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RESISTIVE ELECTRICAL FIELD GRADING OF INSULATION OIL-SOLID INTERFACES

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There is always a need for more compact designs of power transformers free of partial discharges, in order to save cost on the construction and required material resources. The physical geometric constrictions inside the transformer tank would demand field-grading techniques to homogenise the field strength distribution on oil-solid interfaces, when required. Standard filler materials such as carbon black or silicon carbide (SiC) have a too high electrical conductivity yielding an appropriate grading field strength values for air-related applications. Because insulation oil has a higher electrical breakdown strength, the electrical conductivity must be engineered to lower values in order to reach a higher effective grading field strength. This paper presents the investigation of a new material system based on a phenolic resin Lerg FL-500 and the electrically functionalized ceramic filler particles Merck Iriotec®7550 that enable a resistive electrical field grading in insulation oil. In order to verify the principle functionality of the proposed field grading system, a layer is applied on a substrate surface representing possible oil-solid-interface inside oil-filled power transformers.

First, the manuscript describes the methods of specimen preparation and the measurement of the nonlinear current-time behaviour under AC voltage stress for different filler contents. Second, a concurring optical and electrical determination of the partial discharge inception and extinction voltage of a modified Toepler arrangement allows the indirect determination of the electrical field strength distribution along the functionalized layer without the need of direct measurement. To do so, the radius of the circular functional layer is varied and with it the specific grading length. In analogy to state of the art SiC-filled systems, a linear dependency between the effective grading length and the PD inception voltage is observed. The quotient of voltage drop over a varied radius yields the effective graded electric field strength.

1. Introduction

The resistive field grading technique has been the state of the art for rotating high voltage (HV) machines for many decades [1, 2, 3] now. In general, silicon carbide (SiC) particles emerged in a resin matrix are used to secure a field strength of less than streamer voltage gradient of 5 kV/cm in the air domain of the solid insulation near the slot outlet of rotating electrical machines [4]. This article presents the first application resistive field grading method to a solid-oil insulation system. The development of HV power transformers follows a steady trend in meeting the increasing requirements for higher power density and reliability on the one hand and demands on smaller size and cost on the other [5]. In general the design of the insulation system of HV devices is limited by thermal losses of active parts and the degree of homogeneity of the electric field [6, 7, 8] or the occurrence of partial discharges (PD) respectively. In order to achieve a space saving design a weak homogeneous field with a high degree of homogeneity needs to be realized while eliminating partial discharges. So far the electrical field strength distribution in oil filled devices is controlled by the application of barrier systems between the phases in the winding section of high power transformers or for the lead exits versus the ground potential of the tank [9]. Even more complex structures have been designed for the oil side of the bushings in HVDC transformers [10]. The authors expect a big potential of design simplification of the insulation systems in power transformers by the utilisation of resistive field grading technique.

A two steps approach of electric conductivity measurements an PD measurements addresses the aim of the effort to show a positive evidence of electric field grading under insulation oil with a functionalized layer on a solid interface.

2. Materials and Methods

The methodical approach is twofold. First there are electrical conductivity measurement in order to verify and characterize the compound electrically. From the experience of the authors a compound of a conductive filler and a dielectric matrix is inevitably electric conductive. A working mass ratio with one matrix material does not have to work with another matrix material.

Second, the grading capability is characterized by electrical and optical PD measurements.

2.1. Determination of the non-linear electrical conductivity

The phenolic resin Lerg FL-500 served as a matrix. Its typical application is to impregnate and glue laminated densified wood (LDW) or other non-conductive construction materials in power transformers. Although phenol resin is widely used in cellulose based transformer insulation materials, the application on FR4 epoxy boards was hard to realize, because the high water content led to inhomogeneities during curing.

