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Validation of a White-box model of a Distribution Transformer through impulse voltage transfer measurements including non-standard test conditions.

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SUMMARY

Over the last decade, distribution transformers have been highly exposed to the change in the network topology that resulted from the proliferation of distributed renewable energy sources. Several failures of distribution and wind turbine transformers resulted from the severe environment that is imposed not only by lightning but also by frequent switching events and the corresponding internal overvoltages that damaged the insulating structures [1], [2]. Therefore, the procurement and specification of the transformer should consider the adequate insulation coordination based on good modeling and adequate simulation tools. From the perspective of the design, it is mandatory to assure a good dielectric withstand ability to provide a reliable and cost-effective transformer where the insulating material is applied where it is needed and with enough safety margins. This context leads to the search for more accurate design models to evaluate internal voltage resonances and stresses in the insulating structures.

This paper describes the investigation work related with the development and validation of the high frequency model of the transformer by means of experimental tests where impulse voltages of small magnitude were applied, and the correspondent transferred voltages to several tap leads within the windings were measured. These tests included connections with open terminals, differing from the tests defined by the international standards [3], [4], for assessing the white box model performance at higher frequencies, where transformer parameters present greater uncertainty and, therefore, allowed the readjusting of the model for simulating any transient phenomena in the high-frequency range, including switching and lightning overvoltages.

The design of the transformer internal insulation is one of the most important aspects of the electrical design since it is deeply related with the reliability of the transformer. The insulating structure is designed according to the voltage distribution along the windings. Although there is a great knowledge of the transformer behavior at rated voltage and frequency, transient phenomena resulting from an interaction between transformer and network is a different case. Therefore, an accurate modelling tool is necessary to predict and reproduce the internal transformer response.

In this paper it is proposed a model based on a lumped parameter network which represents in detail the internal geometry of the distribution transformer in the so-called white-box model. This type of model is broadly used by manufacturers in the design stage for predicting the internal voltage stresses that arise when applying the standard lightning impulse voltage to the terminals.

KEYWORDS

Transformer White-box model, high-frequency transients, electromagnetic simulation.

1. INTRODUCTION

The transformer insulation design is one of the most important aspects of the design stage since it is an essential point which determines the life expectancy of the transformer. The insulating structure is designed according to the voltage distribution along the windings. When in service, the insulating structure is occasionally exposed to overvoltages that result from the interaction between the transformer and the network. Although there is a great knowledge of the transformer behavior at rated voltage, the same is not exactly true for the transient phenomena. Therefore, it is necessary to have accurate tools to model and reproduce the internal response of the windings to these more demanding conditions, and different approaches have been proposed in literature to achieve this [5], [6], [7].

The proposed model is based on a lumped parameter network which represents in detail the internal geometry of the transformer in the so-called white-box model. This model is broadly used by transformer manufacturers in the design stage.

The model parameters are based on the transformer geometry considering magnetic core, tank, and windings, as well as its material properties. These parameters include inductances, capacitances, and resistances. As shown in [5], each winding is split into a different number of blocks which are represented as Pi equivalent circuits. Parameters of each block are obtained by grouping the parameters of several turns.

2. WHITE-BOX MODELLING

The transformer manufacturers make use of detailed models, the so-called white-box models, for predicting the internal voltage stresses that arise when applying the standard lightning impulse voltage at the terminals. White-box models, also known as internal models, are those whose parameters are calculated from the detailed information about the geometry which is only available to the manufacturer.

White-box models can be classified into three groups: lumped parameters models [8]; distributed parameter models [7], and models based on the electromagnetic field analysis [9]. In this work, a lumped parameter model has been developed for a distribution transformer – Fig 1.

2.1. Lumped parameter model

A great number of white-box models use the lumped parameters approach. The main concept of this approach is to agglomerate groups of winding turns as Pi equivalent circuits known as cells to determine their corresponding inductance, capacitance, and resistance matrices, based on detailed design information and material properties, spatial discretization, and internal connections as depicted in Fig 1.

