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Modular arbitrary waveform dielectric spectroscopy for in-situ aging diagnostics of recessed epoxy specimens exposed to mixed-frequency high voltage stress

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1 Introduction and context

The work proposed in this application letter is embedded within a larger research framework aimed at characterizing the influence of so-called mixed-frequency electric field stress on dry-type insulation materials and systems. However, as detailed on the following pages, the funding offered by the DEIS Graduate Fellowship would be used for a promising self-contained research effort within this framework.

The role of power electronic converters in energy transmission and distribution networks is bound to increase due to their unprecedented flexibility in electrical power conversion and conditioning. Pulse Width Modulated (PWM) waveforms generated with the aid of solid state switches introduce a new type of insulation stress as compared to the conventional 50 Hz sinusoidal waveforms. Their high slew rates (>10 kV/μs) and repetition frequencies (>1 kHz) have been shown to lead to enhanced partial discharge activity and corresponding accelerated aging of wire insulation in inverter-fed induction motors [1] as well as reduced breakdown voltages of oil-impregnated paper insulation [2]. Although the single pulse voltages are typically limited in amplitude to the kV range by the maximal blocking voltage of the semiconductor switch, multilevel topologies employed in Solid-State Transformers [3] result in pulses superimposed to a high low-frequency ac (or dc) voltage of tens of kV, exposing certain parts of the insulation system to both elevated electric fields *and* high slew rates.

Apart from enhanced dielectric heating due to higher harmonics [4], the effects of this mixed-frequency field stress on insulation materials *below partial discharge inception* are to a large extent unknown. Yet, knowledge about low-level degradation and failure mechanisms active under this electric field stress in polymeric insulation is of practical importance for designing a reliable dry-type insulation system for, e.g., Solid-State Transformers. The self-contained work on a versatile diagnostic tool proposed in this research proposal is believed to constitute a valuable contribution in this endeavor.

2 Current Status

A test bench for generating mixed-frequency voltages has been developed in collaboration with the Power Electronics Systems Laboratory (PES) at ETH Zürich. As first test objects, specimens with a simple geometry have been chosen, with the aim of gaining insight into the effects of mixed-frequency stress unobstructed by the complications present in complete practical insulation systems. In order to prevent edge effects from interfering with the observation of degradation and failure mechanisms not related to the erosive action of partial discharge (PD) in the ambient medium (air/oil), a recessed specimen geometry has been realized (see figure 1). Aluminum electrodes (16 mm diameter) are firmly molded into the epoxy polymer to be investigated, the electrode gap being adjustable down to about 50 μm

Figure 1: Recessed epoxy specimen (44 mm diameter) being placed into the dielectric test cell.

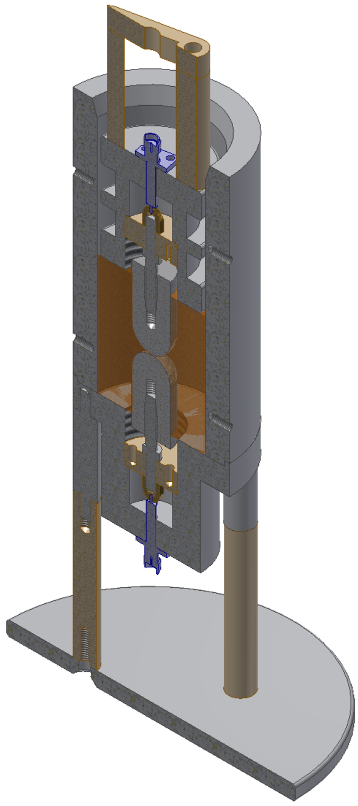


Figure 2: Section view of the dielectric test cell.

with the aid of precision foils. Guard toroids are mounted in the high voltage test vessel in order to homogenize the electric field and to shield the triple points. PD measurements have confirmed that this electrode-insulator arrangement can be driven to breakdown (ac, 50 Hz) with PD magnitudes remaining below the background noise level (<0.5 pC).

