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Erstveröffentlichung in / First published in:

2. Fachtagung Polymere Isolierstoffe und ihre Grenzflächen, Zittau 06.-07.10.2021. VDE Bezirksverein Dresden.

Final edited form was published in "2. Fachtagung Polymere Isolierstoffe und ihre Grenzflächen, Zittau 06.-07.10.2021." VDE.

PARTIAL DISCHARGES OF EPOXY-MICA-INSULATION UNDER HARMONIC DISTORTED VOLTAGES

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The increasing usage of power electronic technologies and the related operational equipment such as inverter-fed drives and solid-state transformers in electrical grids leads to growing harmonic distortion of the voltage waveform. Harmonics modify the shape of a voltage waveform but also affect the peak voltage despite constant RMS voltage. Resulting from this, it was previously found that harmonics not only have an influence on the partial discharge patterns and characteristics but also on the lifetime of model insulations. The epoxy-mica main insulation of rotating electrical machines is partial discharge-resistant to certain extent. Nonetheless, severe production faults should be detected by partial discharge measurements as they may lead to accelerated ageing of the insulation system of the electrical machine. The purpose of this contribution is to investigate the impact of harmonics on the partial discharge characteristics of the main insulation system of rotating electrical machines in general and especially on a test object with an artificial void fault. An assessment of the partial discharge pattern and apparent charge measurement is given. The analysis bases on waveform parameters that describe the harmonic distorted voltage incoporating peak alteration and shape modification. It is shown that the voltage peak altering effect of harmonics plays a superior role compared to changes in the voltage shape and gradients. The effects are more pronounced with the test object with an artificially introduced fault.

1 Introduction

Nowadays, the origin of harmonic distortions of the grid voltage can be lead back to nonlinear loads, inverters as well as resonances of capacitive and inductive elements of operational equipment [1, 2]. In the future, increasing numbers of power electronics-controlled equipment such as variable-frequency drives or solid-state transformers will intensify the harmonic pollution of the grid voltage [3, 4]. Harmonic distortion affects the insulation by increasing dielectric losses [5, 6] and altering the partial discharge (PD) behaviour [7, 8] and hence directly influencing the lifetime of insulation [9–13].

The epoxy-mica main insulation system of rotating electrical machines is designed to permanently withstand PD (Type II insulation) [14] and the materials may be exposed to harmonic distorted voltages when used in machines in the vicinity of power electronics i. e. inverter-fed drives. Consequently, the impact of altered PD behaviour due to harmonics should be investigated carefully since the design of insulation and the resulting lifetime expectations are usually made for purely sinusoidal voltages.

Generally, PD measurements are a fundamental diagnostics tool utilized to assess the production quality and evaluate the long-term performance as well as to find faults that occured during operation. Hereby, the measurement requires sound conditions regarding noise and the evaluation of the results requires good knowledge on common faults. Voltage distortion might hinder high-quality diagnostics and it was already called for the consideration of harmonics in PD measurements [7, 8, 15, 16]. Even more important is to consider the changed disintegrative force of PD when harmonics are present, which, to the knowledge of the authors, has not been investigated in epoxy-mica insulation yet but was occasionally investigated for other insulation systems [12, 17–19].

The aim of this contribution is to investigate the impact of selected harmonic distorted voltages on the apparent charge Q_{IEC} of the PD in the insulation system of a rotating electrical machine. A faultless reference epoxy-mica insulated coil and a coil with an artificially introduced fault within the insulation are investigated in order to identify potential effects of harmonics on the phase-resolved PD pattern (PRPD) and PD characteristics in general. Another objective of this contribution is to correlate voltage distortion parameters to PD activity.

The parameters how to specify harmonic distortion (Section 2), which experimental methods have been used (Section 3) and how the altered voltage waveforms affect the PD behaviour of the main insulation (Section 4) is described in the following.

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2 Fundamentals

2.1 Stator Insulation Failures

Despite being PD-resistant, the manufacturing quality of the insulation system of rotating electrical machines has to be high in order not to introduce larger defects that influence the lifetime of the insulation negatively. The majority of the rotating machine failures is attributed to insulation damage with ageing and internal partial discharges as plausible root causes [20, 21]. One possible cause of error is an inadequate vacuum-pressure impregnation (VPI) during the manufacturing of the form-wound coils. Typical faults include voids and delamination in the main insulation but also between single conductor strands. Additionally, surface discharges close to the field-grading semi-conductive end corona protection may occur [21]. PD measurements after manufacturing are an essential diagnostics tool in order to assess the quality and to find imperfections [14].

