INFLUENCE OF VOLTAGE WAVEFORMS ON PARTIAL DISCHARGES DEVELOPED IN POWER CABLE INSULATION

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Key words: Partial discharge, Inception voltage, Step-up voltage test method, Sinusoidal waveform, DC step waveform; Bipolar rectangular waveform.

The reliability of the power cables strongly depends on the single or multiple stresses that could develop within their insulation system. The electric stresses as overvoltages, dips, harmonics and inter-harmonics contribute to a drastically reduction of the insulation lifetime, damaging the insulation of cables mainly through partial discharges (PD) and charge accumulation. This paper deals with the influence of different applied voltage waveforms on partial discharge activity within the insulating material of power cable. The PD activity was investigated under sinusoidal, DC-step and bipolar rectangular testing voltage waveforms at the frequency of 50 Hz and 0.1 Hz, applied to the micro-cavity embedded in cross-linked polyethylene. Using the step-up voltage test method, the characteristics of PD were assessed. The results show that the sinusoidal waveforms at 0.1 Hz generally provide the lowest partial discharge inception voltage (PDIV) values. The PDIV increases slightly with frequency**.**

1. **INTRODUCTION**

The main element of an underground power distribution line is the power cable, for which the insulation system represents the critical point and this could negatively influence the entire power line availability. Many studies developed in order to enhance underground system's reliability are based on fault monitoring [1].

During time, the performances of the insulating system for power cables have continuous increased. Until 1925, the main insulating material used for underground power cables was the paper oil impregnated, and since then, begging with the development of plastics, different thermoplastic polymers have been introduced. At present, the materials used for power cable insulation systems are: polyethylene (PE), cross-linked polyethylene (XLPE), tree-retardant cross-linked polyethylene (TRXLPE), ethylene-propylene rubber (EPR) and polyvinyl chloride (PVC) etc.

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The current research regarding power cables insulation proposed the development of new physical models to describe the inception and growth of damage from micro cavities in PE subjected to partial discharges (PD) under different voltage waveforms and frequencies [2–5]. Within current scientific literature is supported the hypothesis that the electrical stress is the main stress factor that contributes to a strongly reduction of the power cable insulation lifetime [6, 7].

An efficient tool used to assess the degradation of the insulation, is the PD measurement that could be performed either off-line or on-line [8, 9]. The results obtained after PD measurements represent a good indicator regarding cables insulation degradation status. In these sense, the current approach starts with the assumption that the PD occurring in a micro-void/micro-cavity within an insulating material represents the most important cause of polymeric insulation breakdown in exploitation, under different AC voltages/ frequencies [2].

The effect of different testing voltage waveforms on the PD characteristics is analyzed more detailed in [10, 11]. It was concluded that the frequency is a factor of influence on the PD repetition rate, PD amplitude and PD patterns. The PD phenomena inside micro-cavities from insulating materials have been extensively studied in [12, 13], but not sufficient data were obtained in order to improve the diagnosis procedure based on PD measurement. The aim of this paper is to investigate the influence of different testing voltage waveforms and frequencies on partial discharge activity developed in polyethylene based power cable insulation, in order to offer new data insides for degradation processes and PD modeling.

The main objective of this research is to forecast the lifetime of cable insulation made of polyethylene, having micro defects of different geometry. This type of analysis is useful in optimal design of cable insulation system.

The current paper is based on the step-up voltage test method used to determine the partial discharge inception voltage (PDIV), considering different testing voltage waveforms and frequencies. Comparing with previous research on the same topic, the novelty of the current research refers to PD activity modeling under different testing regimes using different testing voltage waveforms, like: Sinusoidal, DC Step, Bipolar Rectangular. The PD measurements for each voltage waveform were performed at 0.1 Hz and 50 Hz. We assume that the underlying probability distribution of PDIV fits a Weibull distribution, and based on the considerations from [14], the Weibull distribution parameters were estimated using the Maximum Likelihood Estimation (MLE) method. This approach has allowed us to compare directly the effect of different testing voltage waveforms and frequencies on the partial discharge parameters.

2. TEST SETUP AND MEASUREMENTS

In order to perform the investigations, the specimens have been realized using three thermally soldered layers of polyethylene (XLPE-LDPE-XLPE). The design of the samples was established according to the structure of the power cable insulation system. In the LDPE central layer, an artificial micro-cavity of approximately 400 μm was created [12, 13]. The layers were soldered together at 100°C under vacuum conditions in order to exclude the air bubbles between the layers. In order to realize a perfect electric contact between the electrodes and specimen, both surfaces of the specimen were sputtered with gold in spots centered on the artificial micro-cavity (Fig. 1).

