TRANSFORMER MODELING BASED ON STANDARD FREQUENCY RESPONSE MEASUREMENTS

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Abstract: High frequency models of large power transformers are required for analysis of transient interaction phenomena between transformers and the power system. Fast transient overvoltages may lead to transformer dielectric failures. Deeper understanding of the mechanisms may help to take actions against possible damages. This paper describes the simulation principle of transient interaction in matters of a transformer in several steps discriminating between internal and external aspects of simulation and analysis. The three main approaches of transformer high frequency modelling, black box, white box and grey box are compared and two different measurement strategies are discussed. An impedance estimation which is based on standard frequency response measurements was successfully tested with two distribution transformers.

Index Terms - Power Transformer, Transients, Modelling, Vector Fitting, Frequency Response Measurement, Black box, White box, Grey box

1 INTRODUCTION

High frequency models of power transformers can contribute to illuminate transient interaction phenomena between high voltage apparatuses like overhead lines, GIS, reactors and transformers. Not only it enables engineers to clarify mechanisms of transient overvoltage generation and propagation after failures occurred, but also it can help to predict or even prevent problems that may occur in the future. An increase of dielectric related failures of power transformers with unknown specific reasons justifies revising also high frequency models for transient simulation. Due to its high geometric and (di-)electric complexity, calculation of broad band transformer models is one of the most complex tasks in the engineering process of power transformers.

There are several approaches to deliver network representations of power transformers which are able to reproduce transient interaction effects between the different high voltage power facilities. Figure 1 shows a simplified model of a transformer terminating a high voltage overhead line by its impedance. Whereas the broad band modelling of overhead lines is fairly simple in this case, the complexity of the impedance model determines the prediction accuracy of the reflection behaviour. Single ended impedance representations however are not capable of considering coupling effects between phases and between low voltage and high voltage side, i.e. surge transfer is neglected [1]. This paper analyses different solutions for power transformer high frequency modelling and investigates the possibility of using standard

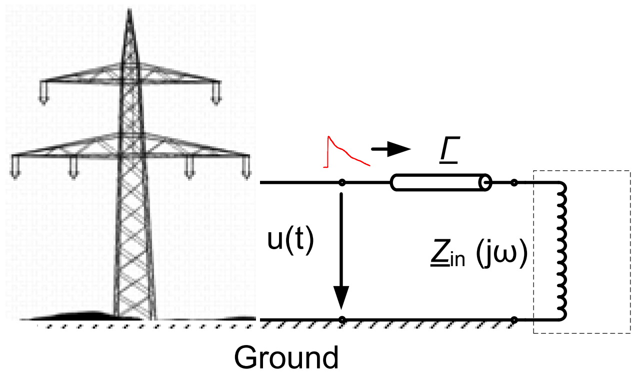

Figure 1: Simplified network model with wave impedance of a high voltage overhead line and the terminating transformer impedance. Transfer of arriving overvoltages to the secondary side is not considered.

frequency response measurements for computation of high frequency representations. For large power transformers, these measurement are done on a routine basis during factory test bays during acceptance tests where the executing personnel is familiar with the measurement proceedings which ensures high reproducibility of the measurement results. Reliability of the measured Frequency responses is a pre-condition for accurate transformer models [2].

2 SIMULATION PRINCIPLE OF TRANSIENT INTERACTION

The main tool for investigation of transient interaction phenomena is time domain electrical network simulation. There are several software packages capable of doing the job. Two of the most common are EMTP-ATP and SPICE.

The simulation process usually consists of the following steps:

a. Creation of the electrical network equivalents of the participating high voltage facilities

b. Building of the network topology

c. Design and integration of the voltage/current source with its excitation waveform

d. Time domain simulation according to the predefined simulation parameters

e. Extraction of monitored node voltages and line currents

f. Subsequent analysis of thermal, mechanical and/or dielectric stress of the apparatuses of interest based on simulated voltage and current waveforms

Figure 2 shows a simplified SPICE arrangement of a single phase transformer model with transient voltage source and line impedance in between.

