PD Recurrence in Cavities at Different Energizing Methods

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Abstract—The measurement of partial discharge (PD) activity has become an invaluable tool for monitoring the insulation condition of high-voltage components in service. In particular, it is important for factories and for the utilities to get an indication of the time to breakdown. In this paper, the authors describe a study on the use of a damped ac voltage (DAC) method and a very low frequency (VLF) method to stress insulation and to detect partial discharge activity. The main goal of this study was to find out whether the PD patterns obtained at 50 (60)-Hz voltage correspond to those obtained at either lower frequency voltage (VLF) or higher frequency voltage (DAC). For this purpose, a combined theoretical and experimental approach for dielectric bounded cavities was used. The effect of the frequency and the shape of the voltage (DAC) on the PD phase-resolved pattern were studied in the laboratory. Tests were performed on dielectric bounded cavities in polyester with the DAC method, the VLF method (0.1 Hz), and the 50 (60)-Hz method. Moreover, the PD phenomenon was theoretically analyzed at different stress frequencies, and a comparison was made between theory and measurement.

Index Terms—Cavity, damped ac, detection, frequency, measurement, partial discharge (PD), testing, very low frequency (VLF).

I. INTRODUCTION

ELECTRICAL discharges that do not completely bridge the distance between two electrodes are known as partial discharges (PDs). Through the years, it has been recognized that PD represents a danger to the life of insulation [1]. As a consequence, many efforts have been spent for understanding the PD phenomenon and for developing PD measurement techniques. Today, PD measurements represent one of the main tools for insulation condition assessment. The importance of the subject is mainly due to the relation between the level of PD activity and the aging of the dielectric materials, hence the interest of utilities on PD measurement techniques.

PD detection techniques and their relative merits are strictly related to the various types of equipment under test. Discharge detection is based on the analysis of physical phenomena determined by discharges. The phenomena under consideration can be analyzed through electrical pulse measurements, light, heat, chemical transformations, and electromagnetic radiation. These different approaches can be conveniently used to estimate dis-

charge characteristics. However, the greatest difficulty is to develop a realistic model of the phenomena and their relation to the signal (or other quantities) detected. Moreover, the detection circuit configuration could play a very important role, and correct arrangement is the prerequisite for valid measurement. In this paper, our attention is focused on the electrical method only.

To detect the presence of PD, a component, e.g., power cable, is usually energized with a 50-Hz power frequency voltage. The use of a 50 (60)-Hz energizing method is, however, not always practically and economically realistic, because of the high capacitive power required. For this reason, other methods that operate at different frequencies have been developed to reduce the charging power. For example, the very low frequency (VLF) method stresses the test object at 0.1 Hz, while the damped ac voltage (DAC) method makes use of damped ac voltages in the range of 20–1000 Hz.

Laboratory experiments on power cables [2], [3] and generator stators [4] showed no fundamental differences between the main PD quantities (e.g., PD inception/extinction voltage, PD magnitude, and PD phase-resolved pattern) obtained with damped ac voltage and 50(60)-Hz ac energizing method. For VLF, some experiments [5], [6] provided results in good accordance to those of the other methods, but in a recent study [7], differences were found. These differences were mainly attributed to a change in the PD inception phenomena [8]. In fact, under low-frequency stress conditions, the time between two PD events is longer when compared to 50(60) Hz. In the case of dielectric bounded cavities, the charge deposited by a PD affects the inception of the next PD. Because the deposited charge decreases in time, this effect is believed to be of less importance at low frequency than at 50(60) Hz.

The object of the study presented in this paper was to determine the influence of frequency and voltage shape (DAC method) on the PD behavior through PD measurements on artificial defects, using different energizing methods. Knowledge of the characteristics of the polyester resin model (dielectric bounded cavities) allowed a theoretical approach toward the discharge behavior. Theory and measurements were evaluated and compared.

Experimental results showed that the PD quantities measured by means of the 50(60)-Hz method can be different from those detected with VLF and DAC methods. The reason of those dissimilarities is that, under certain conditions, the PD process in dielectric bounded cavities is frequency dependent. For this reason, the effect of the voltage frequency on PD activity is analyzed.