The specimens were placed between pseudo-Rogowski stainless steel electrodes and, the entire test cell (electrodes plus the specimen) was immersed in mineral oil, at ambient temperature. It was used mineral oil in order to avoid surface discharges. The high voltage (HV) electrode of the test cell was supplied from a HV power amplifier (Trek 20/20C). The amplifier has an output current in the range of 0 ± 20 mA DC or peak AC.

The set-up test design is shown in Fig. 2.

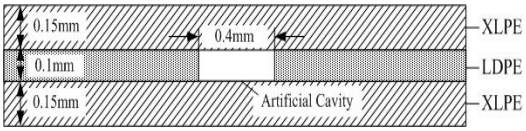


Fig. 1 – Design of the sample: XLPE layer thickness of 0.15 mm; LDPE layer thickness of 0.1 mm; cavity diameter of 0.4 mm.

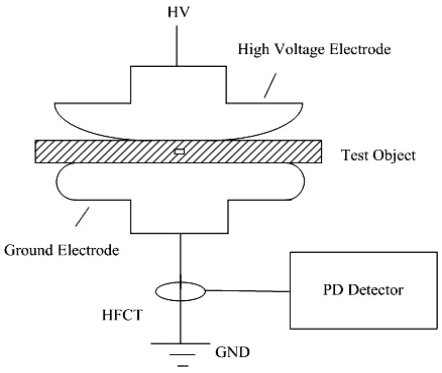


Fig. 2 – Design of the PD test setup [12].

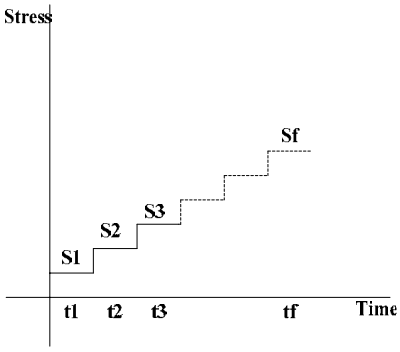


Fig. 3 – Step-up voltage test method [12].

The PD signals were coupled from the ground leads using a High Frequency Current Transformer (HFCT) and the obtained PD signals were processed using a commercial PD detector, PDCheck (bandwidth 40 MHz, sampling rate 100 MS/s)

developed by TechImp. The measurements were performed according to IEEE 400.2: 2004 and IEEE 400.3: 2006 specifications [15, 16].

Three different voltage waveforms at the frequencies of 50 Hz and 0.1 Hz (very low frequency VLF) have been applied on the same specimen:

(a) Sinusoidal Waveform (hereinafter W_1 regime);

(b) DC Step Waveform (hereinafter W_2 regime, which reproduce in steps the sinusoidal waveform);

(c) Bipolar Rectangular Waveform (hereinafter W_3 regime).

In order to determine the characteristic of PD, the step-up voltage test method, described in Fig. 3, was applied, as in [14]. This test method involved a strict measurement procedure, as follows:

– Stress S_1 was imposed to the insulation during one minute for regimes of 50 Hz and 2 minutes for regimes of 0.1 Hz;

– If no PD activity was observed, then the stress level was raised to the S_2 with a step of 100 V, and with the same applied period of time;

– This operation continues until the PD activity was detected;

– The final stress S_f was used for the PDIV estimation;

– Once the PDIV was reached, the measurement characteristics of PD was done and, the test was stopped;

– One-minute lapse time was considered between consequently trials, in order to allow the relaxation of the space charge.

For each stress regime, the measurement time was of 1 minute for 50 Hz and of 2 minutes for 0.1 Hz. A number of 5 consecutive trials have been applied on the same specimen. In this sense were obtained for each trial, 5 PD inception voltages. The reference value for PDIV considering each trial was established after another PD measurement at 20% from the highest PDIV measured previously. In order to obtain accurate results the tests have been repeated of 5 times.

3. **RESULTS AND DISCUSSIONS**

The first set of measurements was performed in W1 regime, at 50 Hz, to get a baseline for further comparison. The PDIV thus recorded was about 5.01 kV_{pp} Next, tests with sinusoidal voltages (W1 regime) at very low frequency (0.1 Hz) were done. In this case, discharges incepted at around 5.2 kV_{pp}.

