Investigation of Application of Wavelets to Detect Minor Insulation Failures during Impulse Tests on Power Transformers

by

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INVESTIGATION OF APPLICATION OF WAVELETS TO DETECT MINOR INSULATION FAILURES DURING IMPULSE TESTS ON POWER TRANSFORMERS

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Summary

Several signal analysis methods have been proposed to overcome the limitations associated with conventional techniques for fault detection during the impulse tests on power transformers. One such group of methods employs wavelet transforms with which test waveforms are analyzed to localize the disturbance in both time and frequency. There have been several reported studies on the application of wavelet transforms to identify insulation failures during impulse tests. Some of these studies have utilized simulated waveforms in which the fault is introduced by a mathematical model. Others have used experimental data that do not realistically simulate minor insulation failures during impulse tests.

This thesis presents results of an investigative study to evaluate the applicability of wavelet-based techniques to detect minor insulation failures during impulse tests on power transformers, by considering experimentally generated waveforms obtained using low-voltage and high-voltage tests on model and actual high voltage coils. The results show that wavelet-based techniques are capable of detecting certain impulse test failures that may not be detected by using conventional techniques.

Based on experimental data and analysis, it is shown that wavelet transform can be successfully applied to detect short-duration temporary faults, which occur within the first 2 μs of the neutral current waveforms. This is not possible by the use of the conventional neutral-current method. It was also found that apart from short-duration temporary faults which occur within the first 2 μs, turn-to-turn faults can be detected using neutral current method. Furthermore, results presented in the thesis do not support the conclusion in some published literature that wavelets can detect minute faults that can not be detected by the neutral-current method.

Table of Contents

List of Figures

List of Tables

Chapter 1

Introduction

The objective of this research was to investigate the suitability of wavelet transform application for detection of minor insulation failures during impulse tests on power transformers. This chapter provides the background and motivation behind the research, the objectives of the investigation, and an overview of the thesis.

1.1 Testing of Power Transformers

The reliability of a power system greatly depends on the reliable operation of power transformers in the power system. Reliability of power transformers can be improved by subjecting them to rigorous testing, in accordance with a well defined test plan with effective test specifications resulting from a joint effort between the manufactures and users of power transformers. The written test plan and specifications should take into consideration the anticipated operating environment of the transformer, including factors such as atmospheric and environmental conditions, type of grounding, characteristics of the protective devices, presence of capacitor banks, power system conditions (short circuits, load rejection, resonance) as well as lightning and switching transients. In addition to rating data of a transformer, the user should include in the specifications and test plan any information or requirements pertaining to service conditions, usual and/or unusual, which may have impact on operational characteristics of the transformer. Selection of appropriate tests and the specifications of correct test levels, which ensure transformer reliability in service, are part of the joint effort [1]. There are several national and international standards available for transformer testing [2–7].

1.2 Impulse Tests on Power Transformers

Impulse testing began on commercial basis in 1933 when the first rules were formulated pertaining to its conduct [8]. The purpose of conducting impulse tests on a transformer is to give a reasonable demonstration that the transformer will withstand electrical stresses due to transient overvoltages in practice. Low frequency dielectric tests do not demonstrate impulse strength because the low frequency test voltage is of lower magnitude and is uniformly distributed throughout the winding, whereas lightning voltage is generally of much higher magnitude and may cause a radical departure from a uniform distribution. Therefore, impulse tests, will give a more adequate demonstration of the sufficiency of the dielectric strength of transformer for service conditions.

There are two types of impulse tests; lightning impulse test and switching impulse test. The purpose of the lightning impulse test is to check the dielectric strength of transformer insulation against overvoltages of atmospheric origin, while the aim of the switching impulse test is to verify the dielectric strength of transformers against switching surges [9].

In switching impulse tests (Section 2.7), owing to a better, nearly linear, distribution of voltage throughout the winding, the fault normally involves major deterioration in the form of a short circuit between sections, parts of a winding or even between windings or to ground. These types of faults cause significant changes in the voltage wave either as a complete collapse of the wave or a shortening of the tail or, sometimes, as a temporary dip in the trace. Hence, the voltage records on switching impulse tests are commonly considered to be sufficiently sensitive to enable the detection of most faults, and will not be investigated in the current research.