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Fig. 1. Test specimen of cast polyester between two brass electrodes.

TABLE I
SPECIMEN PROPERTIES

Sample dimensions	Sample 1	Sample 2	Sample 3	Sample 4
d [mm]	3.90	2.80	3.15	3.85
D_m [mm]	2.52	2.00	2.92	3.17
D_m = cavity diameter - d = electrode gap				

II. PROPOSED APPROACH

For this study, cast polyester test specimens were used. They consisted of a spherical air filled cavity (diameter D_m : 2–3 mm) placed between two brass electrodes cast in polyester resin ($\epsilon_r = 3.45$), as shown in Fig. 1. To avoid field concentration at the electrode edges and to obtain a uniform field in the central area, electrodes with a Rogowski profile [1] were used. The specimens were immersed in oil to prevent unwanted surface discharges during the tests. In Table I, the characteristics of the test specimens are reported.

Partial discharges were ignited and detected in the test specimens using the three different energizing methods mentioned above. A PD occurring in a cavity deposits a dipolar charge distribution at the site of the discharge. In general, this quantity is not directly measurable. Hence, measuring partial discharges is based on the measurement of the charge displacement in the leads to a sample, the so-called apparent discharge magnitude. Nevertheless, this apparent discharge magnitude is a good representation of the intensity of the internal discharge. In fact, the charge displacement in the leads to a sample is directly related to the energy dissipated during the discharge event and to the dimensions of the discharge site [1]. In the classical method for PD measurement (called phase resolved method), the acquired PD data consist of a sequence of pulses. Every pulse is characterized by its charge and by the time at which it occurs. Often, instead of the PD occurrence time, the ac phase at which the pulse occurs is given.

To obtain a stable discharge pattern, the cavities were first conditioned for 1 h at 50-Hz energizing. During the first min-

Fig. 2. The 50-Hz PD phase resolved test circuit.

utes of PD activity, in fact, a change of the condition of the cavity walls can lead to quite sensitive PD quantity changes [9]–[12]. After this conditioning period, the PD measurements were performed at different frequencies.

Since the parameters of the test specimens are known, they could be used, together with the voltage stress, for a theoretical assessment of the PD pattern. For this purpose, the PD modeling proposed by Niemeyer [13], [14] has been chosen as a reference point. Niemeyer's model describes the streamer discharge phenomenon [1], [9] occurring in a dielectric bounded spheroidal cavity and gives analytical tools for the estimation of the main PD quantities.

Two main topics are addressed in this paper:

- 1) the effect of the test voltage frequency on the PD inception delay, PD magnitude, and PD phase patterns;
- 2) the effect of the voltage shape on partial discharge activity (this point is particularly interesting for the DAC method, because of the relatively small number of voltage cycles that is used to stress the test object).

Both of these topics are of significant practical importance. Many diagnostic methods, in which different voltage frequencies are used for stressing the insulation of HV components, are now on the market and in fact used in the field. In order to assess the condition of the insulation that is normally stressed at 50(60) Hz, by measurements at lower or higher frequencies, the dependence of the PD phenomena or the changes of the measured PD quantities with frequency have to be known [7].

III. EXPERIMENTAL

A. Test Setup

The samples were energized with 50-Hz voltage, damped oscillating voltage waves (260, 520, and 930 Hz) and VLF test voltages at 0.1 Hz. All measurements were performed at room temperature (20–25 °C).

50(60)-Hz Method: The 50-Hz ac test circuit consisted of a 50-kV step-up transformer, a 1-MΩ damping resistor to reduce the short circuit current in case of breakdown, and a coupling capacitor in series with a detection impedance to couple the PD signals, as is shown in Fig. 2. The PD signals measured by the circuit were processed and displayed by TEAS 570 partial discharge analyzing system (bandwidth from 40 kHz to 400 kHz). The pulse resolution of the detection circuit was 10 μs (one power frequency cycle of 50 Hz is divided in 2000 phase windows). During a test, sequences of PD pulses are acquired. Every pulse is characterized by its ac phase position and its charge (phase resolved detection).

