Dielectric Behaviour of High Permittivity Silicone Rubber At Distorted Voltage Stress

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1 Introduction

Power electronics are becoming an essential component in power systems, most notably for better integration of renewable energy systems or to increase flexibility in the electrical grid. Nonetheless, the application of power electronics can introduce additional electrical stress in form of harmonics up to several kHz in the electric grid [1], [2]. These harmonics result in a distortion of sinusoidal voltage waveform, leading to a so-called harmonic distorted voltage. In this paper, the distorted voltage waveform is composed of a fundamental voltage (AC50 Hz) superimposed with a second voltage of the harmonic frequency (ACHF). Such harmonic distorted voltages can lead to a compromised operation of an electrical equipment, as they cause not only additional electrical stress, but also an enhanced thermal stress in the insulation system [1]–[5]. An example is the study case presented in [1], where a compromised field grading system caused by harmonic frequencies is proven to be the main reason for equipment failure.

The influence of harmonic distorted voltages on different field grading techniques are summarized as below:

- Resistive field grading with nonlinear semi-conductive material

The additional electric stress caused by harmonic frequencies result in higher dielectric losses and consequently induce “hot-spots” in the insulation system. The temperature increase is most pronounced on the semi-conductive field grading layer, which is attributed to higher ohmic losses [3].

- Geometric field grading with larger area

[1], [6] proved that harmonic distorted voltages have no significant influence on geometric field grading, as the field distribution is independent of frequency.

- Refractive field grading with nonlinear relative permittivity

As of yet, the effects of harmonics on refractive field grading have not been studied adequately. However, an influence of harmonics on the effec-
tiveness of refractive field grading cannot be excluded since the nonlinear permittivity is strongly dependent on the electric field strength, temperature and frequency [7].

To ensure the long-term reliability of an insulation system in an electrical equipment, it is important to consider every possible aspect of operational electrical stress. This contribution investigates the dielectric behaviour of silicone elastomers with refractive field grading properties under sinusoidal and harmonic distorted voltages. The dielectric properties provide not only fundamental knowledge of the dielectric under different parameters, but also serve as data for the computation of a numerical model for harmonic distorted voltages. While the numerical model is part of future works, this contribution discusses the experimental results.

2 Test Setup and Procedure

Three functionally filled silicone elastomers (f-SiR) with a thickness \( d = (1 \pm 0.05) \text{ mm} \) serve as test samples. The f-SiR material contains ferroelectric particles as fillers.

Dielectric properties such as the DC-conductivity \( \sigma_{\text{DC}} \) and the complex relative permittivity \( \varepsilon^* \) of the f-SiR samples are determined at first. The DC-conductivity \( \sigma_{\text{DC}} \) of the test samples is measured using an electrometer (Keithley Multimeter 6517B) at voltages up to 1000 VDC [8]. It should be noted that the measurements of the \( \sigma_{\text{DC}} \) are conducted on one f-SiR sample due to long measurement times and that the values presented in this paper are determined after 24h of measurement.

\[
\sigma_{\text{DC}} = \frac{Id}{U_{\text{DC}A_M}} \quad (1)
\]

A test setup as shown in Figure 1 is constructed for the measurements of the complex relative permittivity \( \varepsilon^* \) and the dielectric loss \( P_\delta \).

![Figure 1: Test setup for measurements under sinusoidal and harmonic distorted voltages](image)

The middle frequency voltage is generated using a signal generator, amplified and transformed via a ferrite-core transformer. Voltages up to 2 kV at frequencies between 350 Hz and 2 kHz are possible. For the harmonic distorted voltages, the grid voltage \( U_{\text{rms},50 \text{ Hz}} \) is superimposed with the middle frequency voltage \( U_{\text{rms,HF}} \). With the test voltage \( U_{\text{rms}} \) ranging between 250 V and 1000 V, and at a constant value of the Total Harmonic Distorted (THD), the amplitudes of the respective frequencies are determined using:

\[
U_{\text{rms},50 \text{ Hz}} = \frac{U_{\text{rms}}}{\sqrt{1 + \text{THD}^2}} \quad (2)
\]

\[
U_{\text{rms, HF}} = U_{\text{rms},50 \text{ Hz}} \times \text{THD} \quad (3)
\]

As precautionary measures against electrical flashovers or high currents during a breakdown, a series resistor \( R_v \), a filter capacitor \( C_s \) and a spark gap (SG) are integrated in the test setup. The voltage and current is measured with a gas insulated capacitive voltage divider and a coaxial shunt (1 kΩ ± 5%). Both signals are sampled using a 16-bit data acquisition system (DAQ) at a sample rate of 2 MS/s for a total of three seconds.

