Study Committee A2

Power Transformers and Reactors

Paper 10251_2022

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

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Motivation

- 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 .
- 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.
- 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.

Introduction

- 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.

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.
- 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.

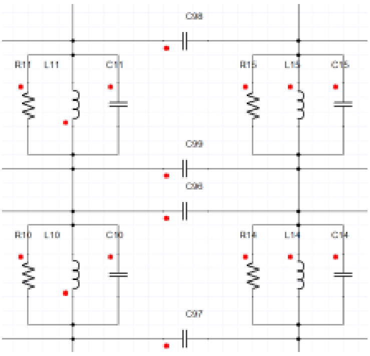

Fig. 1. *Detail of four winding cells coupled by capacitive and inductive effects.*

- 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.

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White-Box Modelling

- 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.
- 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.
- 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 2, 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.

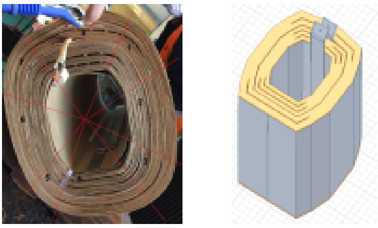

Fig. 2. *Transformer windings split into 8 parts for capacitance calculations*

- 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. Inductance matrix has been calculated by performing a magneto-harmonic simulation thus inducing the eddy currents in the LV winding.

Experimental Setup

- The tested transformer is depicted in Fig 3. 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.

Fig. 3. *Tested transformer.*

- 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.

Fig. 4. *Recurrent surge generator and oscilloscope used on the experiments.*

- A large set of measurements of node-ground voltages were performed, representing voltage transfer between terminals. The specifications are graphically represented in Fig 5, where the first case of comparison has been taken as an example. In this case the impulse wave has been applied in terminal 2, whereas terminal 1 and LV INT are grounded and the voltage response is measured in terminal LV EXT.

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Results

- Voltage transferred measurements were performed between different terminal points applying voltage with standardized shape (1.2 / 50 µS) and a peak value of 250 volts. The same voltage waveshape was used in the simulations.

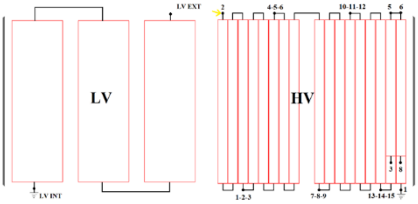

Fig. 5. *Transformer window cutaway schematic layout featuring the voltage regulation and the dedicated tap leads locations within the windings*.

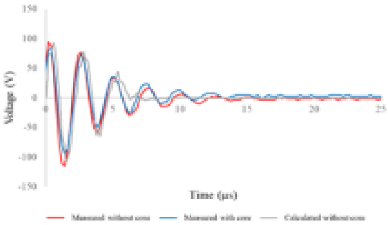

Fig. 6. *Comparison case, lead LV EXT: (Impulse applied in 2, LV INT and 1 grounded)*

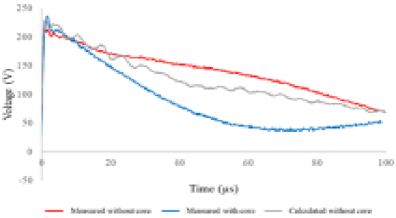

Fig. 7. *Comparison case, lead 13-14-15: (Impulse applied in 1, LV INT, LV EXT and 1 grounded)*

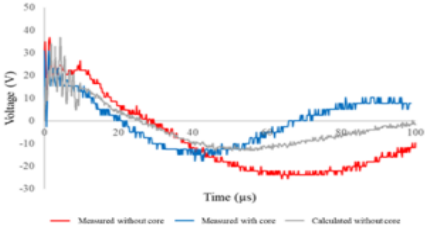

Fig. 8. *Comparison case, lead 4-5-6: (Impulse applied in 1, LV INT, LV EXT and 1 grounded)*

Discussion

- 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.

Conclusions

- 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 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. This approach will be considered in future work.
- The accuracy of the model can be increased taking several actions, as consider frequency-dependent parameters or developing a better damping model. Geometric factors for capacitance calculation should be recalibrated with FEM since there is still room for improvement.