# PARTIAL DISCHARGE AGING OF POLYMERIC INSULATION FOIL UNDER HARMONIC DISTORTED VOLTAGE STRESS

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The partial discharge aging of polyethylene terephthalate (PET) foil with permanent surface discharge stress is investigated using different harmonic distorted voltage waveforms. Distorted voltage waveforms alter the partial discharge behavior of insulation arrangements by affecting characteristics such as the apparent charge and repetition rate. Consequentially, an influence of the harmonic distorted voltages on the partial discharge aging of insulation materials is expected. The goal of this contribution is to identify the influence of the different harmonic voltage waveforms on the lifetime of the PET foil when constantly exposed to surface discharges.

## 1. Introduction

Power electronic technologies such as inverter-fed drives and solid-state transformers become gradually more common in electric power distribution systems and utilized operational equipment. The steep switching characteristics of the semiconductor switches can lead to increasing harmonic voltage distortion in the vicinity of power converters. Distorted voltages affect insulation systems of operational equipment by increasing the dielectric losses and altering the partial discharge (PD) behavior. The latter is especially relevant since PDs are a major cause of (polymeric) insulation material deterioration.

PDs typically occur at defects within or in the vicinity of insulation materials. The location, size and shape of the defects varies strongly [1]. Previous publications focused on the effect of harmonic distorted voltages on the electrical treeing process and, consequentially, the limited lifetime of the insulation material [2–6]. The literature draws an inconsistent picture of the effect of each harmonic parameter, namely the total harmonic distortion (THD) and the harmonic order $h$, on the measured lifetime with PDs: Some investigations found a lifetime-decreasing inluence of the harmonic distortion [2, 4]. Others have observed higher lifetimes despite harmonic distorted voltages [5, 7].

Apart from electrical treeing, the influence of harmonic distortion on surface discharges and their deterioration of polymeric insulation foil has been investigated in [7] using a sphere-plate electrode arrangement to trigger discharges. These discharges occur on the surface of a polymeric insulation foil and deteriorate the material until breakdown. They are reproducible and give the possibility to achieve high breakdown sample numbers to increase the statistical significance of the investigations. The impact of harmonic voltage distortion on the measurable PD characteristics (apparent charge, repetition rate) has been carried out using a similar sphere-plate arrangement with a polyethylene terephthalate (PET) foil in between [8]. The study concluded that the harmonics affect the measured values considerably but neither harmonic order $h$ nor THD have an unambiguous influence [8].

Furthermore, previous lifetime investigations [2–6] focus on constant root-mean-square (RMS) voltages while varying the harmonic parameters. Harmonic distortion affects the peak-to-RMS ratio and hence some voltage waveforms have higher voltage amplitudes than others. Higher voltages clearly impact the PD behavior and therefore also the consequential aging [8, 9]. Apart from that, with higher harmonic order, the voltage gradient d$u$/d$t$ of the voltage increases. The general shape of the voltage waveform with harmonics changes drastically and leads to repeated re-inception of PDs during one voltage period (Figure 1).

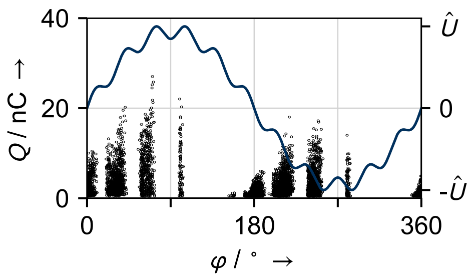



Figure 1: Exemplary phase-resolved PD pattern of surface discharges on PET foil between a sphere-plate electrode arrangement; $h$ = 11, THD = 10% [8].

In this publication, the voltage amplitude varying influence of harmonics is excluded by generating the voltage waveforms in a way that the peak voltage is constant while adjusting the THD and harmonic order *h*. As a result, the effect of the harmonics on the voltage gradient of the waveforms is in focus. Ultimately, the goal of this study is to measure the impact of the parameters of harmonic distorted voltages (THD, *h*) on the lifetime of PET foil under permanent surface discharge exposure.

## 2. Experimental Setup and Procedure

The aging tests are carried out as time-to-failure (TTF) measurements on an exemplary electrode arrangement.