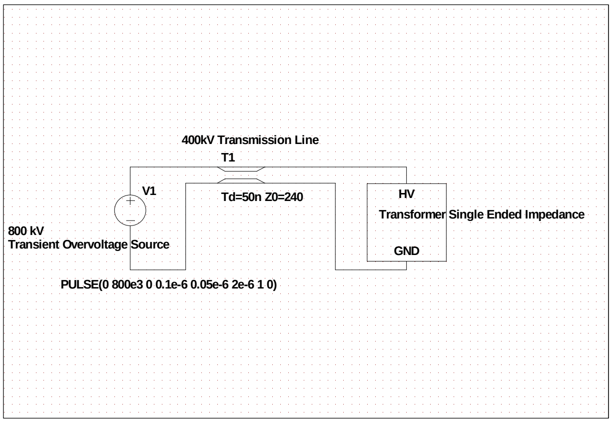

Figure 2: Black box modelling process

During the first steps of the transient interaction simulation (a.-e.) the question of the type of high frequency transformer model comes second. As long as the model is capable of representing the electrical terminal behaviour satisfactorily in terms of frequency bandwidth and accuracy, any model type is suitable. The goal of the first simulation is a quantitative macro view about what is happening between the elements of the network. The waveform of the excitation source can be synthetic (e.g. chopped lightning impulse) or derived from foregone measurements. In the case where the source is stationary AC or DC, switching events can trigger the transients.

Only the last step of the whole simulation process (f.) requires detailed design information about the object under test: For example with the simulated voltages at the transformer terminals, dielectric stress can be calculated from the voltage distribution along the winding using detailed modelling techniques. This step usually involves the manufacturer of the high voltage device.

3 BROAD BAND HIGH FREQUENCY MODELLING OF POWER TRANSFORMERS

3.1 Black box models

Black box models are linear time-invariant multipole network models representing the same electrical behaviour as the real transformer ideals over a wide frequency range. A well-established view is the admittance matrix form. The various terminals are excited by voltage sources which lead to current responses at the terminals:

$$\begin{pmatrix} \underline{I}_1(j\omega) \\ \vdots \\ \underline{I}_n(j\omega) \end{pmatrix} = \begin{pmatrix} \underline{Y}_{11}(j\omega) & \cdots & \underline{Y}_{1n}(j\omega) \\ \vdots & \ddots & \vdots \\ \underline{Y}_{n1}(j\omega) & \cdots & \underline{Y}_{nn}(j\omega) \end{pmatrix} \cdot \begin{pmatrix} \underline{U}_1(j\omega) \\ \vdots \\ \underline{U}_n(j\omega) \end{pmatrix} \quad (1)$$

Figure 1 illustrates the black box representation of a large high voltage three phase transformer for the windings sets of two voltage sides.

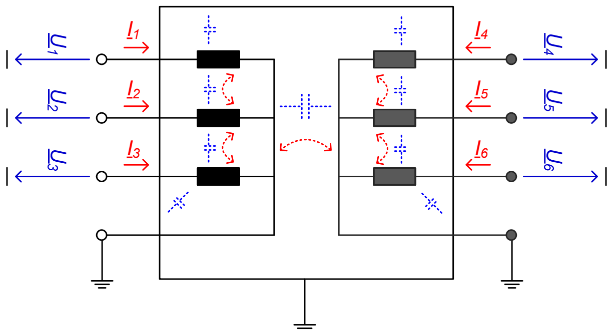

Figure 3: Comprehensive 6 port linear transformer black box model

On high voltage levels, the neutral terminals of power transformers are tight to ground. All terminal voltages are referenced to ground potential. This leads to a 6 port representation (high and medium voltage side) for a transformer with eight (e.g. YNyn0, standard grid) or seven terminals (e.g. YNdX, generator step-up). Tertiary winding terminals are not taken into account here but can be analogously considered. Besides the admittance form, there are several equivalent matrix forms like impedance and transmission line which can be converted into each other. A comprehensive transformer admittance model is described by a 6x6 matrix containing 36 admittance elements.

The advantage of the black box approach is that there is no need for detailed design information about the transformer in order to create a model. All model data is based on terminal measurements, hence the accuracy of black box models is mainly determined by this preconditional step. Of course, the band width is determined by the measurements, too.

The results of the measurements however exist in a numerical form whereas an analytical form is needed for simulation purposes. Hence extraction of analytical data from the measurements is needed. Vector Fitting (VF) is a suitable tool and one of the most approved methods for this task across many applications [3]. From the measured admittance matrix

$$\underline{\boldsymbol{Y}}(\boldsymbol{j\omega}) = \underline{\boldsymbol{I}}(\boldsymbol{j\omega}) \cdot \underline{\boldsymbol{U}}(\boldsymbol{j\omega})^{-\boldsymbol{1}} \qquad (2)$$

the VF algorithm builds an analytical representation consisting of complex conjugate pairs of poles and residues:

$$\underline{\boldsymbol{Y}}(\boldsymbol{j\omega}) \approx \underline{\boldsymbol{Y}_{\boldsymbol{fit}}}(\boldsymbol{j\omega}) = \sum_{\boldsymbol{n=1}}^{\boldsymbol{N}} \frac{\boldsymbol{R_n}}{j\omega - p_n} + \boldsymbol{R_0} \qquad (3)$$