The set of measurements performed in W2 regime, at 50 Hz, indicated the maximum PDIV value of 6.56 kV_{pp}, with approx. 24% larger than the reference. The measurement data for W2 regime at 0.1 Hz indicated a maximum PDIV value of 6.37 kV_{pp}. In the same way, the measurement test in W3 regime was done, at 50 Hz and 0.1 Hz.

During testing, the apparent charge Q_{max} (in pC) carried by a PD and the repetition rate N_w for a cycle (in PD pulse per cycle, ppc) have been also measured (Table 1).

Table 1

PD parameters assessed with step-up voltage test in a microcavity of 400 μm in XLPE

Sinusoidal Waveform(W1)	
50 Hz	0.1 Hz
PDIV = 5.01 kV_{PP}	PDIV = 5.2 kV_{PP}
Q_{max}= 5477.54 pC	Q_{max}= 2134.82 pC
N_W = 4.3 ppc	N_W = 5.8 ppc
DC Step Waveform (W2)	
50 Hz	0.1 Hz
PDIV = 6.56 kV_{PP}	PDIV = 6.37 kV_{PP}
Q_{max}= 6874.25 pC	Q_{max}= 3802. 60 pC
N_W = 2 ppc	N_W = 3.8 ppc
Bipolar Rectangular Waveform (W3)	
50 Hz	0.1 Hz
PDIV = 6.08 kV_{PP}	PDIV = 2.3 kV_{PP}
Q_{max}= 3009,4365 pC	Q_{max} =1525,2785 pC
N_W = 0.1 ppc	N_W = 2.2 ppc

Based on the obtained results, one can observe that the effect of the frequency on the repetition rate N_w and apparent charge Q_{max} is evident. For each testing voltage waveform regime at 50 Hz, the values of Q_{max} and N_w are higher than at 0.1 Hz. Not a very good correlation is obtained for PDIV between waveform and frequency for different regimes of testing (Fig. 4).

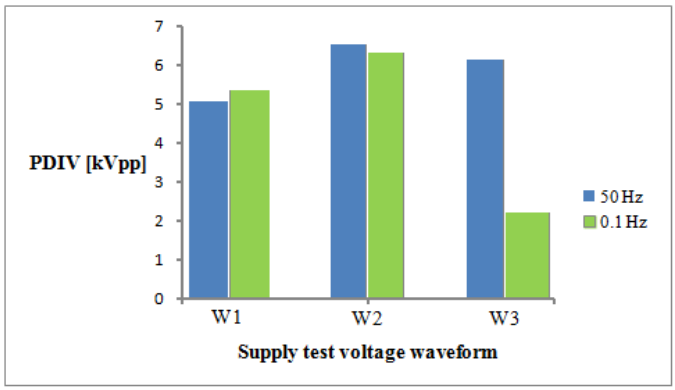


Fig. 4 – PDIV values recorded during the different test sessions.

The dependence of PDIV on supply voltage frequency has been reported very rarely and some authors [9, 11] considered that PDIV is almost independent of frequency. In our tests, a reduction of PDIV was established, considering the tests at W1-50 Hz regime, for frequencies ranging in the interval of few hundred mHz to some tens of Hz.

The measurement data have been processed and the PD patterns (Fig. 5, 7, 9) and DP pulse spectra (Fig. 6, 8, 10) have been obtained. It can observe that the PD magnitudes do not change substantially with the applied frequency.

During the W3 regime at 0.1 Hz, the repetition frequency is very low, almost 2.2 PDs per cycle (Table 1). This finding could be explained as follows: the supply voltage cycle is long enough to allow electrons at the cavity surface to get into deep traps. And because de-trapping from micro-cavity surfaces is the main mechanism that generates starting electrons once PD activity has been incepted [15], the performed measurements have the expected results.

Regarding the PD pulse spectra, the highest amplitude, of about $7 \cdot 10^{-2}$ V is observed at 50 Hz in W_2 regime. The lower amplitude level was established at $1.6 \cdot 10^{-2}$V for 50 Hz in W_1 testing regime. Data proceeding for 0.1 Hz indicated the values of the signal amplitude below $1.5 \cdot 10^{-2}$ V.

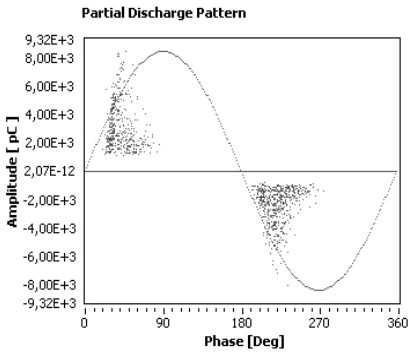


Fig. 5 – PD pattern at 50 Hz in W1 regime: PDIV=5.016 kVpp [18].

