Comparing Two Topology Transformer Hysteresis Models with Power Transformer Measurements

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Power transformer modelling and simulation can require detailed material and design information. However, this detailed transformer information is usually not entirely available. Therefore, we use a single-phase supplement excitation setup to measure the transformer core hysteresis characteristic. In this study we compare two transformer topology models, based on standard data and supplement measurements, with measurement from a 3-limb, 2-winding, 50 kVA power transformer. The first model uses the capacitance-permeance analogy to model the transformer in the magnetic domain. The second model uses the principle of duality and the Jiles-Atherton model for hysteresis implementation. We have found that both transformer topology models show a deviation in power losses below 10\% compared to the single-phase measurement setup. In addition, the validity of the models under AC and DC excitation is analysed using measurement from no-load, back-to-back and back-to-back with superimposed DC tests. These results may be useful for studies where already installed power transformers need to be modelled including their hysteresis characteristic.

\textbf{Index Terms}—Magnetic Hysteresis, Gyrators, Power Transformers, Transformer Cores

I. INTRODUCTION

\textsc{E}lectromagnetic power transformer models are used to study the transformer interaction with the surrounding grid and transformer effects. However, the technical challenge of power transformer modelling is the quality and availability of the transformer data. The goal is to set up a transformer topology model including the hysteresis characteristic. Therefore, we use data from the data sheet, the factory acceptance test and the additional hysteresis measurement only. Based on the data, two transformer topology models are derived. The models are validated with laboratory measurements. The first topology model, further referred to as ”ReCap”, is based on the capacitance-permeance analogy. The duality model is based on the duality between electric and magnetic circuits. The requirement is to accurately simulate the terminal voltage and current behaviour of the transformer during AC and mixed AC/DC excitation. The models are validated with measurements on a 3-limb 2-winding 50 kVA power transformer.

II. TRANSFORMER EQUIVALENT CIRCUIT MODELS

A. ReCap Model

The ReCap model is based on the capacitance-permeance analogy \cite{2}. The capacitance-permeance analogy links the effort variable and flow variable of the electrical and magnetic domain. The analogy links the electric voltage to the magnetic flux rate $\dot{\phi}$ and the electric current to the magnetomotive force $F$ (mmf). The magnetic and electric domain are linked with an interface. This interface has to be able to properly convert the electrical quantities to the magnetic quantities and therefore has to satisfy the following equations:

\begin{equation}
I_1 = GV_2 \quad \& \quad I_2 = GV_1
\end{equation}

A gyrator fulfills these equations and is used as the interface. The capacitance-permeance analogy approach to model magnetic circuits has the following advantages \cite{3}:

- Dissipating losses are modelled using electrical resistances.
- Magnetic fields store energy. Capacitors used in the electric circuit emulate this behavior. Therefore, the energy relationship is preserved.
- When modelling any physical phenomena (mechanic, hydraulic, ...) with lumped circuit elements the effort and flow variables are chosen such that the product has the unit of power. This also applies for the capacitance-permeance analogy.
- The circuit model topology is similar to the physical magnetic topology.
- Energy flow, storage and dissipation are preserved.

B. Duality Based Circuit Model

ReluMagnetic and electric networks are transformed into the respective other domain using the topological principle of duality. The duality transformation transforms the nodes/loops of the magnetic circuit into loops/nodes of the equivalent electric circuit. Reluctances are converted into inductances. The principle of duality can also be applied to transformers. The topologically-correct model includes the magnetic hysteresis of the core material in the form of an inverse Jiles-Atherton (JA) model, according to \cite{4}. The JA parameters are identified using a particle swarm optimization (PSO) procedure.

III. MODEL VALIDATION

A single-phase measurement setup is used to measure the transformer core hysteresis and to validate the two topology models. In the single-phase measurement setup the windings of the outer two limbs of the transformer are connected to a power amplifier. The single-phase measurement setup reduces the magnetic coupling between the middle and the outer limbs to a minimum. Therefore, the core material hysteresis can be measured with only one measurement setup. All hysteresis...
elements in the topology model are based on the same hysteresis characteristic. For the first assessment of the model accuracy, the Φ-I characteristic, the magnetic flux and the current waveforms of the simulations are compared to the measurement, as depicted in Fig. 1. The ReCap model hysteresis characteristic shows a high correlation with the measurement over the entire excitation range. Also in deep saturation the core material behavior is emulated with good accuracy. The simulated magnetic flux over time in the ReCap model deviated in a narrow band from the measured magnetic flux with the same pattern in every period. The simulated current in the ReCap model has a high phase accuracy and overestimates the measured current amplitude of 50.8 A by +0.4 A. The hysteresis characteristic of the duality model shows also a high correlation with the measurement. The simulated power loss is 6% below the measured power loss. Below the knee point, the hysteresis of the duality model encloses the measured hysteresis characteristic. The simulated flux has a high phase and amplitude accuracy. The simulated current has high phase accuracy but overestimated the measured current amplitude of 50.8 A by +1.0 A.

For the verification during normal transformer operation situations, three test cases are selected for: no-load, back-to-back and back-to-back with superimposed DC. The back-to-back test are used to superimpose a DC-excitation via the transformer neutral with one transformer neutral on ground potential. For the measurement two similar but not identical transformers (Tx1 build in 1972, Tx2 build in 1990) are used. In the simulation both transformers are implemented with the parameters of Tx1, which could be one reason for deviation between the measurements and simulations. Both models show a high phase and amplitude accuracy in the three test cases. The ReCap model is numerical more stable than the duality model, due to numerical integration in the hysteresis implementation of the duality model. The numerical stability in the ReCap model results in a faster simulation time, compared to the duality model. The hysteresis model parameters in the ReCap model do not reflect a physical behavior, but preserves energy flow, storage and dissipation, whereas the hysteresis parameter of the JA model attempt to reflect the physical behavior of the core material.

IV. CONCLUSION

In conclusion, two topology based electric transformer models have been derived from standard transformer data and one additional single-phase hysteresis measurement. The hysteresis model parameters are derived with optimization algorithms from the single-phase hysteresis measurement. Both models are validated with measurements on a 50 kVA power transformer and, both models show a high phase and amplitude accuracy up to deep saturation. Back-to-back measurements and simulations proofed the model accuracy also under mixed AC/DC excitation. Therefore, the two topology models can be used to investigate the transformer terminal behaviour regarding the current and voltage waveforms. Further improvements could be achieved by adjustments in the optimization algorithms for the determination of the hysteresis model parameters. This enables utility owners and manufacturers to study the interaction between the transformer and the surrounding network, without the need of complex and time consuming models.

REFERENCES