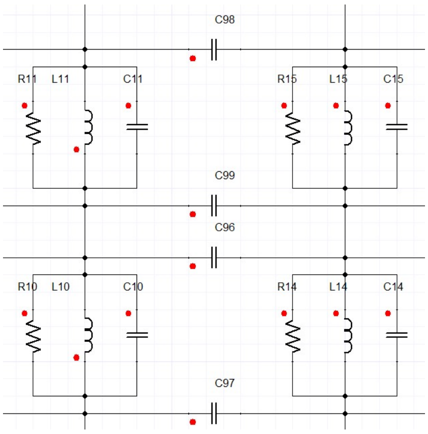

Fig 1. Detail of four winding cells coupled by capacitive and inductive effects.

Resistances are responsible for the damping of the impulse wave and influence the decaying of the magnitude of the oscillations along the time. Inductances represent the leakage flux related to the magnetic coupling of the turns among the windings - namely self and mutual inductance - and finally, capacitors model the electrical coupling due to the capacitive effect of the insulation.

A generic transformer model is extremely complex due to the great design variety of the magnetic core and the windings. Typical distribution transformer design presents some characteristics that need to be specifically addressed like, for instance, the use of HV layer type windings consisting of cylindrical or oval shape with several options for the type of conductors.

For a frequency range above a few kHz, out of the normal operation limits, transformer parameters are more difficult to determine. At very high frequencies, transformer windings behave as electric transmission lines with dissipative and coupled parameters, where the theory of the electromagnetic waves in lossy transmission lines can be applied [7].

2.2. Determination of transformer parameters

The modeling approach depends heavily on the transformer construction and the type of windings. The test transformer in this case is a typical oil immersed distribution transformer with LV and HV foil and multi-layer type windings respectively, which is a very usual configuration in this range of voltages. The core type is pseudo-octagonal which brings about additional issues when calculating inductances and capacitances in comparison with circular transformers. Fig 2 shows the transformer in the factory.

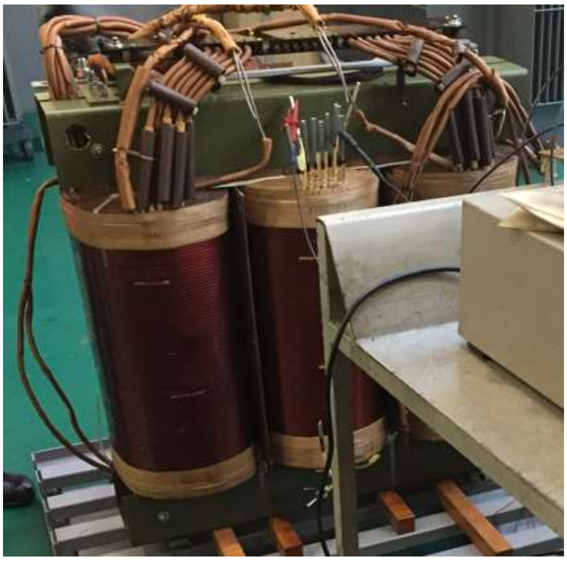

Fig 2. Test transformer in the factory featuring several (dedicated and voltage regulation) tap leads.

2.2.1 Capacitances

Capacitances have been calculated by using adaptations of the basic formulas for plate and cylindrical capacitors. This is allowed because the layers and turns are so close to each other that the influence of the edges is negligible.

Basic formulas derive into the so-called turn-to-turn capacity calculation C_T [10].

$$C_T = \frac{\varepsilon_0 \varepsilon_p \pi D_m (w + t_p)}{t_p} \tag{1}$$

where ε_0 is the vacuum permittivity and ε_p is the insulation relative dielectric permittivity respectively; D_m is the average winding diameter w the radial conductor dimension and t_p the radial insulation dimension.

Equation (1) can be applied to calculate the series capacitance in LV group of turns and HV layers.

Equation (1) for the turn-to-turn capacity can also be applied in the radial direction. For the radial capacitance in the ducts of LV and HV pure plate and cylindrical capacitors can be considered.