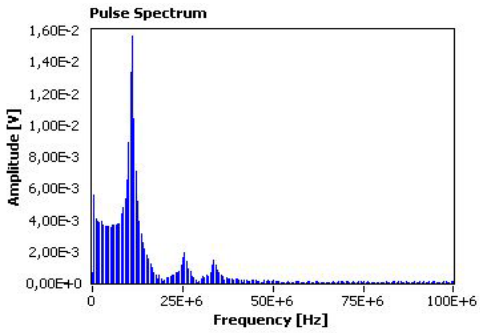


Fig. 6 – PD pulse spectrum at 50 Hz in W_1 testing regime.

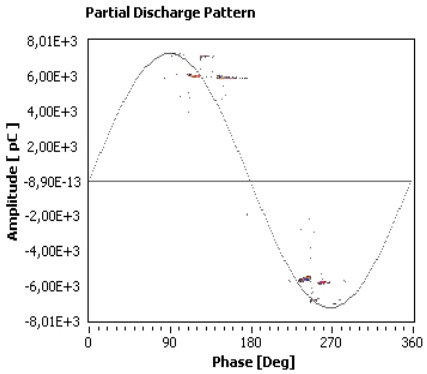


Fig. 7 – PD pattern at 50 Hz in W2 testing regime: PDIV = 6.56 kVp [18].

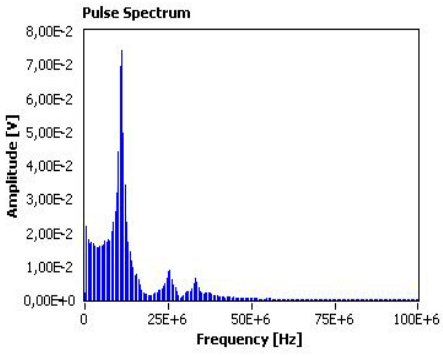


Fig. 8 – PD pulse spectrum at 50 Hz in W_2 regime.

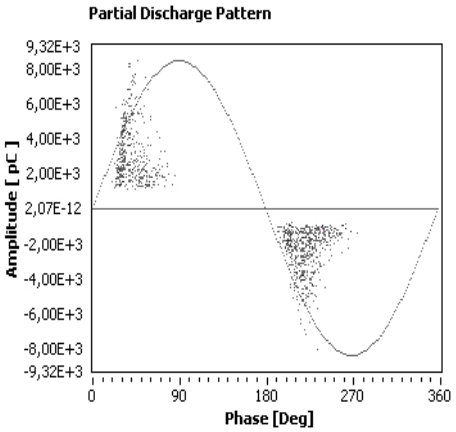


Fig. 9 – PD pattern at 50 Hz in W3 testing regime: PDIV= 6.08 kVpp.

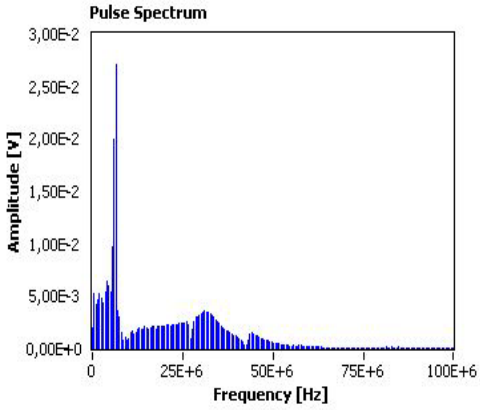


Fig. 10 – PD pulse spectrum at 50 Hz in W_3 regime.

In order to assess the degradation process of the sample under PD activity, the 2-parameter Weibull distribution was applied. The theoretical approach regarding the Weibull distribution is presented detailed in [13, 17]. As known, the parameters of the Weibull distribution, especially the shape parameter β, have a strongly impact on the reliability and operational performance of an entity. On these sense if $\beta > 1$, reliability decreases meanwhile failure rate increases and if $\beta < 1$ the failuare rate decreases. In our case, β is in strong correlation with the PD parameters and sample reliability/ remaining life.

