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Dielectric Heating of Polymers as a Consequence of High Harmonic Voltage Distortion

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Abstract—Harmonic distorted voltage waveforms can lead to excessive heat in the insulation of electrical equipment. The prospectively increasing number of power electronic devices in electrical grids requires the careful examination of the consequences of harmonics, which are introduced due to the operating principle of the semiconductor switches. Investigations of the thermal breakdown of solid dielectrics that may occur as a consequence of harmonic distortion on the voltage waveform of electrical grids are presented in this contribution. A thermo-electrical multi-frequency model allows the calculation of the overtemperature in the material. The calculations are confirmed by breakdown experiments of phenolic paper and epoxy resin. Generally, the additional dielectric losses due to the harmonic voltage distortion increase the possibility of exceeding the thermal equilibrium. However, modern insulation materials like the investigated epoxy resin have very low loss factors which is favourable for good thermal performance even with severely distorted voltages.

Index Terms—dielectric heating, epoxy resin, phenolic paper, dielectric losses, thermal breakdown

I. INTRODUCTION

The need for flexible and efficient electrical equipment leads to the extensive use of power electronics in electrical grids as well as in mobile applications [1–3]. The high frequency switching of power electronics, such as the converters of variable speed drives, leads to the distortion of the grid voltage [4]. Typically, the low-order harmonic distortions range in between 150 Hz and 2500 Hz with established limits for low-voltage (LV) and medium-voltage (MV) grids by IEEE Std. 519 [5], IEC 61000-2-2 [6] and IEC 61000-2-4 [7]. Furthermore, high frequency oscillations in the kHz range can be excited due to resonance effects [4, 8]. Harmonic distorted voltages can lead to the accelerated aging of electrical equipment as a result of additional dielectric losses and their effect on partial discharges (PD) [9, 10]. Dielectric heating as a consequence of the conduction and polarization losses in insulation materials results in elevated temperatures and, possibly, thermal breakdown [11]. One example how severely distorted voltage leads to catastrophic effects on high-voltage assets is the Eagle Pass installation failure [12].

Dielectric heating mostly affects solid insulation materials due to frequency dependent polarization losses and limited heat transfer capacity. Especially in voluminous insulations at high ambient temperatures, critical situations may arise if dielectric losses tip over the thermal equilibrium hence resulting in a thermal breakdown. The thermo-electrical calculation models help to optimize the design process of operational equipment by identifying areas with elevated temperature due to dielectric heating.

In MV equipment such as instrument transformers, epoxy resin is a popular casting and impregnation material. It has low dielectric losses, while a filler such as quartz increases its thermal conductivity and mechanical stability favourably [11]. Phenolic paper is utilized in bushings and in old oil-filled transformers, although being more and more replaced by alternatives such as resin-impregnated paper [11]. In contrast to epoxy resin, phenolic paper has high dielectric losses due to high electric conductivity and a high permittivity [11]. The goal of this contribution is to present a thermo-electrical multi-frequency model that allows the calculation of the dielectric heating in materials even if the voltage is distorted by harmonics. Qualitative evidence is produced with breakdown experiments carried out on two materials: epoxy resin and phenolic paper.

II. DIELECTRIC HEATING

Polarization and conduction losses in dielectrics cause dielectric heating [13–15]. Generally, the dielectric loss $P_\delta$ can be quantified by

$$P_\delta = 2\pi f U^2 \varepsilon'_r C_0 \tan \delta ,$$

where $f$ is the frequency of the voltage, $U$ is the RMS of the voltage, $C_0$ is the geometric capacity of the test object and $\varepsilon'_r$ is the real dielectric permittivity of the material [14]. The dielectric loss factor $\tan \delta$ incorporates conductivity and polarization losses [11]. In the case of distorted voltages, more than one frequency exists in the voltage waveform hence multiple loss components have to be superpositioned:

$$P_\delta = \sum_{n=1}^{\infty} 2\pi n f_0 U_n^2 \varepsilon'_{r,n} C_0 (\tan \delta)_n ,$$

where $n$ is the number of harmonic and $f_0$ is corresponding fundamental frequency. It has to be noted that the superposition of the dielectric loss components is sufficiently accurate for linear materials such as epoxy resin [14, 16, 17] but must not be used for nonlinear, electrical field-dependent materials e.g. with field grading functionality [18]. The generated heat in the electrically stressed insulation material dissipates through the mechanisms of heat transfer.
Not only the heat capacity and thermal conductivity of the material, but also its surroundings, determine the temperature distribution in the test object. The increased temperature in turn leads to increased dielectric losses through increased conductivity and altered polarization mechanisms. In summary, the interaction of elevated temperature and then again increased dielectric losses leads to the risk of thermal runaway resulting in a thermal breakdown [14]. This then corresponds to an unstable, ever-increasing current through the insulation leading to the destruction of the material. Moreover, [17] verifies that reduced breakdown voltages can be attributed to excessive heating caused by high frequency distortion.