It is of course of practical interest to be able to detect and quantify changes in the insulation material that precede its breakdown. The complex dielectric permittivity of the epoxy polymer has thus been chosen as a prospective aging marker, aimed at tracking the invisible microscopic changes occurring during the insulation's lifetime. To this end a prototype of a fully coaxial, modular broadband dielectric spectrometer has been built, including a tailor-made measurement cell for the recessed specimens. A schematic view of the setup is given in figure 3 whereas a section view of the test cell is shown in figure 2.

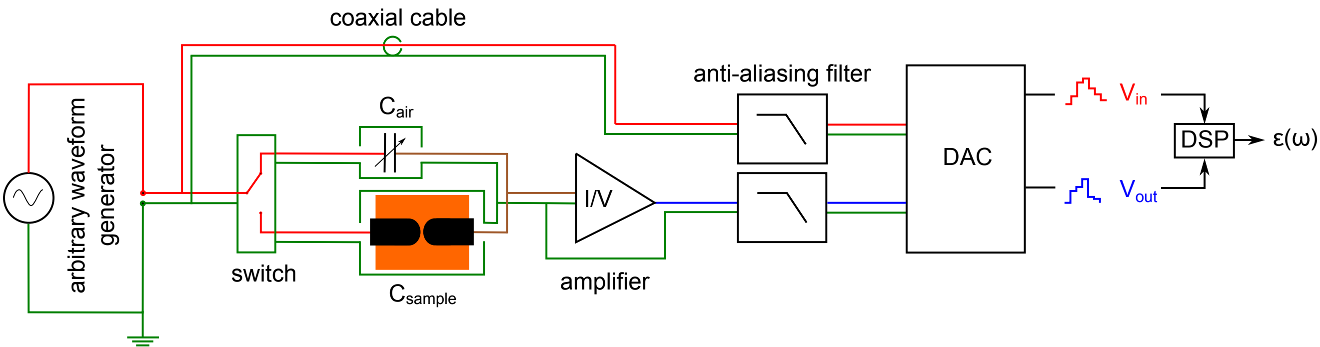
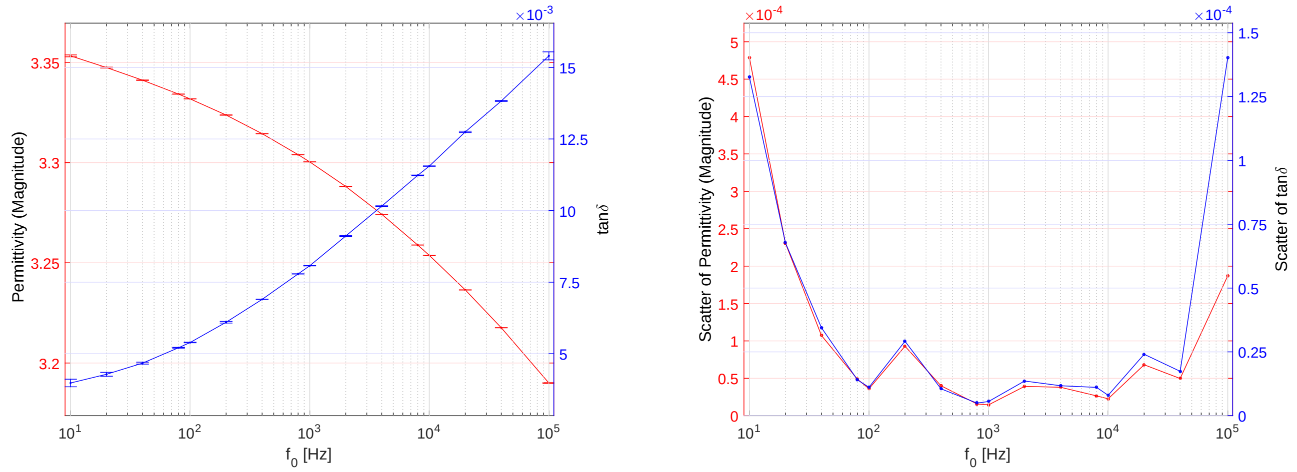


Figure 3: Scheme of the modular dielectric spectrometry setup.