The Weibull parameters have been determined using an Excel Worksheet developed according to Dorner's model [17]. In Table 2, are presented the parameters obtained at 50 Hz for all the three waveforms W1, W2, W3 testing regimes. Fig. 11a and Fig. 11b show the Weibull probability of inception voltages of PDIV plots at 50 Hz for each applied waveform. In the case of W1, at 50 Hz, the reliability of the sample is strongly affected if one considerers the value of the shape parameter which has a value greater than 1.

This means that if the PD tests will continue using the aged sample, under this voltage waveform, the PDIV will decrease as the inception probability will decrease and the sample will breakdown.

Table 2

Weibull parameters for PDIV at 50 Hz, in different wave form regimes

Sinusoidal Waveform			
Weibull parameters		Confidence Intervals	
		Inf (90%)	Sup (90%)
β	1.22	0.69	2.92
α	334.3	165.58	600.30
R	0.69		

DC Step Waveform			
Weibull parameters		Confidence Intervals	
		Inf (90%)	Sup (90%)
β	0.71	0.41	1.71
α	1319.4	397.82	3583.85
R	0.90		
Bipolar Rectangular Waveform			
Weibull parameters		Confidence Intervals	
		Inf (90%)	Sup (90%)
β	1.89	1.08	4.53
α	131.3	83.48	191.57
R	0.85		

For W_2, the PD parameters and sample reliability have smaller influence on the Weibull parameters, the PDIV tend to increase, that means the sample could be stressed at higher levels. For W_3, the reliability of the sample decrease (β = 1.89).

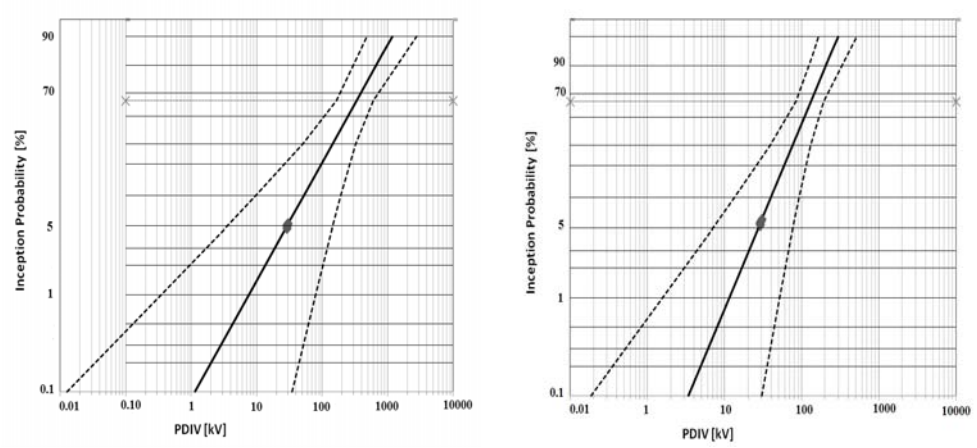


Fig. 11 – PDIV Weibull probability plot at 50 Hz: a) in W_1 regime; b) in W3 regime.

As a conclusion, even if the test conditions are the same for all the three applied waveforms, the characteristic life is higher only in the case of the DC Step waveform regime (α = 1 319.4). The results obtained considering the statistical analysis of the PD parameters underline the fact that some specific testing waveforms affect the lifetime distribution of the insulating materials.

This aspect is quite important in the case of diagnosis of power cable using waveforms different from the sinusoidal. Prevoius research underline that diagnosis of power cables using oscillating voltage [12, 13] is not destructive. In this paper it was shown, according to the statistical analysis of the measurement results, that PD measurement at DC Step have a small influence on the sample lifetime. This means that this testing waveform is less destructive comparing with sinusoidal or biploar

rectangular waveform. In the same time, the current results can be used as a tool to improve the on-site testing conditions of the power cables insulation.

4. **CONCLUSIONS**

In this paper, the influence of sinusoidal, DC step and bipolar rectangular testing voltage waveforms on partial discharge parameters was investigated at 50 Hz and at 0.1 Hz, using polyethylene samples with spherical micro-cavities embedded. A complete analysis of the experimental results was performed using the statistical data processing, applied using the Weibull model. It was found that under AC voltage waveform, the PDIV is about 5.01 kV_{pp} and the characteristic life is strongly affected. In the case of DC step waveform, the PDIV has a higher value (6.56 kV_{pp}) which implies a higher reliability (90%) and a life distribution about 1319.4 hours.

In order to improve the reliability centered maintenance strategies for power cables, the use of test supplies whose output voltage differs in waveform or / and frequency from the power frequency/ sinusoidal waveform should be considered.

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