III. METHODS

A. Specimen

Two material samples are investigated: a) epoxy resin with 67 vol% quartz filler and b) phenolic paper. The epoxy resin test object is in a casted sphere-plate arrangement according to IEC 60455-2 [19] in order to achieve very high electrical field strengths in the material. The phenolic paper plates are stressed in a cylinder-plate arrangement according to IEC 60243-1 [20] (Figure 1). All electrodes are made of stainless steel. The test objects are placed within a heated oil bath in order to adjust the ambient temperature up to 110 °C and to avoid surface discharges and flashovers. The temperature is measured with a thermocouple in the bottom electrode. The current discharges and flashovers. The temperature is measured with a commercial dielectric dissipation factor extractor via coaxial cable from the bottom electrode.

The dielectric properties of epoxy resin and phenolic paper are measured with a commercial dielectric dissipation factor measurement system. The thermal conductivity $\lambda$ and heat capacity $c_p$ are taken from the material’s data sheet (Table I).

![Figure 1: Test objects, a) epoxy resin sphere-plate arrangement, b) phenolic paper cylinder-plate arrangement](image)

**Table I: Material properties of the test specimens, mean of three measured specimens**

<table>
<thead>
<tr>
<th></th>
<th>Epoxy Resin</th>
<th>Phenolic Paper</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon'$</td>
<td>100 °C; 50 Hz</td>
<td>5.07</td>
</tr>
<tr>
<td>$\tan \delta$</td>
<td>100 °C; 50 Hz</td>
<td>0.10</td>
</tr>
<tr>
<td>$\lambda$ in Wm$^{-1}$ K$^{-1}$</td>
<td>0.30</td>
<td>0.20</td>
</tr>
<tr>
<td>$c_p$ in Jkg$^{-1}$ K$^{-1}$</td>
<td>3800</td>
<td>3800</td>
</tr>
</tbody>
</table>

B. Thermo-electrical Multi-frequency Model

The FEM calculation model incorporates the electrical stress of multiple frequency components and the subsequent heat dissipation of the generated dielectric losses. Multiple frequencies are represented by separate steady-state studies of which the computed heat source density of the fundamental frequency study is shared with the harmonic frequency study. The calculated temperature distribution in the specimens is the result of the superimposition of the two studies. Cross-checking the calculated total heat source density of the model with previously published experimental results [18] quantifies deviations to below 10 %. The model incorporates both specimen geometries and dielectric parameters in order to obtain the temperature distribution based on dielectric heating.

C. Experimental Procedure and Setup

The voltage $U_q$ for the breakdown experiments is generated by a controlled transformer and an amplifier fed by the programmable voltage source (Figure 2). The highest used voltage is $U_q = 30$ kV RMS. A total harmonic distortion (THD) of 20 % is applied for frequencies up to 850 Hz corresponding to the 17th harmonic (H17). The RMS of the voltage is held constant regardless of the superimposed harmonic. The voltage is increased stepwise to obtain the thermal equilibrium voltage. For each step, a voltage proportional current $I_{DUT}$ is measured via the transimpedance amplifier for 300 s. The oncoming thermal breakdown is detected when the current $I_{DUT}$ increases without reaching a steady-state during the voltage step interval. The overcurrent protection of the x75 amplifier automatically shuts down the voltage supply in the case of breakdown. Besides the current measurement, PD measurements with a coupling capacitor $C_{PD}$ and a measurement impedance CPL accompany the procedure in order to rule out PD aging as the cause for the breakdown. The resistor $R_d$ limits the current and the inductance $L_d$ filters the noise on the measured PD signal that is originating from the power supply. A gas capacitor $C_G$ and the low voltage capacitor $C_M$ serve together as a calibrated, frequency-stable voltage divider which feeds the measurement signal back to the voltage control device.

![Figure 2: Circuit diagram of the experimental setup with PD and current measurement of the DUT](image)
Figure 3: Calculated temperature distribution and overtemperature due to different harmonics within the phenolic paper specimen, \( U_q = 10\text{kV RMS with THD} = 20\% \)

Figure 4: Breakdown field strength calculated from RMS voltages of phenolic paper stressed by voltage waveforms with different harmonics, \( \vartheta_{\text{amb}} = 100\text{°C, THD} = 20\% \)

IV. RESULTS

A. Phenolic Paper

The calculation of the temperature distribution shows that already the pure 50 Hz stress elevates the temperature in the centre of the arrangement up to +9 K (Figure 3). The dielectric losses due to additional harmonics, even though the RMS of the voltage is constant, lead to an additional dielectric heating resulting in an overtemperature of up to +14.5 K.