Merck Iriotec®7550 is a non-linear electrically conductive, ceramic flake like pigment with a median size of 4 µm (max. 15 µm) and a 20:1 aspect ratio. It is produced as core-shell particle on dielectric mica substrate coated with a semiconducting, granular, doped tin oxide layer surrounding (Figure 1). The powder resistivity of the pigments is adjusted during production by variation in doping level, details in the water born precipitation process (nucleation, crystallization) of the oxide layer and the following calcination step. The pigments functionalized the phenolic resin to a non-linear conductive compound and are therefore an appropriate candidate material for resistive field grading in mineral oil.

Figure 1: TEM image of Iriotec®7550 particle in cross section, with mica core and doped tin oxide shell.

Etched and cut single layer ($d_{Cu} = 50$ µm) FR4 circuit boards (RI > 15 GΩ, $d = 5$ mm) served as specimen carrier for the determination of electric conductivity and the field grading behaviour (Figure 2).

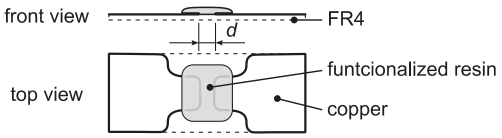
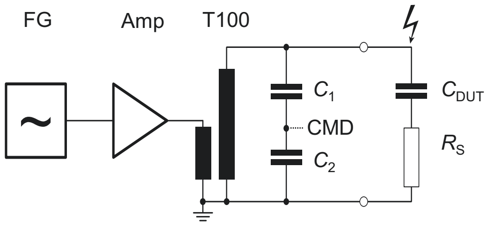


Figure 2 Conductivity specimen geometry

It is the author's experience that the determination of electric conductivity with high DC voltage according to IEC 62631-3-2 [11] may result in misleading measurement values when dealing with AC voltage applications. Homo space charges will occur in the necessary insulation specimen near the corresponding electrodes and lower the effective field-strength near the electrodes. For this reason, the measurements are performed with high AC voltage equivalent to the dominant electric stress in a power transformer. The measurement circuit (Figure 3) therefore consists of a frequency generator (FG) with a power amplifier (Amp), HV test transformer, a calibrated capacitive divider (CMD), a shunt R_S and the specimen (C_{DUT}). An oscilloscope (100 MHz, 8-bit vertical resolution) acquirers the voltage and current data synchronously. In order to suppress possible signal noise the measured peak values are averaged out of 64 single triggered sine voltage events.



FG - frequency generator
Amp - power amplifier
T100 - HV test transformer
CMD - capacitive measurement divider
C_1/C_2 - ratio 1000/1
C_{DUT} - device under test
R_S - shunt

Figure 3 Test circuit for electric conductivity measurements with AC voltage

At a low frequency of $f_n = 50$ Hz and the resulting low currents the shunt restive value is constant and the current through the specimen can be determined by the voltage drop over the shunt - Eq. (1).

$$i(t) = \frac{u(t)}{R_S} \tag{1}$$

Precise current measurements always require a high voltage quality, a synthetic source has been utilized in order to diminish the voltage harmonics effects in case of standard net feeding (Figure 4 a)). Especially high frequency contents such as harmonics lead to apparent non-linearity, due to the then low blind resistance X_C (Equation 2) of the dominant capacitive test objects (Figure 2).

$$X_C = \frac{1}{2\pi f C} \qquad (2)$$

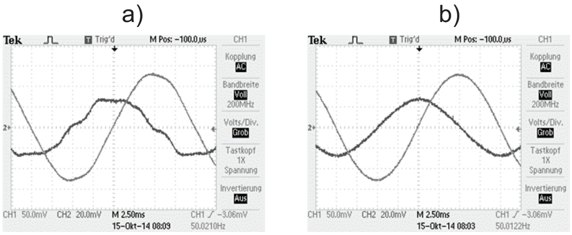


Figure 4: u-i-oscillograms with a) distorted net sine voltage and b) pure 50 Hz sine

To determine the electric conductivity with AC voltage the current peak value at the voltage peak is evaluated (Figure 5) to generate a characteristic curve (Figure 8) for the investigated material mixtures.