(a) Absolute value and $\tan\delta$ of the complex permittivity under harmonic excitation at room temperature.

(b) Scatter of measurement values (3 standard deviations of the calculated mean value shown in figure 4a).

Figure 4: First experimental results (proof of concept). The tested specimen is shown in figure 1 and has a vacuum capacitance of 0.61 pF inside the test cell.

Proof of concept measurement results with sinusoidal excitation are displayed in figure 4, showing the absolute value of the complex permittivity and the loss factor of a specimen of vacuum capacitance 0.61 pF (figure 4a) as well as the typical dispersions of the measured values (figure 4b). It should be noted that the current amplitude at 10 Hz is about 1 nA, well below the measurement range of most commercial table-top broadband impedance analyzers.

Dielectric spectroscopy is particularly interesting in the presented context, as broadband insulation stressing naturally lends itself to arbitrary waveform dielectric spectroscopy (also known as *Arbitrary Waveform Impedance Spectroscopy* (AWIS) [5]). Arbitrary multiharmonic excitation voltages can be applied in the low-voltage setup presented here[1], and thus this particular spectroscopic technique can be thoroughly studied in a high-precision setup in order to optimize its performance and learn about its limitations. This is certainly desirable before implementing a high voltage version thereof on the test bench for direct on-line monitoring. What makes the setup especially attractive for an in-depth study of this technique in conjunction with non-standard specimens is the high measurement precision[2] ($\tan\delta_{\mathrm{min}}$ well below 10^{-4} for $20\,\mathrm{Hz} < f_0 < 40\,\mathrm{kHz}$) as well as its inherent flexibility due to its modular makeup.

3 Proposed work within the DEIS Graduate Fellowship

As outlined above, the funding made available within the Fellowship would allow an in-depth analysis of dielectric spectroscopy under broadband excitation for the proposed non-standard electrode-insulator configuration. More specifically the following points will be addressed:

- Assessment of the setup's *accuracy* by comparison with results from commercial instruments on conventional parallel plate samples. Examination of the potential influence of electric field non-uniformity within the dielectric.
- The superposition principle is the fundamental working hypothesis of arbitrary waveform dielectric spectroscopy. As the voltage amplitudes of the different harmonics can differ by as much as

[1] 8 kpoints per period with 14 bit vertical input resolution.

[2] Precision rather than accuracy is the most relevant figure of merit in aging diagnostics as primarily *relative* changes of material properties are of interest.

three orders of magnitude this hypothesis should be validated in a low-noise setup, where possible departures from linearity can be quantified.

- Determining how the the measurement precision (and accuracy) is influenced by arbitrary waveform parameters (e.g. number of harmonics as well as their amplitude and phase distributions).
- Quantifying the dependence of measurement precision on acquisition parameters (sampling frequency, number of phase averages, vertical resolution/loading factor of the analog to digital converter, etc.).
- Finally, merging the knowledge from the above points into a suggestion for a measurement setup allowing in-situ aging diagnostics under mixed-frequency high voltage stress.

4 Value and expected impact of results

Employing dielectric spectroscopy in the context of mixed-frequency voltages is a promising route to new on-line monitoring applications in both research and industrial environments. A well-characterized modular setup constitutes a versatile diagnostic tool for the study of low-level degradation of polymeric insulation materials aged under mixed-frequency field stress and, simultaneously, paves the way for in-situ aging diagnostics under mixed-frequency stress. Specifically, the above-mentioned research goals include the following benefits:

- Enhanced knowledge about the intricacies of dielectric response measurements with non-uniform fields (this is of course extendable to the diagnostics of other practically relevant configurations, e.g. electrical treeing).
- Being able to decide when the linearity hypothesis is not valid prevents erroneous conclusions from multiharmonic measurements alone.
- Due to its modular nature, individual components can be replaced when moving towards on-line monitoring applications in high-voltage settings (e.g. current sensing by a current transformer). It is then important to know about the required system/acquisition parameters to achieve a predefined precision on, e.g., loss factor measurements.

5 Availability of resources

All resources (devices, materials, processing facilities) required for the work suggested in this proposal are available in our laboratory.

References

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