction voltage level as well.

The correlation between the height of voltage steps and the smoothness of PWM voltage waveform is illustrated in Figure 8. As the level of PD extinction threshold is at about 10 kV$_{pp}$, one may conclude from the figure that the qualitative change of the PD characteristics starts taking place already at smoothness level above 0.1. It is therefore postulated that at this point the way the insulation system degrades will also change, gradually approaching the rate under sinusoidal excitation.

The measurement technique introduced in this paper enables characterization of PD properties in an object exposed to PWM shaped voltages of different level of smoothness. This presented approach utilizes a two level inverter. However, the principles can be adapted to a multi-level waveform as well, by extending the introduced classification.

The presented approach uses the non-smoothened PWM signal as a synchronization channel to classify the captured trace, which obviously implies that additional measurements are needed apart from determining the voltage across the insulation system. This can be avoided if the transfer function between non filtered PWM signal and the PD detector voltage is known [19]. By using the Fourier transform on the smoothened signal and by applying the transfer function the non-smoothed signal can be recreated. This calculated result may then be applied as the synchronization channel, which implicates that only two measurement channels are needed.

The present study has shown that the number and amplitude of PDs per modulated period exhibits different characteristics depending on the PWM smoothness level. For the studied cavity (diameter 4 mm) in a polycarbonate block, the most significant change in number of detected PDs lies between smoothness levels of 0.028 and 0.11, whereas the average PD amplitude reaches the same level as for sinusoidal excitation already earlier. It has additionally been observed that PDs appearing at short rise times have larger amplitude, which agrees well with observations presented in [15] for semi-square shaped voltages. For increasing smoothness the PD amplitude remains approximately constant, but at a lower level. Thus the influence of rise time on insulation system behavior appears similar for both PWM and semi-square voltage shapes. It also appears that the remaining voltage steps in the smoothened PWM train should remain at lower level than the extinction threshold for reaching the same intensity of PD exposure (in number and amplitude) as under sinusoidal excitation.

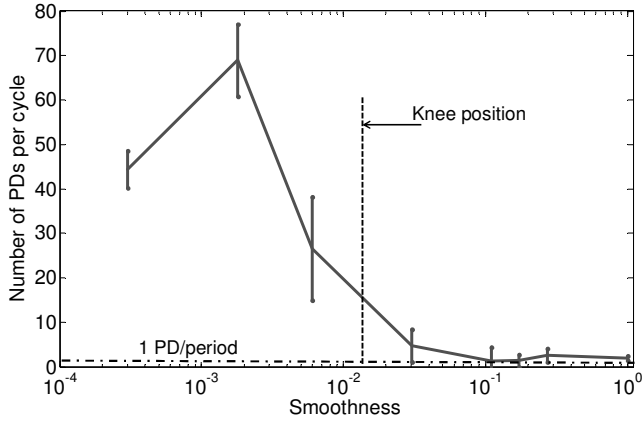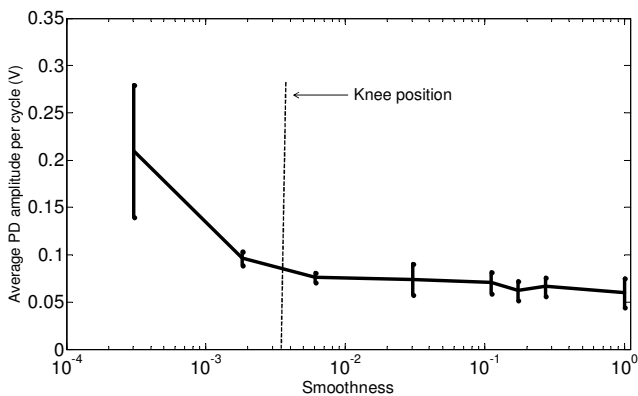To definitely conclude if the smoothened PWM shapes may



**Figure 7** Average PD amplitude with standard deviation indicated. Note that the PD amplitude increases significantly at shorter rise times. The standard deviation is indicated for each measured value.
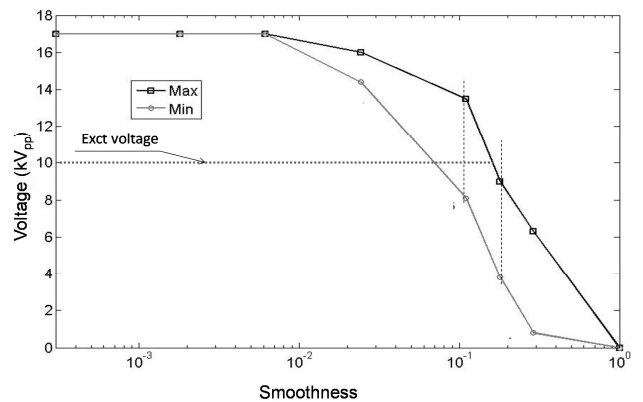


**Figure 8** The relation between peak- to peak value of voltage step and smoothness. Note the indicated area where the PD pattern gradually approaches the sinusoidal PRPD pattern as well as the indicated extinction voltage level.

secure similar life time of an insulation system, more investigations are needed. Several directions of the further studies are therefore foreseen. The first and probably most important one, particularly from an industrial perspective, is to precisely establish the level of smoothness required for obtaining the same PD exposure as at sinusoidal excitation. Here time-to-breakdown investigations [20] can provide the ultimate answer, but such studies require long time and large resources to obtain statistically significant results. A faster approach is to perform studies of the gradual degradation on the endplates before breakdown has occurred, as was done on dielectrically insulated cavities for different level of smoothness [19, 20]. The second direction should be devoted to further investigate the influence of voltage level on the smoothening required to reduce the PD exposure. The presented hypothesis should also be further validated on various insulation systems, such for example as twisted pairs and corona needles.

Finally, with this technique it is now possible to measure PD in-service also for equipment subjected to PWM voltages.

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