The real \( \varepsilon' \) and imaginary \( \varepsilon'' \) part of the complex permittivity can be obtained by measuring the sinusoidal voltage \( u(t) \) and the current \( i(t) \) for a certain period \( T \).

\[
P_\delta = \frac{1}{T} \int_{t=0}^{T} u(t) i(t) \, dt \quad (4)
\]

This allows the calculation of the complex power in terms of the active power \( P \) according to (4), the apparent power \( S \) and the reactive power \( Q \):

\[
S = U_{\text{rms}} I_{\text{rms}} \quad (5)
\]

\[
Q = \sqrt{S^2 - P^2} \quad (6)
\]

Consequently, the dielectric loss tangent \( \tan \delta \) as well as the real \( \varepsilon' \) and imaginary \( \varepsilon'' \) part of the complex permittivity can be determined (7)-(9):

\[
\tan \delta = \frac{P}{Q} \quad (7)
\]

\[
\varepsilon' = \frac{Q d}{\omega \varepsilon_0 A_M U_{\text{rms}}^2} \quad (8)
\]

\[
\varepsilon'' = \varepsilon' \tan \delta \quad (9)
\]

Under harmonic distorted voltages, the dielectric loss of a material can be quantified in terms of the dielectric loss \( P_\delta \) based on their dielectric properties (10) [5], [9], [10]:
\[ P_\delta = \sum_{n=1}^{\infty} E_{\text{rms},n}^2 (2\pi f_n \varepsilon''_{n}) C_0 d^2 \]  
(10)

By substituting the volume \( V \) of the sample, the heat loss density \( Q_d \), which quantifies the volume-related dielectric loss can be determined (11):

\[ Q_d = \frac{P_\delta}{V} \]  
(11)

Eq. (10) is however only applicable for linear dielectrics, where the linear dielectric response can be represented using the superposition theory in the case of a harmonic distorted voltage. For a nonlinear dielectric, the dielectric loss can only be determined directly using (4), where the test voltage \( u(t) \) takes the form of the harmonic distorted voltage with an amplitude of \( U_{\text{rms}} \) (Figure 2).

To ensure measurement accuracy, a reference method as proposed in [11] is first conducted before every measurement. To compute a numerical model that simulates the operational stress as realistic as possible, a large dataset is required. Extensive measurements are conducted under different frequencies \( f \), temperatures \( \vartheta \), electric field strengths \( E \) and harmonic orders \( n \) (Table 1).

![Figure 2: Example of a harmonic distorted voltage composed of two AC-voltages, \( U_{50}(t) \) at 50 Hz and \( U_{550}(t) \) at 550 Hz](image)

The experiments are conducted with a guard ring electrode arrangement with an effective area of \( A_M = 20 \text{ cm}^2 \). The samples are pre-conditioned through heating in an oven at 90 °C for 96 h before the start of every experiment to remove moisture in the sample. For the measurements under sinusoidal and harmonic distorted voltages, the electrode arrangement, including the sample, is immersed in silicone oil to avoid partial discharges during measurements.

3 Dielectric Properties at Sinusoidal Voltages

The DC-conductivity \( \sigma_{\text{DC}} \) of f-SiR and its electric field strength dependence is depicted in Figure 3 under the influence of different temperatures.

![Figure 3: Electric field strength dependence of the of the DC conductivity of f-SiR under the influence of temperature](image)

Generally, the \( \sigma_{\text{DC}} \) increases with increasing electric field strength. Regardless of the electric field strength, higher temperature results in a decrease of the \( \sigma_{\text{DC}} \). A comparison of the values at 30 °C and 80 °C shows that the values of \( \sigma_{\text{DC}} \) are five times less after the temperature enhancement.

Meanwhile, both real \( \varepsilon' \) and imaginary \( \varepsilon'' \) relative permittivity of f-SiR are strongly dependent on the frequency, electrical field strength, and temperature (Figure 4).

![Figure 4: Overview of test parameters](image)

Regarding the influence of temperature, enhanced temperatures lead to a decrease in the values of the DC-conductivity \( \sigma_{\text{DC}} \) and the complex permittivity \( \varepsilon' \) and \( \varepsilon'' \). The lower values of \( \sigma_{\text{DC}} \) at high temperatures (Figure 3) can possibly be a result of thermal expansion of the polymer matrix. Temperature agitation causes the polymer chains to expand, leading to increased distances between contacting particles and consequently a decrease in connecting networks in the polymer matrix [12]. Apart from that, external thermal agitation can randomise the dipole alignments, which counteracts dipole orientation towards the field direction [13], [14]. This explains the decrease of \( \varepsilon' \) and \( \varepsilon'' \) with increasing temperatures in Figure 4.
The electric field dependence of field dependence of both $\varepsilon'_r$ and $\varepsilon''_r$ can be attributed to a nonlinear relationship between polarization $P$ and the electric field strength $E$ [13]. The steeper slopes of both $\varepsilon'_r$ and $\varepsilon''_r$ between 0.75 kVmm$^{-1}$ and 1 kVmm$^{-1}$ indicate a threshold of the electric field strength $E_{th}$, where the material exhibit nonlinear properties when $E_{th}$ is exceeded. Despite a sinusoidal voltage stress, the current through the nonlinear dielectric typically exhibits a distorted waveform [10].