Lightning impulse voltage test simulates travelling waves due to lightning strikes and line flashovers. The standard full-wave lightning impulse voltage wave shape is one where the voltage reaches crest magnitude in 1.2 μs, then decays to 50% of the crest magnitude in 50 μs. Such a wave is said to have a wave shape of 1.2/50 μs. In this thesis "impulse test" is used to describe lightning impulse voltage test. More details on impulse tests are given in Chapter 2.

Given the nature of impulse test failures, one of the most important matters to consider is the detection of such failures. The most common method of fault detection is the *neutral-current method*, which consists in comparing the neutral currents produced when a standard lightning impulse is applied to the HV winding terminal at the basic insulation level (BIL) and at a reduced level. Assuming a constant shape of the test impulse over the test-voltage range, the neutral currents are expected to have the same form, provided the test object remains linear. Any nonlinearity observed at higher test voltages implies a disqualifying internal breakdown in the winding, which can be revealed by a usually minor difference between the compared current oscillograms. Section 2.5 deals with different techniques for the interpretation of impulse test results in detail.

Several signal analysis methods have been proposed and some have been implemented to overcome the limitations associated with the fault detection techniques based on the neutral current method. The implementation of these methods have been made possible by considerable improvements in the processing capacity, and data collection hardware. One such group of methods employs *frequency-response* analysis. These methods analyze the captured waveforms in the frequency domain and one such method which has been included into standards [6] is the *transfer-function* method.

In the *transfer-function* method [10, 11], the frequency domain graphs deconvoluted from the test-voltage and neutral current records obtained respectively at full and reduced test levels are compared. The transfer function of a transformer is a characteristic feature and, is in theory, independent of the shape of the applied voltage impulse. The difference between the transfer functions recorded at BIL and at the reduced test level manifests itself as either a frequency shift or pole-height attenuation; empirical interpretation attributes the former to a local breakdown and the latter to partial discharge. This distinction is of great practical importance, since even a minor local breakdown disqualifies the transformer whereas a partial discharge may be tolerated at the BIL, provided the insulation is not damaged [10].

Another type of methods may be categorized as *time-frequency* analysis. In these methods, the waveforms acquired during impulse test are analyzed to localize the disturbance in both time and frequency. One such method is the *wavelet transform* (WT). In the current research work, the main focus was on the applicability of WT to detect minor insulation failures, which occur during impulse tests on power transformers.

1.3 Motivation Behind the Research

Due to the multiresolution property of WT, it can zoom in on the particular details of a signal. One direct consequence of such treatment will be the possibility of accurately locating in time all abrupt changes in the signal and estimating their frequency components as well. Therefore, the use of WT has been suggested in previous work [12, 13] for the detection of insulation failures during impulse tests.

There have been several studies [12–17] on the application of WT to identify insulation failures during impulse tests. Some of these studies have utilized simulated waveforms in which the fault is introduced by a mathematical model. One of these models, simulates the fault current by superimposing a short duration, low amplitude, fast decaying and oscillating signal onto the neutral current. Others have used experimental waveforms for their research work in which faults were simulated by shorting the turns of a coil or a transformer model. These research efforts replicate *permanent faults* within transformer windings.

Following are some of the limitations of the research work carried out in this area and reported in literature.

1. Some have proposed WT for detection of minor insulation failures during impulse using simulated waveforms [12, 13, 15]. The main limitation is the lack of experimental verification using an appropriate method to create minor insulation failures during impulse tests.

2. The neutral current with minor fault due to a minor insulation failure during an impulse test has been simulated using a mathematical model [12, 13], the appropriateness of which has not been verified by experimental results.

3. There are other published works [14, 16, 17] that have used experimental results

to demonstrate the suitability of WT to detect faults. However, they have used *permanent faults* to create neutral currents with minor fault. i.e. minor insulation failures during impulse tests are created by shorting the turns or winding discs using a copper wire.

4. Although the published work demonstrates the use of wavelet functions in this particular application, unfortunately all studies using wavelet analysis have suffered from an apparent lack of *quantitative* results. Also, more work is required in this area to select an optimum wavelet function for fault detection.