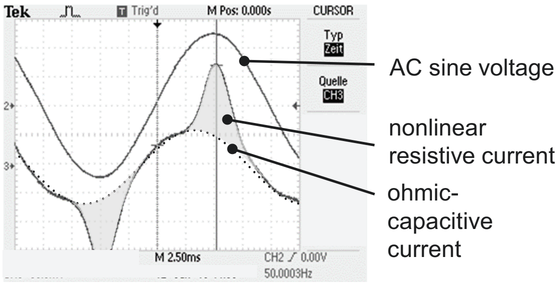


Figure 5: General u-i-oscillogram for a non-linear conductive material.

The test samples are dried in an oven for at least 24 hours and were then placed in a glass test vessel (Duran DN 300 desiccator) on a stand free of partial discharges (Figure 6). The hermetic lid secures steady test conditions for the measurements under mineral oil according to [11].

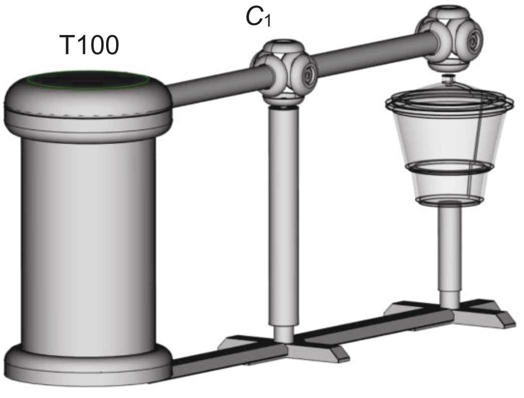


Figure 6 HV test kit with transformer, measurement capacitor and glass desiccator

2.2. Proof of field grading capability

The field grading capability and the specific behaviour is not determined directly by corresponding field strength measurement probes but indirectly by investigating the PD behaviour of the setup according to Figure 7.

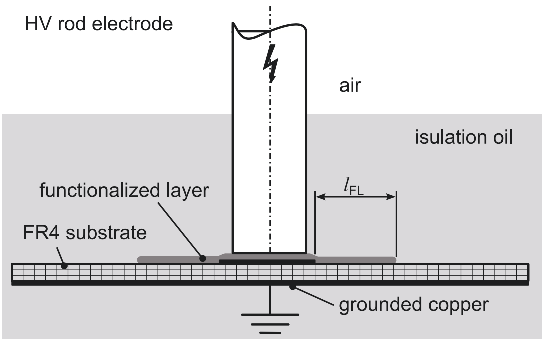


Figure 7 Toepler arrangement with functionalised grading layer

It consists of a FR4 double side circuit board. The etching leaves a $d = 12$ mm circular area of the upper copper layer which serves as the HV electrode; the full non-etched lower copper layer serves as ground electrode. A circular stencil supported the manual application of an overlapping layer of electrical functionalized resin coaxial on the upper copper electrode. The metal HV rod electrode rested on the specimen by its weight and establish a secure electric connection. The method to determine the effective mean electric field strength bases on the following assumption: An untreated specimen will show a low PD inception voltage (PDIV) due to triple point in the vicinity of the sharp edge of the circular HV electrode, the FR4 material ($\varepsilon_r \approx 4$) and the insulation oil ($\varepsilon_r \approx 2.2$). Because the arrangement is coaxial arranged, it can be assumed to behave 2D-rotational in the first instance. Due to the thin layer, even a 1D-dimensional situation can be assumed. If the material is working properly, the arrangement behaves like the end corona protection of a stator bar on rotating electrical machine: a variation of the functionalized layer diameter should show a proportional behaviour between effective grading length and inception voltage. Ideally, the layer will create a linear voltage drop, while PD incept only when the maximum inception field strength E_{Dh} is reached at the layers edge. The voltage drop per unit length (radius) is then equal to the effective grading field strength. The determination of the PDIV and PD extinction voltage (PDEV) is performed ten times per specimen with a certain functional length in order to investigate the reproducibility.