The breakdown experiments reveal declining electric field strengths with increasing harmonic distortion (Figure 4). An exception from this is the 17th harmonic for which the breakdown field strength is higher than for the 9th harmonic. The variances of the five measured specimens overlap between the voltage waveforms emphasising the limited statistical significance. The current measurement during the experiments as well as the optical investigations of the specimens after breakdown indicate an excessive temperature and thermal breakdown in the center of the specimens. The presented electrical field strengths are calculated from the RMS voltage since the dielectric losses and the subsequent heating provoke the thermal breakdown. No PD were detected during the experiments.

B. Epoxy Resin

Compared to phenolic paper, the epoxy resin material has very low dielectric losses. Even at an ambient temperature of \( \vartheta_{\text{amb}} = 100\text{°C} \), the factor \( \varepsilon' \cdot \tan \delta \), representing the dielectric losses of the material, is approx. 3% of that of phenolic paper (Table I). The resulting temperature distribution (Figure 5) reveals less than one K overtemperature in the vicinity of the sphere electrode. Consequently, the electric field strength to initiate the thermal breakdown is significantly higher. Ultimately, no thermal breakdown could be observed and only electrical breakdowns are likely e.g. as a result of PD. Figure 6 shows the breakdown electric field strength calculated from the peak voltage, which for harmonic distorted voltages is different from \( \sqrt{2}U_{\text{RMS}} \). In contrast to the thermal breakdown of the phenolic paper specimens (Section IV-A) where the RMS voltage is relevant, the peak voltage or peak field strength is decisive when PDs occur. The three specimens have very high breakdown field strengths at \( \vartheta_{\text{amb}} = 23\text{°C} \). No increasing current and no PD are detected before the breakdown so that an electrical breakdown is suspected. The obtained values are in the range of \( \tilde{E}_{\text{BD}} = (35 \ldots 42) \text{kV mm}^{-1} \).

At higher temperatures, PDs are detected in the last voltage steps leading to the assumption that aging is the main cause...
of breakdown. The superimposed 17th harmonic has a minor impact on the illustrated breakdown field strength. A likely origin of the PDs is that due to the different thermal expansion of the epoxy resin and the stainless steel electrode, microscopical voids emerge around the electrode resulting in alteration of the electrical field. The electrical field strength exceeds the dielectric strength of the gas-filled void so that PD occur. It has to be considered when interpreting the results that only three epoxy resin specimens were measured for each voltage-temperature stress.

V. DISCUSSION

Generally, harmonic distortion of the voltage waveform results in higher dielectric losses and higher temperatures in the insulating material. The impact of the harmonics is strongly depending on the overall dielectric losses of the materials resulting in the different behavior of phenolic paper (high dielectric losses) and epoxy resin (low dielectric losses). Harmonics cause up to approx. $\Delta \theta = 14.5$K overtemperature in the investigated phenolic paper arrangement, leading to lower breakdown field strengths that can be traced back to thermal breakdown. In contrast, the calculations revealed marginal dielectric heating in the epoxy resin arrangement. No thermal breakdown occured although the epoxy resin specimens were stressed by high electrical field strengths and high temperatures. The results are in agreement with previous publications that investigated the dielectric heating of polymers. In [14], epoxy resin was also found to be little sensitive to thermal runaway even when stressed with significantly distorted voltage waveforms although no breakdown experiments or temperature measurements were carried out. The results in [15] and [17] show a directly measured temperature increase of several K and consequently facilitated thermal breakdown for other polymeric insulation materials but with voltage distortion in the kHz range. Until now, the influence of the harmonics below one kHz on the dielectric heating has not been sufficiently investigated by calculation or experiments.

For both materials in this investigation, the calculation and experiments are in good qualitative concurrence. The observed influence of the harmonics on the breakdown field strengths of phenolic paper can be well explained by the calculated temperature distributions. The same applies to the results of epoxy resin since the negligible temperature increase does not evoke a thermal breakdown. The general approach of including harmonic distortion in the calculation model by superimposing two separate dielectric studies delivers plausible results.

VI. CONCLUSIONS

A calculation model for the temperature distribution in dielectrics under harmonic distorted voltage stress has been presented and qualitatively verified by breakdown experiments. Materials with high dielectric losses such as phenolic paper are prone to thermal breakdown particularly when additional dielectric losses due to harmonics of the stressing voltage cause further heating. The calculations reveal a severely increased temperature due to dielectric losses which are confirmed by lower breakdown voltages if harmonics are present. The presented methods are also applicable for materials with low dielectric losses although no severe influence on the breakdown was determined in this investigation. Under any circumstances, additionally generated heat due to dielectric losses, even if a thermal breakdown is not imminent, may lead to accelerated aging as a result of the higher temperature. Hence in practice, especially in electrical environments with poor power quality, harmonics should be taken into account when designing insulation systems. The presented calculation method allows a sufficiently simple evaluation of the losses within the insulation while requiring only fundamental dielectric measurements.

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