2.2 Quantifying the Effect of Harmonics

A distorted voltage waveform can be defined by the voltage U and the phase φ of each frequency component. The total harmonic distortion (THD) simplifies the definition of the voltage waveform and is generally accepted as the most important measure when it comes to harmonic analysis [22].

$$\mathrm{THD} = \frac{\sqrt{\sum_{n=2}^{\infty} U_n^2}}{U_1} \tag{1}$$

The THD quantifies the harmonic content by putting the RMS voltage of each frequency component U_n in relation to the fundamental frequency voltage U_1. It has to be noted, that also the phase of each harmonic influences the peak voltage and the waveform gradient $\mathrm{d}u/\mathrm{d}t$.

The obvious influence of harmonics on the voltage waveform is the increasing or decreasing of the peak compared to the RMS. While for purely sinusoidal voltages the factor $\sqrt{2}$ is universally known, the matter complicates if higher frequency components are present. A set of distortion indicators [12] can be used in order to quantify the effect of harmonics on the voltage waveform and hence providing impact parameters to be used in the evaluation later on. The peak factor K_p represents the peak modification of the waveform compared to a purely sinusoidal, in other words, the discrepancy from the standard $\sqrt{2}$ peak-to-RMS ratio. The peak factor K_p can be below 1, since harmonics may reduce the peak voltage compared to the undistorted sinusoidal.

$$K_\mathrm{p} = \frac{U_\mathrm{p}}{U_{1,\mathrm{p}}} \tag{2}$$

Naturally, not only the voltage u and its frequency decomposition:

$$u = \sum_{n=1}^{N} U_n \sin(n\omega_0 t + \varphi_\mathrm{n}), \tag{3}$$

but also its derivative

$$\frac{\mathrm{d}u}{\mathrm{d}t} = \sum_{n=1}^{N} n\omega_0 U_n \cos(n\omega_0 t + \varphi_\mathrm{n}), \tag{4}$$

is influenced by the harmonics n. φ_n is the phase in relation to the fundamental waveform of each harmonic. ω_0 describes the angular frequency of the fundamental voltage. N is the highest order harmonic.

Dividing (4) by the RMS $\mathrm{d}u/\mathrm{d}t$ of a purely sinusoidal waveform with the same fundamental voltage magnitude then yields a relative waveshape factor [12, 13]:

$$K_\mathrm{s} = \sqrt{\sum_{n=1}^{N} n^2 \left(\frac{U_n}{U_1}\right)^2} \tag{5}$$

The shape factor allows a basic voltage gradient-based comparison between waveforms with different harmonics. A drawback is that K_s is not sensitive to the phase of the harmonic which influences the $\mathrm{d}u/\mathrm{d}t$ of the voltage waveform especially for low orders of harmonics. The shape factor K_s tends to 1 for a pure sinusoidal and is higher if the voltage waveform is distorted by harmonics.

2.3 Influence of Harmonics on PD and Ageing

The voltage waveform distortion due to harmonics directly influences the PD mechanism. A theoretical explanation can be developed for simple representations such as the three-capacitor-model for PD [7, 23]. For example, in case of void discharges, the harmonics and the related $\mathrm{d}u/\mathrm{d}t$ change of the voltage affect the theoretical voltage across the void which is decisive for PD inception and repitition within one period. Some experimental findings indicate that the PD inception voltage (PDIV) is sensitive to harmonics, which can be explained by the altered peak of the distorted voltage [16].

Furthermore, it was experimentally proven that for a multitude of model arrangements, harmonics directly influence the apparent charge, PD repitition rate as well as the inception voltage [16, 24, 25]. There is no direct or unambigous relation between the PD parameters and the harmonics since there are many possible harmonic compositions of the voltage [10, 12]. Depending on the THD and phase with respect to the fundamental voltage, the higher frequent voltages can either increase or decrease K_p. At the same time, K_s steadily increases with growing harmonic order and increasing THD. There are no experimental findings yet that indicate some correlation between K_p or K_s and the PD parameters such as apparent charge, number of discharges per period or the phase relation. The matter is more complicated due to the possibility of multiple PD clusters in the PRPD patterns that are correlated to the changed voltage gradients within one period [7, 8, 16]. This makes the interpretation of PRPD patterns difficult even if the voltage is barely distorted [7]. The problem extends to all kinds of pattern matching techniques in order to identify faults from PRPD patterns. Furthermore, pulse-sequence analysis and its plots can be obstructed by harmonics if the voltage waveshape is distorted to such an extent that extra local maxima appear in the voltage waveform within one period [26].

