Doctoral Dissertation
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(37^{th} cycle)

Advanced Methodologies for High Voltage Measurements: From Composite and Combined Waveform to Uncertainty Reduction for Lightning Impulse

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Summary

The energy market, with its increasingly rapid evolution, is driving the electrical grid to integrate and support diverse needs, such as: the increasingly significant integration of renewable sources, which can lead to potential critical issues regarding grid stability; the electrification of transport, demanding more and more energy; and the advent of smart grids, causing the network's configuration to change very quickly. It is therefore necessary to improve the reliability, safety, and efficiency of modern electrical power systems.

A fundamental role in the grid's evolution is played by the tests performed on the grid components. The tests to which components are subject evolve according to growing needs, and it is of primary importance to understand the phenomena these objects undergo before they can be placed on the market. Understanding these phenomena spans from developing the test circuits to measuring the phenomena themselves. Without a definition of the relevant parameters, tests could not be defined.

The presented doctoral work fits within this context, addressing the topic of highvoltage dielectric tests and proposing advanced methodologies to tackle specific challenges in the field of high-voltage measurements. High voltage tests are described in industry standards as all tests where a voltage higher than 1000 V is applied. The research activity have been developed along two main lines: on the one hand, the development and validation of measurement techniques for complex signals, and on the other hand, the improvement of calibration procedures and uncertainty evaluation in lightning impulse measurements.

The first topic involved the study of composite waveforms (lightning impulse (LI) or switching impulse (SI) superimposed on direct current (DC) or alternate current (AC)) and combined waveforms (LI or SI combined with DC or AC), which are increasingly relevant in many applications such as tests on insulating materials, circuit breakers, transformers, and high-power cables like HVDC cables and HVAC cables, etc. The work addressed the challenges associated with the accurate measurement of such signals, often characterized by a wide frequency spectrum and rapid variations. An analysis of the performance of traditional measurement systems was conducted. Specific methodologies were developed and tested for the dynamic characterization and

calibration of these systems, with the goal of extending metrological traceability to these types of waveforms. Part of the work also involved the design and analysis of specific dividers, capable of correctly measuring these phenomena up to voltage values of the order of 400 kV, implementing calibration procedures capable of considering the different spectral components of the signal, and developing software capable of identifying the various waveform components and providing the parameters of interest.

The second research area aimed at reducing uncertainty in the measurement of LI up to 600 kV, a fundamental standard test defined by the IEC 60060-1 standard. Accurate determination of the impulse's characteristic parameters (peak value, front time, time to half-value, and overshoot) is crucial for the validation of grid components. The work addressed the main sources of uncertainty, arising from both the measurement system (divider, digitizer) and the processing of the acquired signal. Advanced techniques for the dynamic characterization of impulse measurement systems were investigated, including methodologies based on step response and the use of deconvolution algorithms for correcting dynamic errors introduced by the system. Particular attention was paid to the evaluation of uncertainty on impulse parameters, exploring alternative approaches to traditional ones for result validation, such as an a posteriori re-evaluation of an international comparison and the use of numerical methods like deconvolution, in order to improve the estimation of uncertainty associated with measurement and calibration results.

The results obtained during the research contribute to the advancement of highvoltage metrology, offering validated tools and methodologies to address the challenges introduced by new technologies and non-conventional waveforms. The techniques developed for measuring composite and combined signals allow for a more precise characterization of electrical phenomena in emerging applications, while the proposed methods for reducing uncertainty in LI measurements enable improved accuracy and reliability of standard qualification tests. The work carried out also supports the strengthening of the metrological traceability chain for these critical quantities, in line with the needs of testing laboratories, research centers, and the electrical industry.