The result is an approximation of the measured input data. The degree of accuracy depends on the ordinal number *N*, the number of poles. Given a defined fitting accuracy, this parameter can be optimised so that *N* becomes minimal [4]. The VF algorithm guarantees BIBO (Bounded-Input Bounded-Output) stability of the created system, i.e. $Re\{p_n\} < 0$. However this doesn't ensure stable time domain simulation results because the passivity condition may be unfulfilled regardless BIBO stability criterion due to measurement inaccuracies and numerical errors. Stability can be recovered by consecutive passivity enforcing [5, 6]. This step is mandatory and several ways to achieve exist. Figure 4 summarizes all necessary steps for black box high frequency modelling of power transformers. As a last step, it is possible to create an equivalent lumped element circuit from single elements of the matrix $\underline{\boldsymbol{Y}_{fit}}(\boldsymbol{j\omega})$ by connecting single RLC resonance circuits (the realisation of the summands in (3)) together in parallel.

3.2 White box models

The high frequency terminal behaviour of power transformers is determined by the geometry of the active part (core, windings) and its electric and

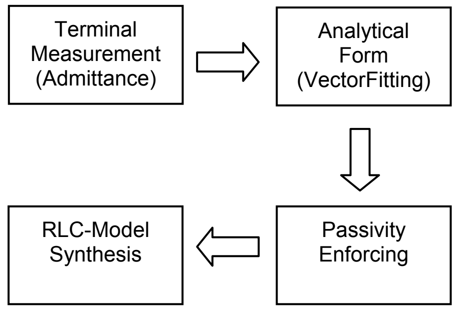

Figure 4: Black box modelling process

magnetic stray field distribution. White box models of power transformers consist of a complex network of lumped elements where each element represents a circuit equivalent for a small piece of the conductive or dielectric arrangement of the active part. For higher frequencies, ground capacitances and capacitances between winding turns and adjacent windings dominate the admittance matrix and resonance characteristic in frequency domain.

Since the creation of white box models requires detailed geometry information of the transformer active part, this approach is reserved to manufacturers. The accuracy of a detailed lumped element model, i.e. accordance between terminal measurement and simulated admittance, depends on the number of lumped elements and the matching of its parameter values. There are two ways to calculate the lumped element parameters:

- Calculation of capacitances, inductances and resistances on the basis of analytical formulas

- Calculation using FEM (finite element method) based simulation

Analytical calculation becomes challenging for inhomogeneous winding designs and windings with interleaved parts or capacitive control lines in parallel to the winding wire. FEM models can be constructed from CAD data. Model complexity is only limited by computing time which easily becomes unfeasible. However, the effort and time for the model creation can be minimized if this process is integrated into the design workflow. Figure 5 shows one section of a disc winding model which illustrates the level of detail.

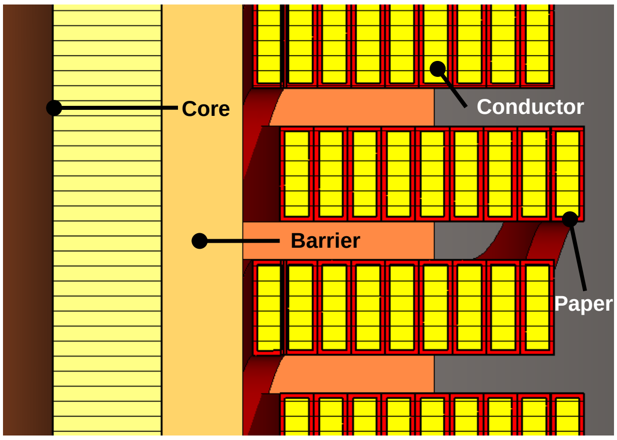

Figure 5: Detailed section of disc winding CAD model.

3.3 Grey box models

Grey box models are simplified lumped element models that do not cover design details but reflect the main features of the frequency dependent admittance. For the low frequency part, the basic electrical elements determine the frequency response: Copper resistance of windings R_{Cu}, leakage inductance of windings L_{σ}, magnetising inductance L_m, core loss resistance R_{Fe}, winding series capacitance C_s, capacitance of inter-winding coupling C_{iw}. Figure 6 shows the simplified circuit diagram of a single transformer phase, neglecting adjacent windings.