Fig. 3. The 0.1-Hz PD phase resolved test circuit.

Fig. 4. Schematic diagram of the damped ac voltage measuring circuit.

VLF Method: For the 0.1-Hz measurements, a VLF system with a sinusoidal test voltage was used. It is essentially composed of an HVAC power source especially developed to supply capacitive loads and a detection impedance in series with a coupling capacitor. The system shows for every PD pulse its magnitude. To also detect the ac phase position at which the PD events occurred, a commercial multichannel oscilloscope was used and connected, as shown in Fig. 3. The time base was triggered by the 0.1-Hz test voltage; thus, a PD phase resolved pattern was obtained.

DAC Method: A schematic diagram of the damped ac voltage test setup, as applied for the experiments, is shown in Fig. 4.

First, the test object was charged with a dc voltage and, after a few seconds, the required peak voltage was reached. At this point, the solid-state switch S with short closure time was closed, resulting in a series resonant circuit consisting of the test object capacitance, some additional capacitance, and an air-core inductor. The circuit resonant frequency was

$$f = \frac{1}{2\pi\sqrt{LC}} \quad (1)$$

where L is the air core inductance and C the additional capacitance connected in parallel to the sample. Both the filter inductance L_f and the sample capacitance C_s are negligible for the calculation of the resonant frequency f because

$$L_f \ll L \quad (2)$$

$$C_s \ll C. \quad (3)$$

TABLE II
CAPACITORS USED FOR THE EXPERIMENTS. CAPACITORS WERE SELECTED TO OBTAIN THREE DIFFERENT FREQUENCIES IN THE RANGE OF 200–1000 HZ

f [Hz]	C_{add} [μ F]	Capacitor connections
260	0.5	4 x 0.5 μ F
520	0.125	4 x 0.5 μ F
930	0.036	4 x 0.5 μ F + 2 x 0.1 μ F

Because the circuit has a relatively low dissipation factor, the result is a damped voltage wave at the resonant frequency f with a decay time τ_d up to 300 ms. Thus, the test object is energized by a few tens of cycles. A specially developed measurement circuit detects PD pulses that occur during the DAC wave. The user's interface for the system consists of an industrial PC that also provides complete control of the measuring cycle. Different values of additional capacitance were used in order to obtain several DAC frequencies, as shown in Table II.

To avoid measuring unwanted discharge signals originating from the additional capacitors, a 40 μ H filter inductor was inserted in the circuit (see Fig. 4). Its presence is negligible for the power circuit used to stress the sample, because the filter inductance is very small when compared to the inductance of the air core (0.75 H).

A characteristic difference between the standard 50 (60) Hz and DAC energizing method is the fact that, for the latter, the PD data are obtained from a relatively small number of voltage cycles.

Calibration: To calibrate all three measurement circuits, a calibrator (Power Diagnostix cal E1) was applied according to IEC 60 270 recommendations. In the case of the VLF system, single pulses have been captured to calibrate the PD amplitude measuring range. In the case of the DAC method and the 50-Hz method, repetitive PD pulses have been used.

B. Results

Partial Discharge Inception Delay: Generally, from the moment of voltage application, PD activity in dielectric bounded cavities starts after a certain delay time. To initiate a partial discharge, a starting electron is required. The probability that this electron will become available, after waiting for an inception delay time, depends mostly on the test voltage and on the diameter of the cavity [13]–[15]. Fig. 5 shows the PD inception delay time as a function of the test voltage at 50 Hz for the specimens listed in Table I. For all samples, the inception delay time is clearly dependent on the applied voltage. At low voltages, a relatively long inception delay time was measured (hundreds of minutes). On the other hand, increasing the voltage considerably decreases the delay time. Also, for the VLF method, the inception delay time was found to be voltage dependent. There were no significant differences between the voltage dependency at VLF and at 50 Hz.

Fig. 5. Partial discharge inception delay time as a function of the test voltage at 50 Hz.