1.4 Objectives of the Research

The objective of this research work was to investigate the applicability of WT to detect minor insulation failures during impulse tests on power transformers, by considering experimentally generated waveforms. The experimental waveforms, in the current research, were generated by utilizing a low-voltage (LV) experimental setup using a recurrent surge generator (RSG), and a high-voltage (HV) experimental setup using a 50 kV impulse generator. In the current investigation, the following were achieved in order to reach the main objective of this research.

1. **Development of a LV experimental setup to generate neutral current waveforms with minor insulation failures during impulse tests.** Minor insulation failures were created on a model transformer using neon lamps and a 1000 V RSG. Since these faults due to minor insulation failures last only a short time, faults created using neon lamps are termed *temporary faults.* Wavelets are suitable for analyzing signals that last for a few microseconds and have relatively high frequency components. When faulty neutral currents are gener-

ated by using the method proposed in the current research work, they create disturbances in the neutral current that are ideal for WT detection.

2. **Development of a HV experimental setup to generate neutral current waveforms with minor insulation failures during impulse tests.** The minor faults between sections of an actual transformer coil were created by using miniature sphere gaps and a 50 kV impulse generator. Artificial faults created by using a sphere gap also produced temporary faults and wavelet-based techniques are suitable for analyzing such signals. Because of lower turn-on voltage of neon lamps, it was planned to use them if the voltage created was insufficient to cause sparkover of sphere gap.

3. **Development and implementation of statistical analysis technique to select the best basis for fault detection.** A quantitative method is proposed to select best basis functions for fault detection. This method assumes that perturbations due to minor insulation failures could be simulated by a short duration, low amplitude, fast decaying and oscillating signal.

4. **Development and implementation of wavelet-based algorithm for de-noising of experimental waveforms.** The proposed algorithm consists of the selection of the wavelet function, number of levels of decomposition, and the threshold rule for a wavelet-based noise reduction technique. Validity of the algorithm will be demonstrated using experimental data.

5. **Analysis of LV and HV experimental results for fault detection using wavelet-based techniques.** Impulse test results were analyzed by using continuous wavelet transform, multiresolution signal decomposition, and wavelet packets.

6. Comparison of the features of proposed wavelet-based techniques with neutral-current method and transfer-function method.

7. Examination of the sensitivity of wavelet-based techniques, and whether or not it represents an improvement over existing techniques.

1.5 Thesis Overview

Chapter 2 is an introduction to impulse tests on power transformers in some detail. The windings of a power transformer are exposed to different types of overvoltages. These overvoltages, their effect on the windings, and a brief overview of the methods to determine transient response of transformers are discussed. This chapter also provides a comprehensive overview of lightning impulse tests as per most recent technical standards. Finally, a short introduction to switching impulse tests is included.

An overview of wavelet theory is given in Chapter 3. In order to understand the wavelet transform better, the Fourier transform is briefly explained. Generally, there are no explicit formulas for the basis functions $\phi(t)$ and $\psi(t)$. Hence most algorithms concerning scaling functions and wavelets are formulated in terms of the filter coefficients. This chapter includes an example of computing the function values of $\phi(t)$ and $\psi(t)$ for the Daubechies 4-coefficient scaling function and wavelet (db2).

A detailed review, in chronological order, of published research work on the application of time-frequency based methods to detect minor faults during impulse tests on power transformers is given in Chapter 4. This is followed by a general discussion which highlights the limitations of the published work, and provides a rationale for the motivation behind the present research. This chapter also provides a brief review of the transfer-function method for detection of impulse test failures.

Chapter 5 describes low-voltage (LV) impulse tests on a model transformer, which was used in the current research to generate neutral current waveforms. The neutral currents were analyzed using wavelet-based techniques to detect artificially created minor insulation failures, and results are reported in Section 5.5. Since the efficiency of WT to detect faults depends on the wavelet function, this chapter proposes a quantitative method to select the optimum wavelet function for impulse failure detection. This chapter also provides an algorithm for denoising. Proposed algorithm consists of basis function, threshold method, and decomposition level. Validity of the algorithm is demonstrated using experimental data.