For an octagonal transformer winding the radial capacitance calculation between layers should be performed by splitting the windings into several parts, as depicted in Fig 3, to consider the existence of oil ducts on some of the parts and their absence on other parts. Each part has a geometry factor assigned. The total radial capacitance is the sum of the capacitances of all parts. To validate this approach, the radial capacitance in the ducts has been calculated in a 3D finite element model as depicted in Fig 4 with the results shown in Table 1.

Fig 3. Transformer windings split into 8 parts for capacitance calculations.

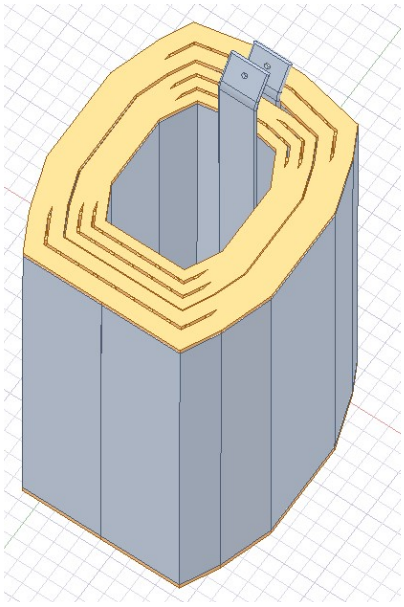

Fig 4. 3D finite element model.

Table 1. LV-HV Radial capacitance (F).

FEM	3.45e-9
ANALYTICAL	3.80e-9

2.2.2 Inductances

While capacitive branches are essential for every transient calculation, inductive branches have a no less important role due to the energy exchange between electrical and magnetic fields which occurs during the transient regime and is responsible for the voltage oscillations.

In this work, self and mutual inductances are calculated using a 2D axisymmetric finite element model based on the diameter resulting from the average turn length of the octagonal geometry. As the magnetic core presence is not considered to be significant at very high frequencies, vacuum magnetic permeability has been considered.

Nevertheless, due to the large surface area of the foil of the LV winding, unlike disk-type windings, the stray magnetic field concentrates on the top and bottom of the winding [11], which cannot be simulated in the typical magnetostatic simulation to compute the inductance matrix. This effect can be considered in different ways as using a complex magnetic permeability or considering the eddy currents generated in the conductive material of the coil. In this work, the inductance matrix has been calculated by performing a magneto-harmonic simulation thus inducing the eddy currents in the LV winding.

2.2.3 Resistances

The resistances firstly have been calculated through an empiric formula based on experimental data from power transformers. After checking the comparison with experimental data, it was observed that on this distribution transformer the typical constant resistive values were uncapable of dissipating the energy of the system thus they were reviewed to match the observed decaying pattern of the oscillations.

3. EXPERIMENTAL TESTS

3.1 Transformer Data

The tested transformer is depicted in Fig 8. It is a three-leg, 500 kVA, core-type, octagonal winding, three-phase power transformer with a rated frequency of 50 Hz. The rated voltages are 11 kV, 0.433 kV, for the high and low voltage respectively with connection group Dyn. Insulation Level for High Voltage is AC 28 kVrms / LI 75 kVpeak.

The transformer is built with 33 foil turns for the LV winding and 1525 turns for the HV layer type winding. The LV winding features inner and outer leads (LV INT and LV EXT) while on the HV winding there are inner and outer leads (leads 2 and 1 respectively). Leads 5-6 and 3-8 are tap leads for voltage regulation. The HV winding features additional tap leads at every three layers that have been installed for measuring purposes only.

3.2 Voltage Transfer Measurements

The tests included non-standard terminal connections with open terminals, differing from those tests defined by the international standards related to impulse testing of power transformers and are suitable for assessing the white-box model performance at higher frequencies, where transformer parameters present greater uncertainty and, thus, allowed the readjusting of the model parameters for simulating any transient phenomena in the high-frequency range, f.e. a lightning overvoltage.