Fig. 6. Percentage of DAC shots that show PD activity as a function of test voltage, for different values of the test frequency; the data were obtained in 20 shots (f = frequency; τ_d = decay time).

Regarding the DAC method, the short time required for stressing the test object allows only measurements of inception delay time in the order of some tens of milliseconds. Moreover, not every damped voltage wave (shot) applied to the polyester samples ignited PD. For these reasons, the number of shots necessary to obtain a pattern with PD was chosen as a quantity linked to the probability for a starting electron to be available (and then to the PD inception delay time). The time interval between two consecutive shots was a few tens of seconds. As opposed to the 50(60)-Hz and VLF methods, the peak value of the applied DAC voltage is not the only parameter influencing the probability for the presence of a starting electron. The frequency and the decay time of the damped ac wave are of importance as well. Fig. 6 shows the relation between the number of shots necessary to obtain a pattern with PD and both the DAC frequency and decay time. To obtain DAC waves at higher frequencies, additional capacitors were connected in series, to decrease the total circuit capacitance, as reported in Table II. Because of this fact, the total dissipation factor of the circuit became higher and so the damping factor of the voltage wave increased. At higher frequencies and a higher damping factor, more shots were necessary to see PD. This was particularly evident for the smaller diameter samples (samples 1 and 2).

To recognize if the PD inception differences observed at different wave shapes were caused mainly by the change in frequency or by the change in decay time, another experiment was performed. Samples were stressed by DAC waves with shorter

Fig. 7. The 50-Hz ac phase-resolved PD pattern at 16 kV (data are referred to sample 4, 6000 cycles).

Fig. 8. The 264-Hz DAC phase-resolved pattern at 24 kV_{peak} (sample 4, 20 cycles).

decay time by adding a 50- Ω resistor in series to the capacitors for the 260-Hz situation. Higher voltages were required for observing a number of shots necessary to obtain a pattern with PD as high as that in the previous measurements at 260 Hz (Fig. 6). The implication is that the number of shots necessary to obtain a pattern with PD is more affected by the DAC wave decay time than by the DAC frequency.

Effect of Test Voltage Frequency on Partial Discharge Magnitude and Phase Pattern: The PD phenomenon is a stochastic process and the PD magnitude can be described by a density function [16], [17]. In the case of partial discharges in cavities, the density function is skewed to the left, resulting in a high probability of small PD and a low probability for large PD. Given certain cavity dimensions and a certain gas pressure in the cavity, the maximum PD magnitude can be calculated. The probability of detecting a PD with this magnitude is, given the skewness of the density function, related to the time of measurement. Thus, the probability of a large partial discharge is expected to be higher in the two minutes of a 50-Hz measurement (Fig. 7) than in the few tens of milliseconds of a damped ac voltage (Fig. 8). Evidently, by increasing the number of DAC shots, the probability of detecting the maximum PD magnitude will increase.

This was sustained by the test results, which showed a slightly decreasing PD magnitude for the DAC method at frequencies of 260 Hz and higher (see Table III). The DAC damping factor did not influence the PD magnitude. Tests performed at a constant DAC frequency and different decay times did not show significant changes in the detected PD magnitude.

TABLE III

MAXIMUM PARTIAL DISCHARGE MAGNITUDE DETECTED IN POLYESTER RESIN TEST SPECIMENS CONTAINING AN ARTIFICIALLY INTRODUCED CAVITY. TEST METHOD: 50-Hz AC ENERGIZING METHOD, DAC METHOD AT 260, 520, AND 930 Hz, AND VLF METHOD AT 0.1 Hz

Sample	1	2	3	4
Test voltage [kV _{rms}]	20	14	14	17
50-Hz AC pd-level [nC]	5.5	12	10.5	45
260-Hz DAC pd-level [nC]	2	3	8	> 20
520-Hz DAC pd-level [nC]	1.2	4	6	16
930-Hz DAC pd-level [nC]	0.8	4	5	12
0.1-Hz VLF pd-level [nC]	4.6	8	3.6	>20

(a)

(b)

Fig. 9. The 0.1-Hz VLF phase resolved patterns. (a) Sample 4 at 14 kV_{rms}, 30 cycles. (b) Sample 3 at 8 kV_{rms}, 30 cycles.