### 2.1. Experimental Setup

The experimental setup consists of an amplifier-driven high-voltage transformer in order to generate arbitrary harmonic distorted voltages up to 30 kV. The electrode arrangement and test objects are in a climate chamber at $23 \pm 0.5$ °C and $30 \pm 3$ % relative humidity. The voltage is measured with a gas-filled voltage divider $C_G - C_M$ and recorded and digitized using a multifunction I/O device (MIO) (Figure 2). A damping inductance $L_d$ reduces the current in the moment of a breakdown of the device under test (DUT).

High-voltage transformers do not have a uniform transfer characteristic for different voltage frequencies. Consequently, the voltage waveforms have to be adjusted to achieve the accurate harmonic content, phase and voltage amplitude. The measured voltage waveforms are adjusted using a Python algorithm setting the fundamental frequency voltage amplitude, the harmonic voltage amplitude and the phase relation between fundamental and harmonic voltage. The peak voltages are adjusted up to a total deviation of $\pm 20$ V. The measurements are carried out for harmonics up to the 31st order (1550 Hz) and a total harmonic distortion up to THD = 20%.

### 2.2. Electrode Arrangement

A sphere-plate electrode with a PET foil (DuPont Melinex® S; nominal thickness of 23 µm) in between triggers surface discharges at the triple point between high-voltage electrode, insulation foil and surrounding air (Figure 3). The high-voltage electrodes are made of stainless steel. A spring-loaded locking bolt generates a force of $F \approx 6$ N on the PET foil to ensure a reproducible electrode contact. A parallel aging setup for up to ten foils with identical electrodes is utilized to accelerate the aging tests

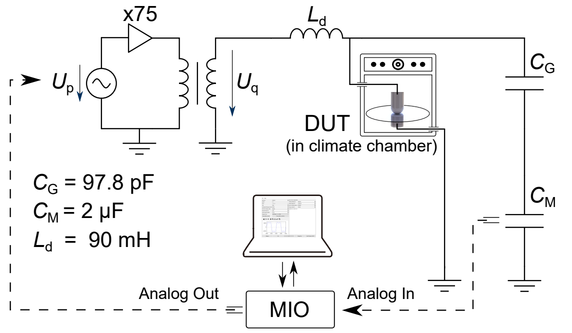
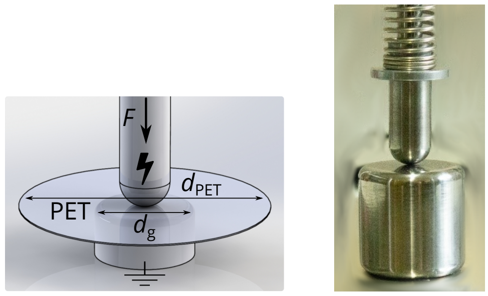



Figure 2: Equivalent circuit of the PD aging test setup.




(a) Drawing (b) Photography

Figure 3: Sphere-plate electrode arrangement with PET foil as a test object.

(Figure 4). The high voltage is turned off in the moment of breakdown. The respective failed test object is identified using an ohmmeter. A low resistance or electrical continuity implies the breakdown of the insulation foil. The breakdown trace is also identified visually.

The electrode arrangement is inspired by [7, 10, 11] and allows reproducible PDs and hence consistent aging test conditions.

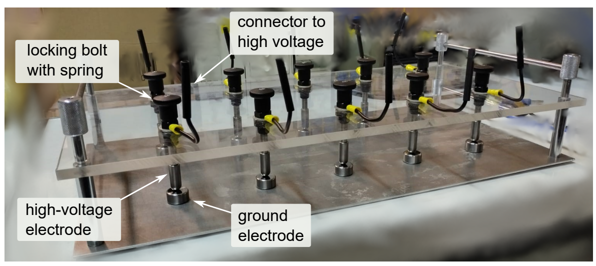



Figure 4: Photography of the parallel aging electrode setup for up to ten foils.

### 2.3. Experimental Procedure

The tests are carried out with various harmonic distorted voltage waveforms at three different voltage levels (Table 1). The harmonic order *h* and THD is varied, while the peak voltage remains constant.