With this approach usually known as the Recurrent Surge Test, a recurrent surge generator applies a voltage pulse to one or more terminals of the transformer and the voltage responses at the other terminals are recorded. The used test equipment is shown in Fig 5.

Fig 5. Recurrent surge generator and oscilloscope used on the experiments.

This test, despite being performed for several years, has some drawbacks. Most recognizable is that results are not always reproducible from one test to another since stray capacitance can appear between the cables that connect to the probes of the oscilloscope. The length of this connection cables should be as minimum as possible, and their path should be as far away as possible from nearby connections or ground.

This experiment also tried to evaluate the magnetic core influence at high frequencies. Two tests have been performed on two different days. On one hand, a Recurrent Surge Test in an isolated phase without the core as depicted in Fig 6a and on the other hand, the same test in the same phase assembled in the transformer core as depicted in Fig 6b. Applied voltages of both tests have the same magnitude but the test without the magnetic core has a voltage wave shape with a small overshoot as depicted in Fig 11.

The influence of the core can be divided into two aspects, one related to the magnetic influence and the other to the capacitive coupling since it is a volume connected to ground. The calculated values presented in this document are related to the model that has no core influence both in capacitive and magnetic perspective.

Fig 6a. Single phase tested without core.

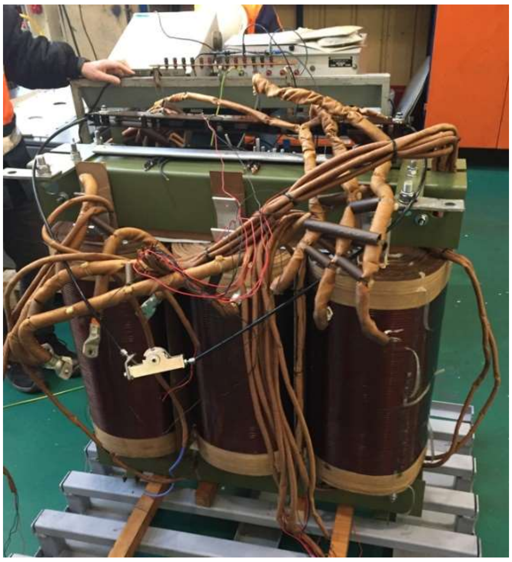

Fig 6b. Transformer tested with core.

A large set of measurements of node-ground voltages were performed, representing voltage transfer between terminals. Fig 7 shows in the first four rows the basic measurement cases which will be shown in this work. These four cases were performed with two alternative tap settings (Max and Min), and with the excitation at either terminal 2 or 1. All chosen cases have the excitation in HV winding since the high series capacitance of the foil type winding makes it impossible to reproduce the standard impulse wave. For this reason, the impulse wave is applied at the HV winding in the standard impulse voltage test.

The specifications shown in Fig 7 are graphically represented in Fig 8, where Case 1 has been taken as an example.

Case	Tap	LV INT	LV EXT	2	1				
	Position					LV EXT	4-5-6	5	13-14-15
1	Max	Grounded		Applied	Grounded	Yes	Yes		
2	Max	Grounded	Grounded	Grounded	Applied				Yes
3	Min	Grounded	Grounded	Applied	Grounded			Yes	
4	Max	Grounded	Grounded	Grounded	Applied		Yes		

Fig 7. Terminal conditions and measurement points.