With regard to the VLF method, the PD magnitude observed at 0.1 Hz was either similar (samples 1 and 4) or lower (samples 2 and 3) if compared to 50 Hz. Also, for the partial discharge phase-resolved pattern (see Fig. 9), two different characteristics were found. For samples 1, 2, and 4 the pattern shows the same features as noticed at 50 Hz with well-marked phase shifting regarding the zero crossing, while sample 3 shows a flat pattern with a less marked phase-shifting.

IV. DISCUSSION

A. Partial Discharge Modeling

The discussion of the results is based on the assumption that the prevailing discharge mechanism was of the “streamer discharge” type [1], [9]. The streamer theory [1], [18], describing the evolution of the streamer discharge, postulates that the space charge formed in an electron avalanche starts to have an effect on the electric field if the avalanche surpasses a critical length, which corresponds a critical electric field. If this occurs, an initiatory electron avalanche can trigger the formation of new avalanches, leading to breakdown. A necessary condition (the streamer criterion) for the discharge inception is given [14], [1]. In the case of dielectric bounded spheroidal cavities, the streamer criterion enables us to estimate the minimal PD inception voltage [13].

There are two requirements for PD inception: a sufficiently high field inside the cavity and the presence of a starting electron. PD is driven by a local field enhancement caused by the cavity itself. This enhanced field is, in general, composed of two contributions. The first one is due to the applied voltage and is the local enhancement of the background field by the cavity. The second one is associated with local space or surface charges that have been left by previous PD activity [13]. The amount of charge depends on the field that caused the discharge. As a consequence, the discharge magnitude is proportional to the field inside the cavity at the inception instant. For this reason, the minimal discharge magnitude is ignited by the inception field. On the other hand, the maximal PD magnitude occurs when the field inside the cavity is maximal. As explained in [14], this situation occurs when both the above mentioned field contributions are equal, maximal, and acting in the same direction.

The charge deposited by PD contributes to the potential difference across the cavity and represents a source of starting electrons. Because the surface of the cavity has a finite conductivity σ_s , the deposited charge decays with an average time constant τ_{cd} . By using the RC cavity model proposed in [14], the time constant can be evaluated as

$$\tau_{cd} = \frac{\epsilon_0 \cdot D_m}{4 \cdot \sigma_s} \quad (4)$$

where ϵ_0 represents the permittivity of vacuum.

A starting electron is the origin of the first avalanche that causes the streamer partial breakdown. According to [14], two main groups of first electron generation mechanisms can be distinguished: volume and surface processes. Volume generation includes radiative gas ionization by energetic photons and field detachment of electrons from negative ions. A plot of the theoretical inception delay time, due to volume generation only, as a function of the cavity diameter can be found in [13]. The second group is electron production from surfaces of insulating materials, which includes detrapping of electrons from traps at the surface, electron release by ion impact and surface photo effect [14]. In this second case, an approximate estimation of the number of electrons generated per second can be obtained if one considers these processes to obey to a Richardson-Schottky type of emission [14]. In fact, in the case of a cavity between insulator surfaces, at the surface of the insulators, traps with depths

in the order of 0.1 to 1 eV are present. If electrons from previous PD events have been trapped in such surface states, they could be detrapped by a Richardson-Schottky process.

These general considerations will be used for the assesment of the experimental results. The effect of different voltage frequency-shape on PD quantities will be analyzed taking into account that the PD duration is of the order of 1–10 ns [1], [9]. With regard to the frequency range dealt within this study, the discharge time is always much smaller than the duration of the ac stress cycle. The frequency can thus not directly influence the PD streamer inception phenomenon. Measurements, in fact, showed that the minimal PD magnitude is not frequency dependent.