This implies that the RMS voltage varies between different harmonic distorted voltage waveforms. Ten foils are stressed until breakdown for each parameter combination.

Table 1: Summary of the applied stress parameters for the PD aging tests.

| Type | Parameter | | Value |
|---|---|---|---|
| Peak Voltage | $\hat{U}$ | V | 3000; 3500; 4000 |
| Total Harm. Dist. | THD | % | (5...20) |
| Harmonic Order | $h$ | | (3...31) |
| Phase Shift | $\varphi$ | ° | 0 |
| Temperature | $\vartheta$ | °C | $23 \pm 0.5$ |
| Rel. Humidity | | % | $30 \pm 3$ |

### 2.4. Weibull-distributed Data

The recorded TTF values are statistically approximated using a two-parameter Weibull distribution. The Weibull distribution is well-suited for TTF investigations and corresponds well to the physical concepts behind the breakdowns [12–14]. Each Weibull approximation is tested against the underlying raw data set with a Kolmogorov-Smirnov test using the *reliability* library implemented in Python [15]. Only one of the 37 available data sets could not be validly approximated by a two-parameter Weibull distribution and was hence excluded.

In the following, the presented values are the 63% quantiles $\eta_{TTF}$ of the approximated Weibull distributions together with the corresponding lower and upper 95% confidence interval (Figure 5). The second important parameter (not shown in detail in this contribution) is the measure of dispersion or Weibull exponent $\delta$.

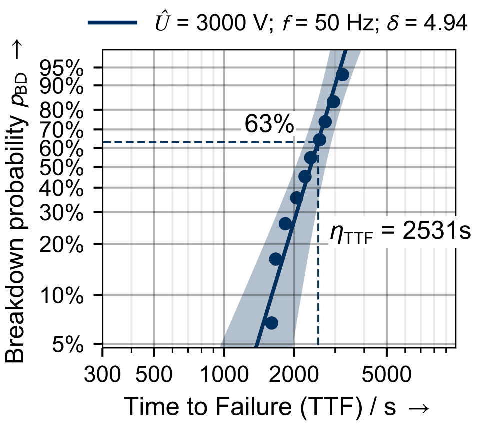



Figure 5: Approximated Weibull distribution of the TTF with a constant voltage test: $\hat{U}$ = 3000 V, $f$ = 50 Hz undistorted.

## 3. Results

The THD and harmonic order $h$ and their impacts on the voltage waveform affect the measured TTF substantially (Figure 6, Figure 7). With constant harmonic order and increasing THD, the lifetime values $\eta_{TTF}$ do not decrease unconditionally. For $h = 3$ and $h = 21$, a downward trend with increasing THD can be observed. This trend is not visible for $h = 15$. The 31st harmonic leads to very low $\eta_{TTF}$ values. Generally, the lifetime at $\hat{U}$ = 4000 V is significantly lower than at 3000 V. Furthermore, the 95% confidence intervals (error bars in Figure 6 and 7) are considerably smaller for higher voltages.

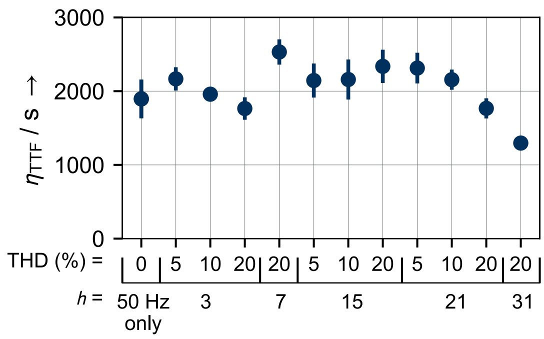



Figure 6: 63% quantile of the TTF measurements $\eta_{TTF}$ with 95% confidence intervals of the approximated Weibull functions for $\hat{U}$ = 3000 V.