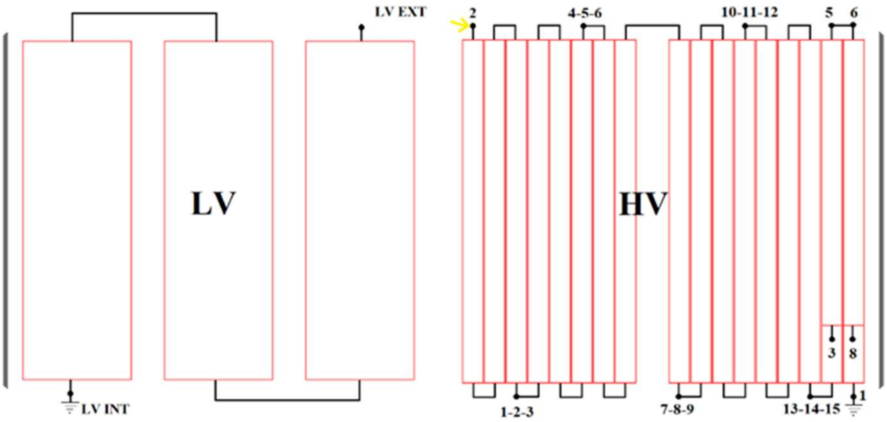

Fig 8. Transformer window cutaway schematic layout featuring the voltage regulation and the dedicated tap leads locations within the windings. Scheme of connections for case 1. Impulse applied on Terminal 2.

4. RESULTS

Voltage transferred measurements were performed between different terminal points applying voltage with standardized shape (1.2 / 50 µS) as depicted in Fig 9. The same voltage waveshape was used in the simulations.

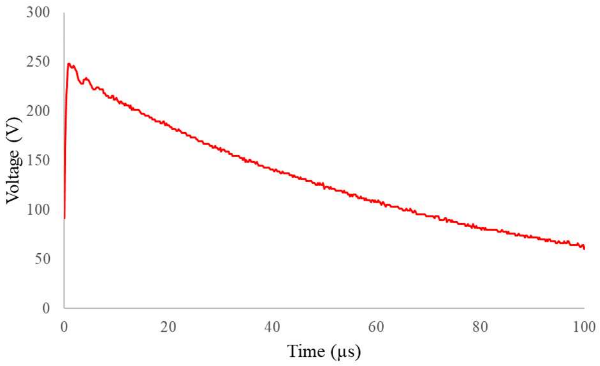

Fig 9. Applied impulse voltage waveshape with a magnitude of 250 volts.

Figs. 10, 11, 12, and 13 show the comparison between the calculated values and the measured results including measurements with and without the core.

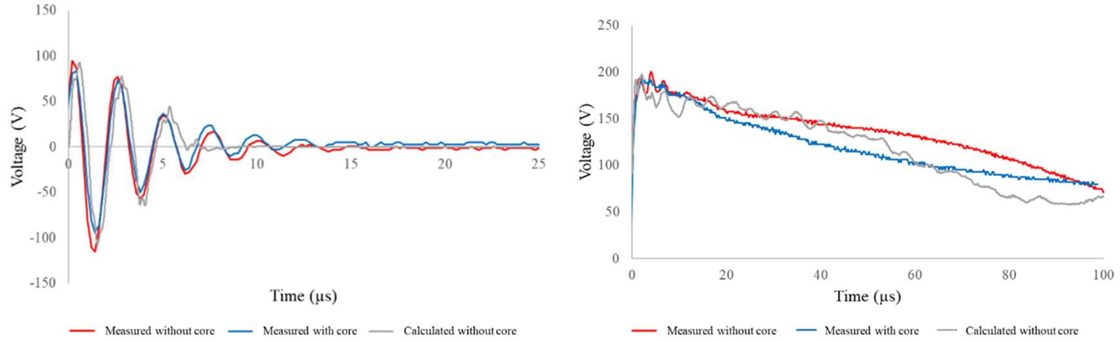

Fig 10. Comparison for Case 1, lead LV EXT (left) and lead 4-5-6 (right), (red: measured without core, blue: measured with core; grey: calculated without core).