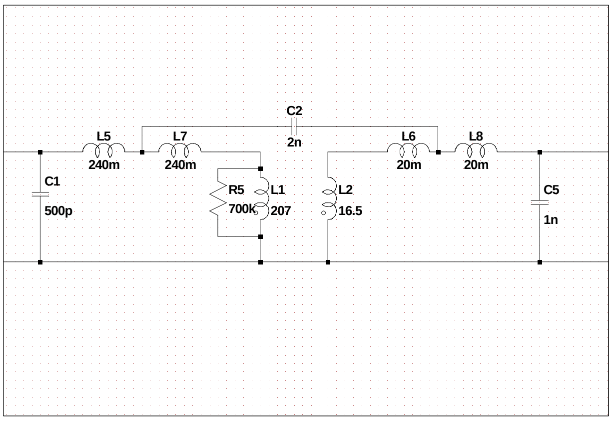

Figure 6: Single phase transformer grey box model using simplified lumped elements network.

Smaller resonances within the several hundred kHz range reflecting the winding structure and inter-winding couplings [7] cannot be reproduced by the model, however a rough admittance approximation is often sufficient for some applications. Figure 7 shows the simulated admittance from HV terminal to neutral.

3.4 Comparison of transformer model types

The most common approaches for high frequency modelling are the black box and the white box models. Black box models, in their comprehensive form, have the same electrical behaviour as the real transformer ideals. Besides, there are black box models of reduced complexity, where either less meaningful couplings are neglected, simplified or approximated. White box models are detailed lumped element models which are derived from the actual design geometry of a power transformers' active part, which allows a deeper system view. Although they do not reflect the input admittance in detail, grey box models may be suitable for a fast transient analysis. There advantage is that no detailed information about the transformer design geometry is needed and measuring expenditure is small. Table 1 shows a comparison of the three different approaches concerning their characteristics.

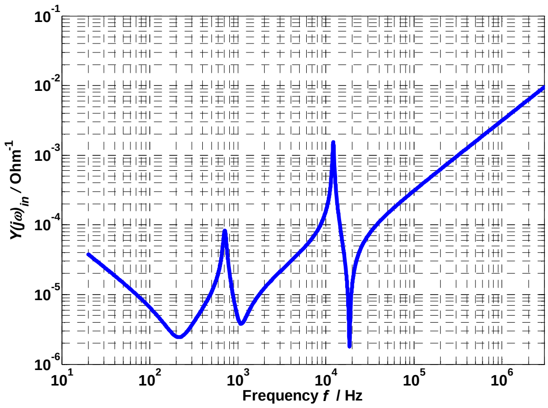

Figure 7: LTspice simulation result of winding admittance.

Table 1: Comparison of black box, white box and grey box models of power transformers

	Black Box	White Box	Grey Box
Feasible Accuracy	High/ Medium	Low/ Medium	High/ Medium
Feasible Bandwidth	High	Low/ Medium	Medium
Data Basis	Measure-ments	Design Geometry, Simulations	Measure-ments, Simulations, Basic Electrical Data
Measuring Expenditure	High	-	Small
Elementary Parts	Poles, Residues, Lumped Elements[1]	Lumped Elements	Poles[3], Residues[3], Lumped Elements[1]
Model Complexity	Medium	High	Small/ Medium
Computing Time	Small/ Medium	Small/High[2]	Small/High[2]
SPICE Capability	Yes[1]	Yes	Yes

[1]: Requires fitting and linear network synthesis
[2]: FEM Simulation time strongly depends on computing power
[3]: Analytical model can be derived through fitting

4 MEASUREMENT CONSIDERATIONS FOR HIGH FREQUENCY MODEL CREATION

4.1 Short circuit method

Black box models are based on terminal measurements. Grey box models can at least be improved in terms of accuracy, if terminal measurements a taken into account besides basic electrical data.

If no simplification is applied, a complete black box model of a three phase transformer needs 36 admittance measurements. One possibility is to short all transformer terminals except one while measuring all *n* terminal currents $\underline{I}_1(j\omega)...\underline{I}_n(j\omega)$ when sourcing the unshorted phase according to the following equations:

$$\begin{pmatrix} \underline{I}_1(j\omega) \\ \vdots \\ \underline{I}_n(j\omega) \end{pmatrix} = \begin{pmatrix} \underline{Y}_{11}(j\omega) & \cdots & \underline{Y}_{1n}(j\omega) \\ \vdots & \ddots & \vdots \\ \underline{Y}_{n1}(j\omega) & \cdots & \underline{Y}_{nn}(j\omega) \end{pmatrix} \cdot \begin{pmatrix} \underline{U}_1(j\omega) \\ 0 \\ \vdots \\ 0 \end{pmatrix} \quad (4)$$

$$\begin{pmatrix} \underline{Y}_{11}(j\omega) \\ \vdots \\ \underline{Y}_{n1}(j\omega) \end{pmatrix} = \begin{pmatrix} \underline{I}_1(j\omega) \\ \vdots \\ \underline{I}_n(j\omega) \end{pmatrix} \cdot \underline{U}_1(j\omega)^{-1} \quad (5)$$