B. Low-Frequency PD Behavior

At lower frequencies, the observed PD behavior does not follow a univocal direction. Measurements demonstrated that, in some cases, the PD magnitude and PD pattern detected at 0.1 Hz are approximately the same as those measured at 50 Hz, while in others, they are quite different. According to [19], the cause of these dissimilarities can be attributed to the charge decay time τ_{cd} . If τ_{cd} is larger than the duration of the period of the applied voltage, i.e.

$$\tau_{cd} \gg \frac{1}{f} \quad (5)$$

we can assume that the charge does not decay between two consecutive PD events. In this case, the deposited charge will strongly contribute to the field in the cavity. This fact is reflected in the PD pattern by the phase shifting and by the presence of PD pulses during the voltage zero crossing.

On the other hand, if the decay time is shorter than the applied voltage period, i.e.

$$\tau_{cd} \ll \frac{1}{f} \quad (6)$$

the deposited charge will not give a significant contribution to the PD process. In this situation, the field in the cavity is due only to the contribution of the applied voltage. Hence, no phase shifting and no PD pulses during the voltage zero crossing are noticeable in the PD pattern. Moreover, the maximum PD magnitude is expected to be half of that observable in the previous situation, since only one field contribution leads the PD process.

An intermediate PD process occurs when

$$\tau_{cd} \approx \frac{1}{f}. \quad (7)$$

Under condition (7), the charge left by a PD can contribute to the inception of the next PD. The Poissonian field contribution depends on the portion of the charge deposited by a first PD and present in the cavity during the successive PD. A pattern with the same characteristics, but less marked, as in the case that (5) is true will probably be noticed, as in the case of sample 3 of Fig. 9.

The decay time of the deposited charge is strongly dependent on the conductivity of the surface of the cavity. For polymers that have not seen PD activity the conductivity is typically in the range of 10^{-14} – 10^{-16} S, while the surface of aged cavities may

reach values as high as 10^{-12} – 10^{-11} S [14]. As a consequence, the charge decay time can be in the range 10^{-3} – 10^3 S [14], for cavities of a few millimeters diameter. This extremely wide range is the cause of the different PD behavior observed in the test specimens.

C. High-Frequency PD Behavior

Experimental results showed that stress frequencies of 260 Hz and above affect the PD process in the polyester resin samples tested. Starting at 260 Hz, a decreasing PD magnitude was observed. This indicates that the voltage across the cavity at which PD occur is close to the minimal inception voltage as can be calculated with the streamer criterion. A possible explanation can be found in the detrapping process of starting electrons that becomes active after a PD event. The charge deposited by a PD at the cavity surface represents a reservoir of starting electrons. The number of possible starting electrons decreases in time, not only because of the finite conductivity of the cavity surface (leakage current), but also because of diffusion of electrons into deeper traps (i.e., “high work function” traps). According to [20], an exponential decay time constant τ_{tr} describes the loss of electrons due to the latter mechanism. In both cases, the electrons will no longer be available to trigger a discharge. The probability that a starting electron is available after a PD event decreases in time, because it is directly proportional to the number of electrons trapped at the cavity surface. When a PD occurs, the voltage across the cavity collapses to the residual value and then it increases again: it will reach the minimal value necessary for the next PD inception after a relatively short time if the frequency is sufficiently high. In this case, the probability to have a starting electron is high and the PD event will be ignited when the voltage across the cavity is close to the minimal inception value. Due to this phenomenon, a lower PD magnitude is to be expected at higher frequencies. At which frequency this phenomenon will likely start to play a role depends on the value of the constant τ_{tr} and on the ratio ν between inception and applied voltage

$$\nu = \frac{U_{inc}}{U_{max}}. \quad (8)$$

As shown in Fig. 10, after an average time Δt_{PD} , the voltage across the cavity again reaches the inception value

$$\Delta t_{PD} = \frac{\frac{\pi}{2} - \arcsin(1 - \nu)}{2 \cdot \pi \cdot f}. \quad (9)$$

If the constant τ_{tr} is larger than the time interval Δt_{PD} , PD are probably ignited when the voltage is close to the inception value. This occurs for frequencies above the threshold value f^* :

$$f^* = \frac{\frac{\pi}{2} - \arcsin(1 - \nu)}{2 \cdot \pi \cdot \tau_{tr}}. \quad (10)$$

It follows for this equation that there is a relation between the test frequency, the overvoltage (above inception voltage), and the “memory effect.” Assuming a time constant τ_{tr} of a few milliseconds [20] and considering the peak voltage a few times higher than the inception voltage, the threshold frequency f^* is, based on (10), a few hundreds of hertz. Thus, for the higher frequencies used in this work, it can be assumed that only very few electrons are lost within a single voltage period.