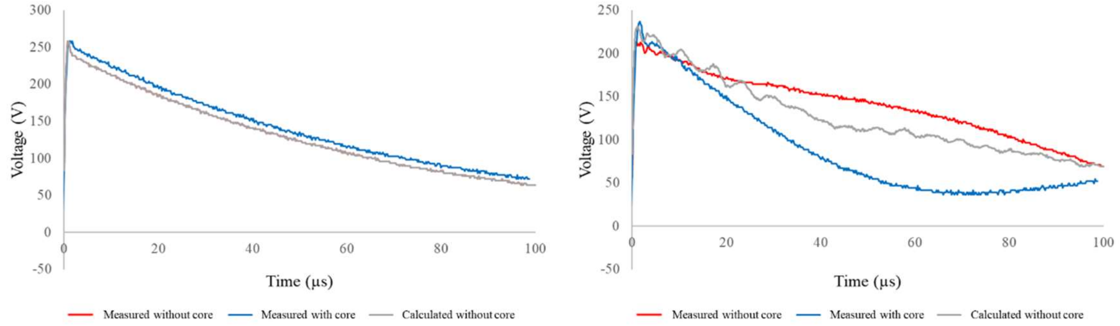

Fig 11. Comparison for Case 2, lead 1 (left) and lead 13-14-15 (right); red: measured without core, blue: measured with core; grey: calculated without core.

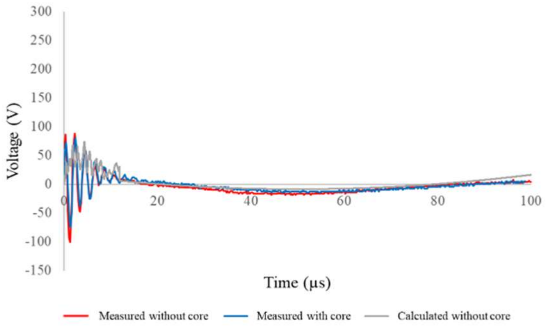

Fig 12. Comparison for Case 3, lead 5 (red: measured without core, blue: measured with core; grey: calculated).

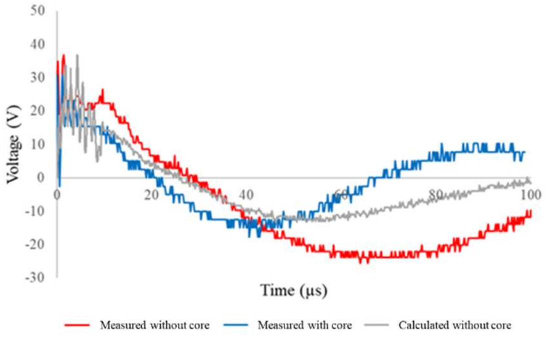

Fig 13. Comparison for Case 4, lead 4-5-6 (red: measured without core, blue: measured with core; grey: calculated).

In all cases, a good agreement was obtained between the magnitudes of the measured and calculated transferred waves for the initial response. For some of the cases the waveshapes start do deviate after some microseconds. Although there are differences in the damping period, the voltage peaks are predicted with reasonable accuracy. Therefore, from the transformer manufacturer prospect, results are acceptable since they allow to predict the critical value for the design of the insulating structures. It should be considered that the model has been initially developed for power transformers so empirical factors must be specifically considered for this distribution transformer.

5. CONCLUSIONS AND FUTURE WORK

Several actions were identified to increase the accuracy of the model:

- The accuracy of the wave in the decaying region can be improved by recalibrating the value of the resistances.
- Geometric factors for capacitance calculation should be recalibrated with FEM since there is still room for improvement.
- Frequency-dependent parameters should be considered.
- The inductance matrix calculated with 3D FEM tools.

A non-standard impulse test procedure has been used for obtaining the voltage response at critical positions within the windings, with alternative terminal conditions.

This work has demonstrated that the white-box model developed for a distribution transformer can accurately simulate the response to high-frequency transient excitations.

The approach is an excellent means of assessing the accuracy of a manufacturer's impulse voltage computational tools, thereby enabling further improvements to the model's parameter determination.

The White-box model can also be validated using a more flexible impulse test methodology like the Small Signal Internal Voltage Transfer Measurements where the test voltage responses are obtained using voltage transfer frequency sweep measurements that are later converted into time domain waveforms. [12] [5]. This approach will be considered in future work.

ACKNOWLEDGEMENT

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