Chapter 6 describes high-voltage (HV) impulse tests on an actual transformer coil. Minor insulation failures were artificially created by using sphere gaps, and neon lamps. Neutral-current waveforms were analyzed using different wavelet-based techniques. These results were compared with other methods, where faults are detected in analyzing waveforms in the time-domain and frequency-domain. Sensitivity of the proposed methods for fault detection is explored by considering faults at different locations along the coil.

Finally, in Chapter 7 conclusions are drawn and the contribution of the research are pointed out. Suggestions are given for future work covering the areas which need further research. Appendices A and B provide details of the impulse generator, technical specifications of the instrumentations used for the experimental work, and HV transformer coil. At the end of the appendices, all the acronyms used in this thesis have been listed.

Chapter 2

Power Transformer Impulse Tests

The windings of power transformers are exposed to voltage surges arising from lightning or switching. Depending on the waveshape of the surges, the internal voltage distribution, thus, the voltage stress on different parts of the insulation system varies. To prevent damage to the transformer due to the breakdown in its insulation system, the equipment must be designed to withstand surges, the peaks of which may be many times the working voltage of the power system. Impulse tests are performed on the power transformer to verify the design of the insulation system for anticipated surges as specified in customer's technical specifications.

2.1 Voltage Appearing Across the Transformer Terminals

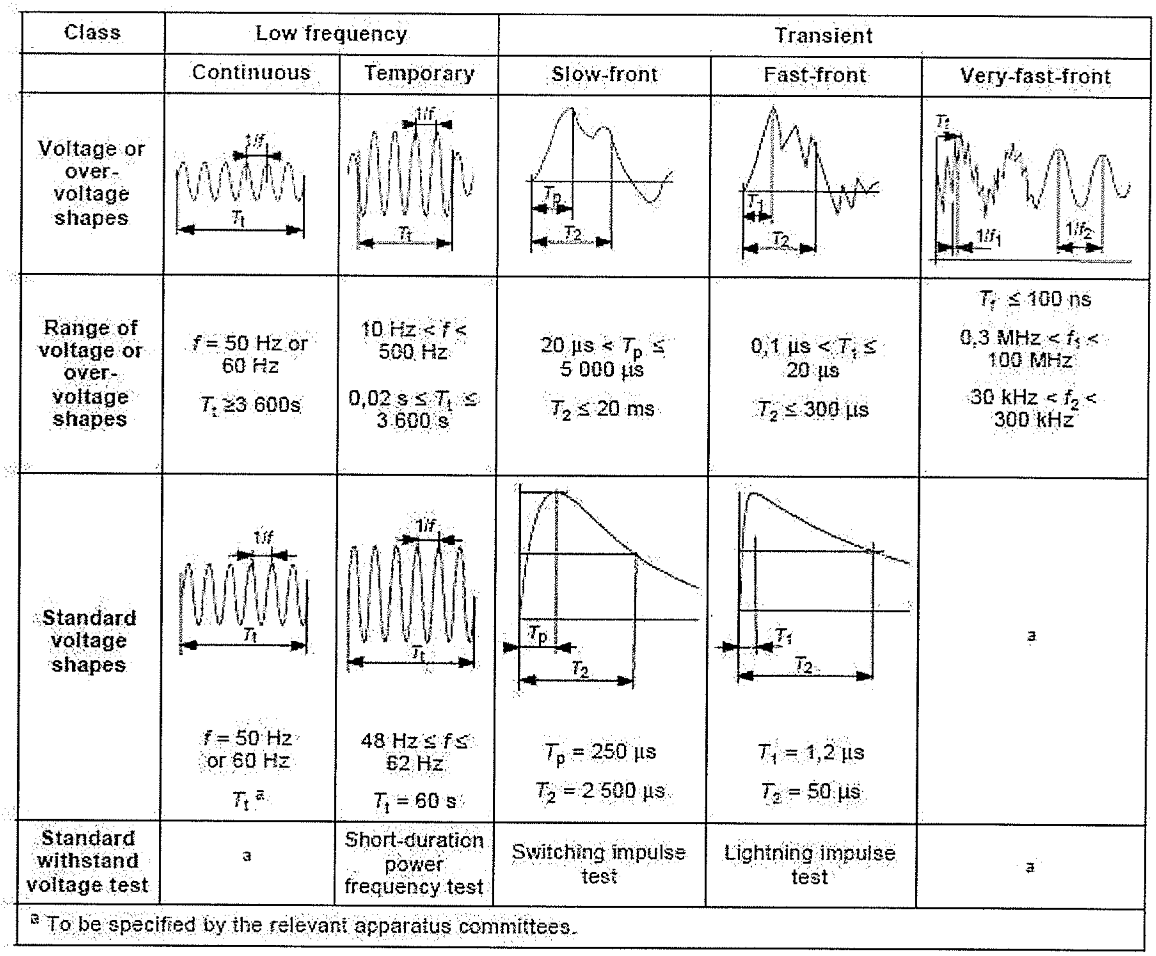
Dielectric tests on power transformers should demonstrate the ability of the transformer to survive different types of voltages that appear across its terminal, and it should not damage the insulation. Type of dielectric tests and their magnitudes should be based upon the conditions that the transformer will experience during its operating lifetime. Fig. 2.1, based on IEC 60071-1 2006 [18], shows the voltage or overvoltage shapes in the system, and corresponding standard voltage shapes applied in a standard withstand voltage test. The voltages to which a transformer's terminals are subjected can be broadly classified as low-frequency and transient.