While an increase in the electrical field strength can result in higher values of $\varepsilon'_r$ and $\varepsilon''_r$, an increase in frequency causes a decrease in both parameters instead. Dipole movements according to the electric field become increasingly delayed at higher frequencies, resulting in lower values of $\varepsilon'_r$ and $\varepsilon''_r$ [9], [13].

### 4 Dielectric Loss at Distorted Voltages

Under harmonic distorted voltages, the dielectric loss is presented in terms of the measured heat source density $Q_d$ in Wm$^{-3}$ and compared with theoretically calculated values (dotted lines) in Figure 5. The calculation is based on the quadratic dependence of the dielectric loss on the electric field strength ($P_\delta \propto E^2$ – see (8)).

A significant increase is seen from 0.75 kVmm$^{-1}$ onwards, where the measured $Q_d$ at 1 kVmm$^{-1}$ is four times higher than that at 0.75 kVmm$^{-1}$ (Figure 5). A comparison of the measurements with the calculated values show that the measurement results agree well with the calculated values for the field strengths between 0.25 kVmm$^{-1}$ and 0.75 kVmm$^{-1}$. However, between 0.75 kVmm$^{-1}$ and 1 kVmm$^{-1}$, a notable deviation of the values is seen, with the measured results being around twice the amount of the calculated values at 1 kVmm$^{-1}$. Here, we see a certain threshold of the electrical field strength similar to the complex permittivity under sinusoidal voltage stress in Figure 4, where the dielectric behaves nonlinear when exceeded. As a result, the theoretical calculation of the dielectric loss $P_\delta$ as well as the heat source density $Q_d$ using the superposition theory (refer (8)) becomes insufficient to represent a distorted voltage stress.

Meanwhile, regardless of the harmonic order $n$ and electric field strength $E$, higher temperatures result in a decrease of the heat source density $Q_d$ (Figure 6).

At 30 °C and 1 kVmm$^{-1}$, $Q_d$ of f-SiR is approximately 20000 Wm$^{-3}$. With increasing temperatures from 30 °C to 80 °C, the values of $Q_d$ decrease by almost 2.7 times to ca. 7500 Wm$^{-3}$ at
1 kVmm⁻¹ (Figure 6). This shows that the loss-induced thermal stress is lower in the material despite higher ambient temperatures and can be attributed to the negative temperature-dependence of the polarisation losses $\varepsilon''$ (Figure 4).

As a reference, insulating silicone rubber (SiR) with lower permittivity $\varepsilon'$ and polarization losses $\varepsilon''$ have significantly lower values at $Q_d = 3.2$ Wm⁻³ under similar conditions (1 kVmm⁻¹, 30 °C) [11]. Multiphysics simulations using the Finite-Element-Method (FEM) in [11] have shown that up until 20 kVmm⁻¹, the heat change in SiR is negligible due to the low values of the heat source density $Q_d$ ($10^2$ Wm⁻³). In comparison to SiR, the high values of $Q_d$ ($10^4$ Wm⁻³) in f-SiR could potentially induce significant heat increase in the material. As of yet, this remains as a hypothesis and can only be verified by multiphysics simulations. However, due to the nonlinear permittivity, the presented FEM-model in [11] is insufficient to model f-SiR under a harmonic distorted voltage stress. Therefore, a revised model for nonlinear dielectrics under the electric stress of a harmonic distorted voltage is necessary and is focus of future research.

5 Conclusion

To thoroughly simulate a harmonic distorted voltage stress, the dielectric properties of the high permittivity silicone rubber (f-SiR) are investigated under multiple dependencies – frequency, temperature and electrical field strength. The complex permittivity becomes nonlinear above an electric field strength threshold value $E_n$, such that the calculation of dielectric losses based on the superposition theory becomes invalid for f-SiR when $E_n$ is exceeded. In such cases, state-of-the-art theoretical models are insufficient to simulate the corresponding electrical stress. As such, further research is required to compute a numerical model for nonlinear dielectrics under harmonic distorted voltages.

6 References

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