The general HV test circuit of the conductivity measurements (Figure 6) also served for the proof of the field grading capability. The PD coupling device *LDIC LDM-5/U* and the PD measurement system *LDIC LDS-6* replace R_S and the oscilloscope respectively Figure 3. An additional blocking impedance $L = 40$ mH and a coupling capacitor $C_K = 0.6$ nF create a standard PD measurement circuit according to [13]. It supports the experiments in order to detect the PD inception voltage of the corresponding specimen although the primary detection device is a *Syntronic CoronaFinder* with a chromatic corrected *Nikon 105 UV* lens. Both are mounted along with a digital camera on an optical bench. The Toepler arrangement (Figure 7) is dedicated for the investigations of triple points and lengthwise stressed interfaces such as in power transformers and undesired creepage discharges.

3. Results

3.1. Non-linear electric behaviour

Non-linear resistive field grading materials show an exponential conductivity behaviour in regard to the applied voltage or electric field strength respectively [14] [15] . Depending on the filling degree, the characteristic curve will vary as two exemplary selected examples show (Figure 8).

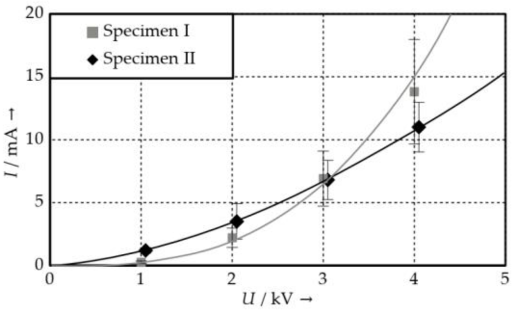


Figure 8 Selected Û-Î-curves for two specimens with different filler content.

The high number of experiments showed, that electric conductivity behaviour does not need to depend linear on filler content for the investigated system. In general, if the filler content is to low the so called percolation limit is not reached and a specimen may perform insulating. When the filling degree is too high, the resin becomes an electric conductor respectively. With the positive outcome from the conductivity measurements for certain filling degrees the filler content of Specimen I was chosen in order to manufacture specimens for the proof of the grading behaviour in insulation oil.

3.2. Electric field strength grading behaviour

When slowly increasing the AC voltage one can easily observe the synchronous inception of PD at the outer edges of either the HV electrode or the functional layer respectively with both the UV camera and the PD measurement system.

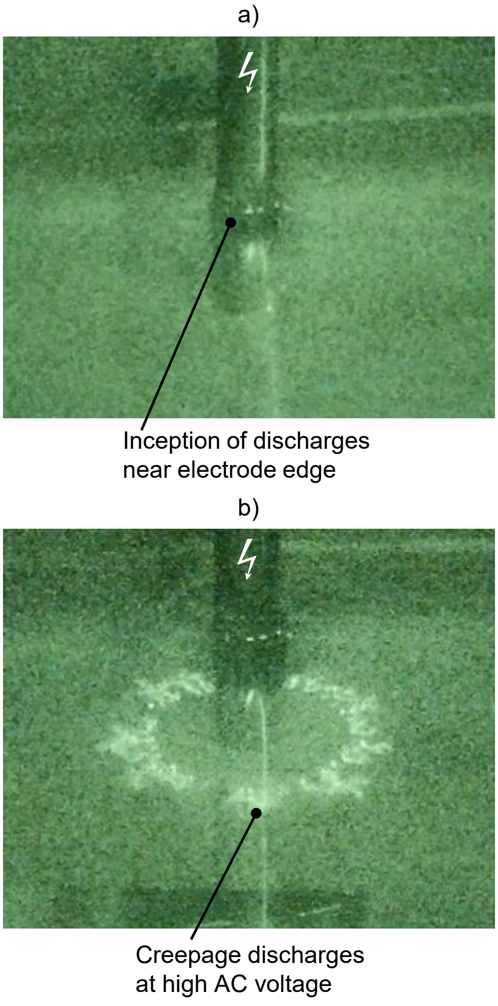


Figure 9 UV camera images of a) untreated specimen and b) specimen with circular applied functionalistic resin layer.