Fig. 10. Time interval Δt_{PD} between two PD events occurred at the minimal inception voltage.

D. Inception Delay Time

In the case of spherical cavities, volume ionization in the gas is the dominating electron generation mechanism if the cavity is virgin (i.e., a cavity in a dielectric without a history of electrical stress). Spherical cavities have a small surface-to-volume ratio and, before the cavity is discharged for the first time, the number of electron traps is limited and a small portion of the surface traps is filled. However, if the cavity has seen PD activity, surface generation processes are not negligible anymore. Fig. 5 shows that for specimens aged for about 1–2 h the inception delay time depends on the voltage rather than on the defect size. Therefore, it might be concluded that the surface generation mechanism, in which the electric field at the cavity surface plays a very important role, is active. Another fact that supports this hypothesis is that it was possible to detect PD by using the DAC method. Since the quite short energizing time required by this method, the probability that starting electrons appear only due to volume generation would be very low for cavity with 2–3 mm diameter, and so practically no PD would be ignited.

In the case of surface generation, the inception delay time exponentially shortens by increasing the applied voltage. This fact leads to a very short inception delay time for voltages sufficiently high. On the other hand, if the applied voltage is too low, quite a long delay time is expected.

With regard to the DAC damping factor, experiments show that it influences the probability of PD inception. The higher the DAC damping factor, the shorter the time during which the PD inception criteria of the cavity are fulfilled. Thus, for a certain maximal voltage wave value, the inception delay is longer for higher damping factor. If the starting electron is not generated before the amplitude of the damped ac voltage is below the theoretical inception value, no PD will be ignited. As a consequence, the probability to have a pattern with PD is low for heavily damped DAC and so the damping factor should be chosen small.

V. CONCLUSION

In this paper, a comparative study regarding different energizing methods for PD detection is presented. A combined theoretical and experimental approach was presented based on laboratory investigation on models of dielectric bounded cavities in polyester resin. The theoretical approach led to an estimation of the PD behavior in the test specimens. Based on this study, the following conclusions can be drawn.

A. Minimal PD Magnitude

The minimal PD magnitude detected was the same for every energizing method. The reason for this is that the PD inception voltage is not dependent on the voltage frequency-shape.

B. Higher Test Frequencies

It is possible to detect partial discharges in cavities using the DAC energizing methods. To obtain a significant number of PD, the number of shots should be large, especially for small cavities and for high damping factors of the voltage wave.

The PD level measured at frequencies above 200 Hz is slightly lower than that observed with the 50-Hz ac energizing method. There is a relation between the starting electron mechanism, the overvoltage (above inception voltage), and the frequency of the test voltage. This relation generally leads to a decreasing PD magnitude at higher frequencies for dielectric bounded cavities.

The damping factor of the DAC has a larger effect on the number of shots necessary to obtain a pattern with PD than the test frequency of the DAC. This fact is directly related to the inception delay time.

C. Lower Test Frequencies

Both the PD magnitude detected and the PD pattern observed demonstrate that the PD process at VLF frequencies can be either very close to that at 50 Hz or quite different. The main reason for this particular behavior is that the deposited charge decay time can change over several orders of magnitude depending on the condition of the cavity surface.