Ultimately, the distorted voltage waveforms and the altered PD characteristics influence the PD ageing of insulation materials. Statistical evidence was brought forward that the lifetime of insulators subjected to partial discharges correlates with K_p and K_s [11–13]. Hereby the peak amplification due to harmonics has the strongest influence for the degradation acceleration [11]. Consequently, harmonic voltage distortion can be incoporated into life models of insulations [10, 12].

3 Experimental Methods

3.1 Test Objects

Two different VPI-manufactured high-voltage rotating machine coils (Figure 1) rated for 11 kV are utilized in this investigation. One test object is a factory-new reference coil, while the other is a faulty coil with an artificial air-filled void inclusion at the inner conductor strands.

Figure 1: Coil of a high-voltage rotating machine

3.2 Test Setup

A PD measurement system and setup according to IEC 60270 [27] is utilized in this investigation. The 35-kV-voltage transformer (T) is fed by arbitrary voltage signals from a National Instruments digital acquisition system (DAQ) via an amplifier (AMP) (Figure 2). The DAQ measures the voltage U_s via the gas-filled voltage divider C_G - C_M and controls primary voltage in order to precisely set the RMS value of the sinusoidal or distorted voltage as well as the phase angle φ of the harmonic with respect to the fundamental (50 Hz). Only single harmonics are superimposed to the fundamental.

The commercial PD measurement system containing a 600 pF coupling capacitance C_PD and the wide-band measuring impedance (CPL) measures, filters and evalutes the PD activity and voltage. R_d and L_d filter unwanted noise from the transformer and amplifier. The exposed conductors of the coil are put on high voltage potential. The conductive outer corona protection tape is connected to ground potential, hence yielding high electric field strenghts within in the main insulation.

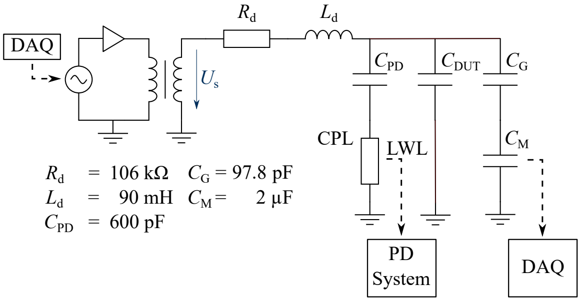


Figure 2: Equivalent circuit

3.3 Test Regime & Harmonic Parameters

In a first step, several harmonic compositions with nearly identical K_P are selected and compared with regard to their PRPD patterns and PD characteristics at 120 % U_R (Table 1). In reality, the coils would not experience such high voltagets during standard operation. The high stress is selected in order to gain distinct and clear results. The measurements show the quantitative influence of K_S when peak and RMS voltage is constant.

As a second step, disregarding the shape factor K_S, the peak factor K_P dependency of the Q_IEC is evaluated at 120 % U_R. A multitude of possible harmonic compositions is selected based on a high variety of K_P that extend the presented measurements in Table 1. The PRPD patterns of the ref-

Table 1: Voltage waveform compositions and the resulting Q_{IEC} of the reference and the faulty test object

#	Harm.	THD	φ	K_{P}	K_{S}	Q_{IEC} Ref.	Q_{IEC} Faulty
		%	°			nC	nC
1	1	0	0	1	1	5.27	10.95
Section 4.1							
2	3	20	60	1.26	1.31	5.14	18.23
3	5	20	0	1.26	1.73	6.70	19.18
4	7	20	180	1.26	2.22	6.00	18.69
5	9	20	0	1.26	2.73	5.55	19.56
6	11	20	115	1.26	3.27	5.42	18.91
7	13	20	0	1.26	3.81	5.13	19.30
Section 4.2							
8	3	10	0	0.86	1.08	1.90	7.28
9	3	20	0	0.89	1.31	1.65	13.15
10	3	10	235	0.90	1.08	1.33	12.54
11	5	5	180	0.95	1.06	2.07	13.90
12	5	5	110	0.96	1.06	1.98	14.17
13	7	5	0	0.99	1.12	4.03	14.90

erence (non-faulty) coil and the coil with the artificial fault are recorded and analyzed.

In all measurements, the PD measuring system records the apparent charge according to IEC 60270 [27] Q_{IEC} in nC for two minutes. The average of the two minute recording is shown in the results.