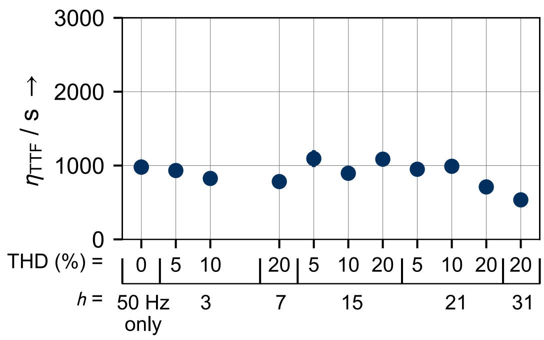



Figure 7: 63% quantile of the TTF measurements $\eta_{TTF}$ with 95% confidence intervals of the approximated Weibull functions for $\hat{U}$ = 4000 V.

When comparing the measured values of $\eta_{TTF}$ in relation to the harmonic order $h$ for different THD values (Figure 8 and Figure 9), substantial differences become obvious: for low THD values of 5% (Figure 8), the measured TTF values are roughly equal or higher for distorted and undistorted (pure 50 Hz) voltages. With substantial harmonic distortion (THD = 20%, Figure 9), a decreasing trend for higher harmonic orders $h > 15$ becomes obvious. Superimposed harmonics up to the order of $h = 15$ lead to equal or higher $\eta_{TTF}$ values.

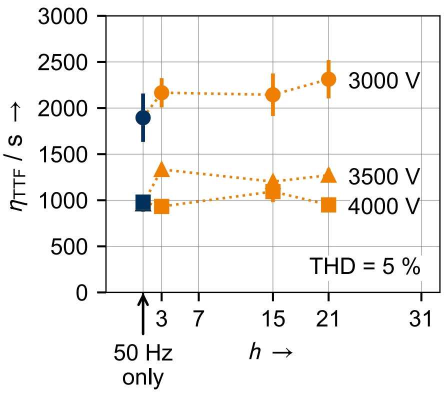



Figure 8: 63% quantile of the TTF measurements $\eta_{TTF}$ with 95% confidence intervals of the approximated Weibull functions as a function of the harmonic order $h$ for THD = 5%.

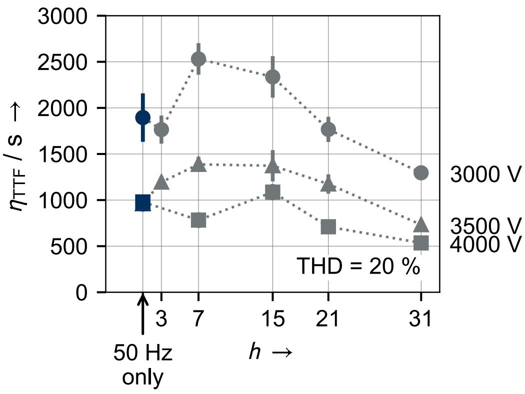



Figure 9: 63% quantile of the TTF measurements $\eta_{TTF}$ with 95% confidence intervals of the approximated Weibull functions as a function of the harmonic order $h$ for THD = 20%.

## 4. Discussion

The measurements reveal that the impact of different harmonics on the PD deterioration and hence the measured lifetime is inconclusive. Low THD values and low order harmonics lead to an equal or slightly higher lifetime. Considerable distortion (THD = 20%; $h > 15$) causes a reduction of the lifetime. The measurement results are in agreement with the previously investigated PD parameters under different harmonic distorted voltages [8] where also an inconclusive picture was drawn. In these investigations, the harmonic order $h$ has a more pronounced impact on the measured PD parameters than the THD. Very similar investigations in [7] traces the main reason for the lifetime influence of the harmonics back to the peak-voltage-enhancing effect. The hereby presented measurement results show that the harmonics' impact voltage waveform regarding the voltage gradients d$u$/d$t$ and waveform shape also affects the polymer aging when PDs are present.

## 5. Conclusions

The impact of harmonics on partial discharge aging is ambiguous. When compared to a purely sinusoidal voltage, low order harmonic-distorted voltages can lead to a higher lifetime. However, the lifetime decreases with high frequency distortion and high total harmonic distortion values. Subsequent investigations should focus on higher superimposed frequencies (e.g. > 10 kHz) in order to map out the impact of higher harmonic orders $h$. Ultimately, understanding PDs on a fundamental level calls for the development of model representations that can incorporate harmonic distorted voltages.

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