REFERENCES

- [1] F. H. Kreuger, *Industrial High Voltage*. Delft, The Netherlands: Delft Univ. Press, 1991.
- [2] E. Gulski, F. J. Wester, J. J. Smit, P. N. Seitz, and M. Turner, "Advanced partial discharge diagnostic of MV power cable system using oscillating wave test system," *IEEE Ind. Electron. Mag.*, vol. 16, pp. 17–25, Mar./Apr. 2000.
- [3] Y. Muramoto, E. Gulski, F. J. Wester, and J. J. Smit, "PD inception conditions and PD pattern of defects in PILC," in *Proc. IEEE 7th Int. Conf. Solid Dielectrics*, June 2001, pp. 369–372.
- [4] E. Gulski, H. J. van Breen, J. J. Smit, P. N. Seitz, and P. Schikarski, "Partial discharge detection in generator stator insulation using oscillating waves," in *Proc. Electrical Insulation Conf. Electrical Manufacturing Coil Winding Conf.*, 2001, pp. 331–334.
- [5] D. Pepper and W. Kalkner, "PD-measurement on typical defects on XLPE-insulated cables at variable frequencies," in *Proc. 10th Int. Symp. High Voltage Engineering*, Montreal, QC, Canada, Aug. 1997.
- [6] M. Muhr and R. Woschitz, "Partial discharge diagnostic," in *Proc. 6th Int. Conf. Properties Applications Dielectric Materials*, June 2000, pp. 223–226.
- [7] J. T. Holbøll and H. Edin, "PD-detection vs. loss measurement at high voltages with variable frequencies," in *Proc. 10th Int. Symp. High Voltage Engineering*, Montreal, QC, Canada, Aug. 1997.

- [8] E. Gulski, "Partial discharge on-site diagnosis of distribution power cable at oscillating voltage," in *Proc. IEEE/ICC Fall 2000 Educational Program*, Oct.-Nov. 2000.
- [9] P. H. F. Morshuis, "Partial Discharge Mechanisms," Ph.D. dissertation, Delft Univ. Technology, Delft, The Netherlands, 1993.
- [10] J. T. Holbøll, "The Resistance of Composite Materials Against Electrical Discharges," Ph.D. dissertation, Technical Univ. Denmark, Lyngby, 1992.
- [11] M. Henriksen, "Partial Discharges in Spherical Cavities in Epoxy Resin," Ph.D. dissertation, Technical Univ. Denmark, Lyngby, 1982.
- [12] V. R. G. C. Hernandez, "Partial Discharges Waveshapes in Spherical Voids Using Ultra Wide Band Techniques," Ph.D. dissertation, Univ. Manchester, Manchester, U.K., 1994.
- [13] F. Gutfleisch and L. Niemeyer, "Measurement and simulation of PD in epoxy voids," *IEEE Trans. Dielect. Elect. Insul.*, vol. 2, pp. 729–743, Oct. 1995.
- [14] L. Niemeyer, "A generalized approach to partial discharge modeling," *IEEE Trans. Dielect. Elect. Insul.*, vol. 2, pp. 510–528, Aug. 1995.
- [15] H.-P. Burgener and K. Fröhlich, "Probability of partial discharge inception in small voids," in *2001 Annu. Rep. Conf. Electrical Insulation and Dielectric Phenomena*, pp. 298–302.
- [16] E. Gulski, "Computer-Aided Recognition of Partial Discharges Using Statistical Tools," Ph.D. dissertation, Delft Univ. Technology, Delft, The Netherlands, 1991.
- [17] E. Gulski and F. H. Kreuger, "Computer-aided recognition of discharge sources," *IEEE Trans. Dielect. Elect. Insul.*, vol. 27, pp. 82–92, Feb. 1992.
- [18] H. Raether, *Electron Avalanches and Breakdown in Gases*. London, U.K.: Butterworths, 1964.
- [19] R. Bodega, A. Cavallini, P. H. F. Morshuis, and F. J. Wester, "The effect of voltage frequency on partial discharge activity," in *2002 Annu. Rep. Conf. Electrical Insulation and Dielectric Phenomena*, pp. 685–689.
- [20] L. Niemeyer, B. Fruth, and F. Gutfleisch, "Simulation of partial discharges in insulation systems," in *Proc. 7th Int. Symp. High Voltage Engineering*, vol. 7, 1991, pp. 24–28.

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