The majority of the voltages that a transformer experiences during its operational life are low-frequency, e.g., the voltage is within ±5% of nominal, and the frequency is within 1% of rated. Sustained relatively lower-frequency (10 to 500 Hz) overvoltage can result from Ferranti rise, load rejection, and ferroresonance. These effects can produce abnormal turn-to-turn and phase-to-phase stresses. Then again, line-to-ground faults can result in unbalance and very high terminal-to-ground voltages, depending upon system grounding. Low-frequency dielectric tests which consist of the applied voltage test, induced test, and partial discharge test demonstrate that the strength of the transformer insulation system has the necessary dielectric strength to withstand the voltages indicated in the tables of standards [3, 5, 7] for low-frequency tests.

Transient voltage refers to a class of excitation caused by events like lightning surges, switching events, and line faults causing voltages with a chopped waveform [19]. Normally, these are aperiodic waves. There are the following three types of transient overvoltage waves that a transformer may be subjected during it life.

2.1.1 Slow-front Transients

Slow-front transient overvoltages are referred to as switching overvoltages. Their frequency depends on the natural frequency of the system and they are produced by some switching-in or switching-out operation or by a network fault. Most of these overvoltages are highly damped phenomena of relatively short duration. According to IEC 60071-1 2006 [18], the shape of a slow-front overvoltage is usually unidirectional



Class	Low frequency		Transient		
	Continuous	Temporary	Slow-front	Fast-front	Very-fast-front
Voltage or over-voltage shapes					
Range of voltage or over-voltage shapes	f = 50 Hz or 60 Hz $T_t \geq 3\,600$s	10 Hz < f < 500 Hz 0,02 s ≤ T_t ≤ 3 600 s	20 µs < T_p ≤ 5 000 µs T_2 ≤ 20 ms	0,1 µs < T_1 ≤ 20 µs T_2 ≤ 300 µs	T_f ≤ 100 ns 0,3 MHz < f_1 < 100 MHz 30 kHz < f_2 < 300 kHz
Standard voltage shapes	f = 50 Hz or 60 Hz T_t [a]	48 Hz ≤ f ≤ 62 Hz T_t = 60 s	T_p = 250 µs T_2 = 2 500 µs	T_1 = 1,2 µs T_2 = 50 µs	[a]
Standard withstand voltage test	[a]	Short-duration power frequency test	Switching impulse test	Lightning impulse test	[a]

[a] To be specified by the relevant apparatus committees.

Figure 2.1: Classes and shapes of overvoltages, standard voltage shapes and standard withstand voltage tests

with time to peak between 20 to 5,000 μs; the total duration is less than 20 ms.

Overvoltages due to switching surges generally have crest magnitudes, which range from about 1.0 to 3.0 pu for phase-to-ground surges and from about 2.0 to 4.0 pu for phase-to-phase surges (in pu of the phase-to-ground crest voltage base) with higher values sometimes encountered as a result of a system resonant condition. Waveshapes vary considerably with rise times ranging from 50 to thousands of microseconds, and times to half value in the range of hundreds of microseconds to thousands of