4 Results

4.1 Constant Peak Factor K_{P}

In this test regime, the PD characteristics of the test objects are measured at different voltage waveforms with nearly identical peak factors K_{p}. The voltage waveform compositions are defined by the harmonic order (e. g. 3H is the third harmonic which equals to 150 Hz), THD and phase φ (Table 1). The waveforms were intentionally selected with an identical K_{p} and RMS voltage hence a constant peak voltage but a high variety of K_{s}.

The peak and shape factor relative to the purely sinusoidal waveform are derived as specified in section 2.2. The measured apparent charge Q_{IEC} is significantly lower for the reference (non-faulty) test object as compared to the faulty coil having the artificial air-filled void. Figure 3 demonstrates that when K_{p} is constant, no direct correlation between K_{s} and Q_{IEC} can be found. Although the peak voltage is held constant, the measured Q_{IEC} fluctuates around $5.7\,\mathrm{nC} \pm 35\,\%$ for the reference test object and $19\,\mathrm{nC} \pm 7\,\%$ for the faulty test object.

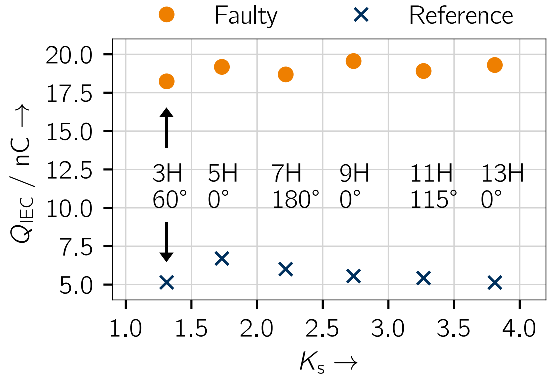


Figure 3: Apparent charge Q_{IEC} of the reference and faulty test object as a function of the shape factor K_{s}, peak factor K_{p} constant, see Table 1 #2-7

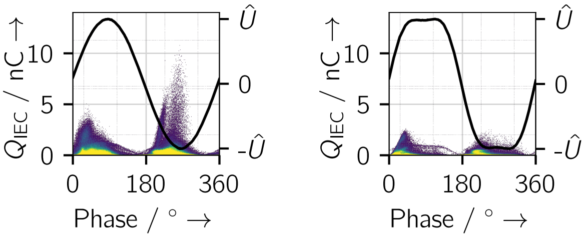
It must be taken into account that the different voltage waveform compositions look severely different and the recorded PRPD patterns are clearly depending on the voltage gradient $\mathrm{d}u/\mathrm{d}t$ (Figure 4). With each voltage rise within the voltage waveform's period, PD peaks can be detected. A polarity-dependency is visible and becomes visually stronger when harmonics are present. Although the local voltage maxima become narrower with higher harmonic order, the peak Q_{IEC} remain almost constant. In contrast, the test object with the artificial void shows significantly higher Q_{IEC} amplitudes and no clear polarity effect (Figure 5). With superimposed harmonics, PD clusters with higher amplitude can be detected which result in increasing Q_{IEC} values.

4.2 Variable Peak Factor K_{p}

The peak factor K_{p} of a voltage waveform can be modified by changing the harmonic order, THD and phase φ. Table 1 #8-13 only shows a selection of the investigated voltage waveforms with variable K_{p}. Generally speaking, the measured Q_{IEC} of the PD increases with increasing peak factors (Figure 6). The upward trend is more pronounced for the faulty test object supposedly due to the strong PD within the air void. The cluster of measured combinations at $K_{\mathrm{p}} = 1.26$ are the measurements #2-7 that are discussed in section 4.1. The majority of the compositions with low K_{p} and hence low Q_{IEC} are third harmonic distortions (3H in Figure 6).

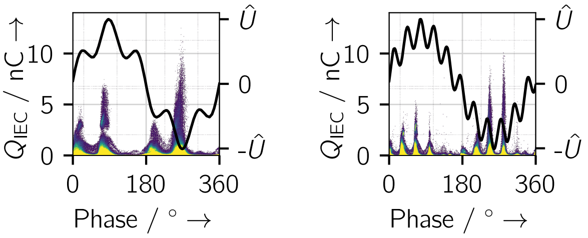
5 Discussion

Generally, the measurements indicate that the discussed literature findings are applicable to PD in the insulation system of rotating electrical machines. The peak voltage is predominant for the Q_{IEC} of PD



(a) #1: Pure Sinusoidal

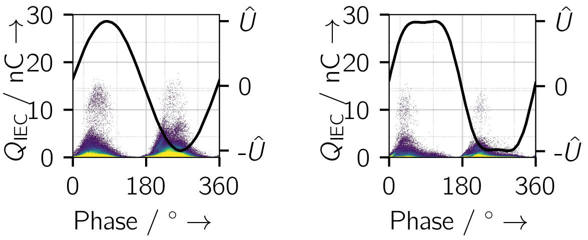
(b) #8: 3rd Harmonic, 10 % THD, $\varphi = 0°$