Along with the repetition of the experiments, all arrangements, without and with functional layer, show a very reproducible behaviour in terms of PDIV and PDEV. The dependency between the PDIV and PDEV and the functional length of the specimen can be assumed linear for the investigated range (Figure 10). The slope of the characteristic curve then equals the effective grading field strength of the grading system.

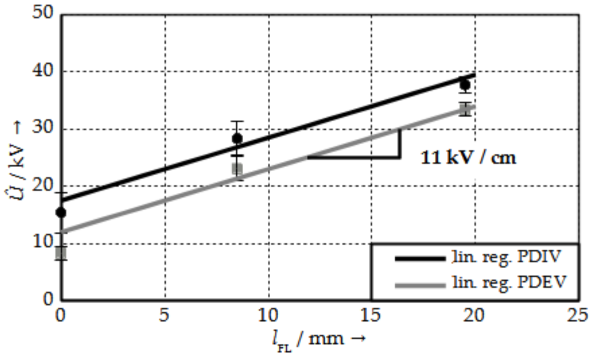


Figure 10 Characteristic grading curve and potential gradient.

4. Discussion

The primary aim of a feasibility study on resistive field grading under insulation oil is successfully conducted. The approximate linearity of the characteristic curve as in Figure 10 shows a reproducible behaviour. The chosen procedure is suitable for characterizing functional resins with different filler contents for the field grading ability. The indication of PD inception at the layers edge can be determined independently twofold: electrically and optically. A different filler or the amount alters the electric conductivity of a functionalized resin; the grading field strength will differ respectively. A generalisation to imply directly on a certain grading field strength from a measured conductivity is incorrect. A functionalized resin layer with the same filler content as presented in Figure 10 will show a higher grading field strength when the capacity of the layer versus ground would be lower, e.g. with a thicker insulation or larger free distance respectively. During all experiments, no significant heating was observed (e.g. schlieren formation due to different oil densities) as known from SiC-based grading systems for air of rotating electrical machines. There is a general indirect proportional relationship between grading field strength and generated heat: the lower the grading field strength, the higher the necessary resistive current, the higher the ohmic losses. This fact is positive for possible future applications in oil, because the grading field strength can be higher than in air and the heat transfer with oil is higher, too. The general field strength distribution within the chosen arrangement resembles with the situation of an end corona protection system (ECP) of a high-voltage rotating machine. Figure 11 depicts the electric potential and field strength distribution for the peak AC voltage stress in stationary condition.

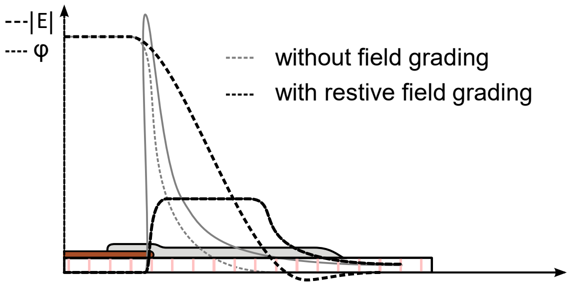


Figure 11 General distribution of electric potential φ and field strength E of grading system.

5. Conclusion and Outlook

The presented results successfully proof the possibility of resistive field grading in mineral oil. The developed method consist of two steps analogue to ECP materials. First - measuring the *U-I*-behaviour with appropriate specimen, second varying the functional length determining the mean grading field strength of the grading system by means of detecting PD inception. Therefore, a sophisticated field strength measurement system is not necessary in the first place, which does not mean that this might help to optimize complex designs in transformers in the future.

Feasible applications for the new grading system could be the oil side of HV bushings in regard to [9], board barrier systems and wooden support structures in HV power transformers. Especially in HVDC power transformers [5] the system may help to reduce accumulating space charges, too. The results are a suitable fundament for further investigations regarding the influence of temperature and lifetime.

Acknowledgement

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