(c) #5: 9th Harmonic, 20 % THD, $\varphi = 0°$

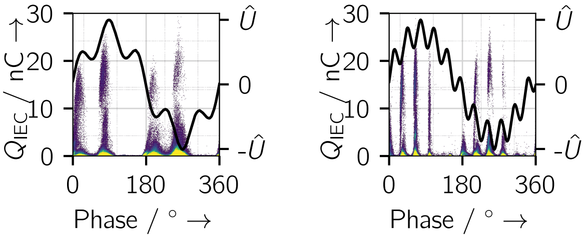
(d) #6: 11th Harmonic, 20 % THD, $\varphi = 115°$

Figure 4: Impact of different harmonics on PRPD patterns of the reference coil at 120 % U_{R}, constant K_{p}.



(a) #1: Pure Sinusoidal

(b) #8: 3rd Harmonic, 10 % THD, $\varphi = 0°$



(c) #5: 5th Harmonic, 20 % THD, $\varphi = 0°$

(d) #6: 11th Harmonic, 20 % THD, $\varphi = 115°$

Figure 5: Impact of different harmonics on PRPD patterns of the reference coil with air-filled void at 120 % U_{R}, constant K_{p}.

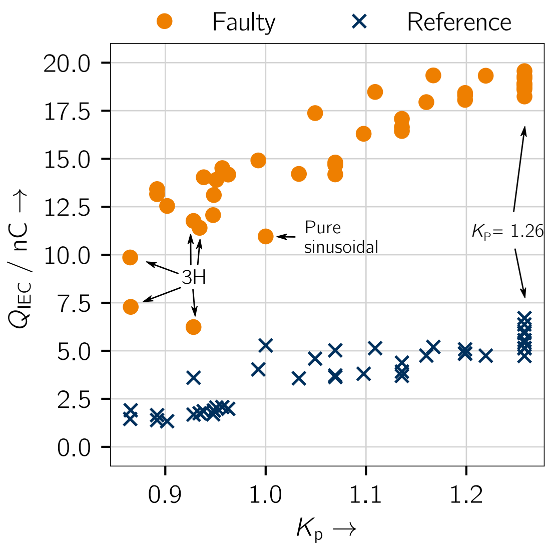


Figure 6: Apparent charge Q_{IEC} of the reference and faulty test object as a function of the peak factor K_{p}

while the shape of the voltage waveform and hence the voltage gradient $\mathrm{d}u/\mathrm{d}t$, approximated through K_{s}, plays a subordinate role. Nonetheless, the Q_{IEC} measurements show obervable differences even for constant peak voltage that cannot be correlated to the shape factor. The 'flat top' voltage waveforms (Figure 4 (b)) that are produced by superimposing the third harmonic lead to exceptionally low Q_{IEC} values. These compositions seem to have a good trade-off between lower peak voltage and still limited voltage gradient leading to weaker PD activity.

The PRPD patterns change significantly with the distinct compositions. As previously noted [16], the PD occur when the voltage gradient $\mathrm{d}u/\mathrm{d}t$ is highest. Even low harmonic distortion e.g. $\mathrm{THD} = 5\,\%$ influences the measured Q_{IEC} significantly which should be kept in mind for PD measurements, especially when compliance to standards is required.

The use of parameters such as the peak factor K_{p} and the shape factor K_{s} in order to correlate voltage waveform modification with PD activity works well within certain limits. The measurements indicate that there are influences that are not yet covered by these factors but may play a role in PD activity and, even more important, PD-induced ageing.

6 Conclusion

This contribution presents the influence of the harmonic distortion of the voltage on partial discharge activity in the insulation of rotating electrical machines. General differences in the Q_{IEC} measurements were pointed out by comparing a factory-new reference coil with a typical epoxy-mica insulation system of a electrical machine to a sample coil with an artificial air-void fault.

The altered voltage peak due to the harmonics dominates the PD behaviour when voltage distortion occurs. Some uncertainty remains about the exact effect of the voltage shape and gradients which require more detailed measurements on simple, reproducible specimens in the future. Prospectively, the hypothetical correlation between changed PD activity and lifetime of insulations should be subject to further research.

Acknowledgments

This research was funded by the European Social Fund (ESF) and the Free State of Saxony (https://www.strukturfonds.sachsen.de).

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