On the one hand, for the low frequency part of the admittance, this measurement approach is not suitable since the magnetic circuit is shorted, i.e. only the short circuit impedance (leakage inductance) is considered. For a time domain transient simulation this means that oscillations with longer time periods will not appear. On the other hand, shorting of terminals is not easy on large power transformers. Depending on the voltage level, bushings are several metres long and shorts have to be done using copper braids. The reproducibility naturally deteriorates with increasing frequency [Wimmer] and limits the accuracy of black box models.

Time and effort for all 36 admittance measurements is high. In practice one would try to reduce this number by taking advantage of the symmetry properties of the matrix elements and similarities amongst the phases.

4.2 Model creation using standard frequency response measurements

Another possibility for determination of the admittances is the utilisation of frequency response measurements, often referred to as FRA (Frequency Response Analysis) measurement data. Figure 8 shows the common measurement setup for the so-called end-to-end measurement. The transfer function $\underline{TF}(j\omega)$ is defined as the ratio of the voltages at both ends of the winding, terminated with 50 Ω-Resistors:

$$\underline{TF}(j\omega) = \frac{\underline{U}_2(j\omega)}{\underline{U}_1(j\omega)} \quad (6)$$

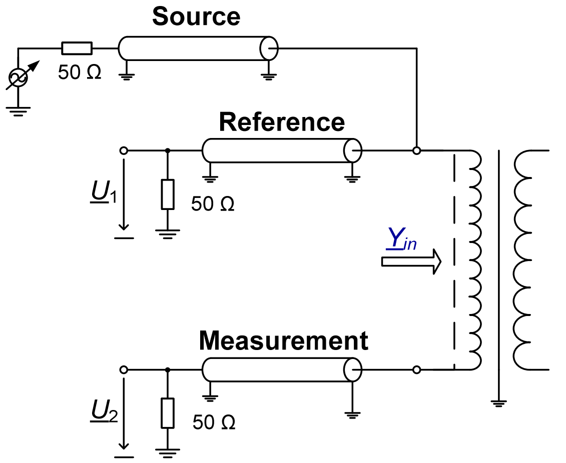

Figure 8: End-to-End winding frequency response measurement.

$\underline{TF}(j\omega)$ is determined by the winding admittance $\underline{Y}_{in}(j\omega)$. An approximation can be found using the voltage divider ratio defined $\underline{Y}_{in}(j\omega)$ and the 50 Ω termination resistance:

$$\underline{Y}_{in}(j\omega) \approx \frac{\underline{TF}(j\omega)}{R\cdot\left(1-\underline{TF}(j\omega)\right)} \quad (7)$$

This neglects all currents flowing through the ground stray capacitances; hence its validity is limited and deteriorates with increasing frequency.

5 EXAMPLE: IMPEDANCE CALCULATION OF DISTRIBUTION TRANSFORMERS USING FRA DATA

The above described approach was carried out on two distribution transformers (400 kVA and 160 kVA). Of course, these transformers are small compared to large power transformers but the principle of approximation can be tested anyhow. As a reference, an impedance measurement was done using the setup shown in Figure 9.

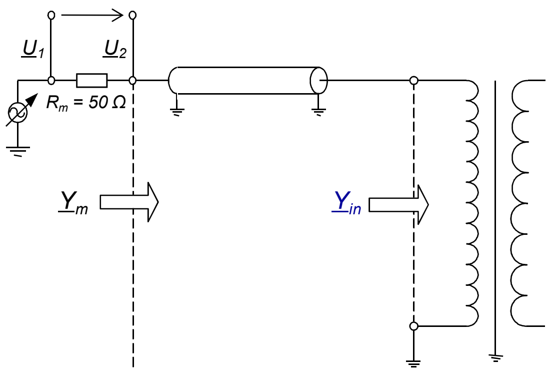

Figure 9: End-to-End winding impedance measurement.

The determination of the impedance is equivalent to the admittance case. Due to complete calibration (short, open, load) the influence of the measurement lead can be neglected. Figure 10 shows the measurement results of the measured and estimated impedance up to 6 MHz.

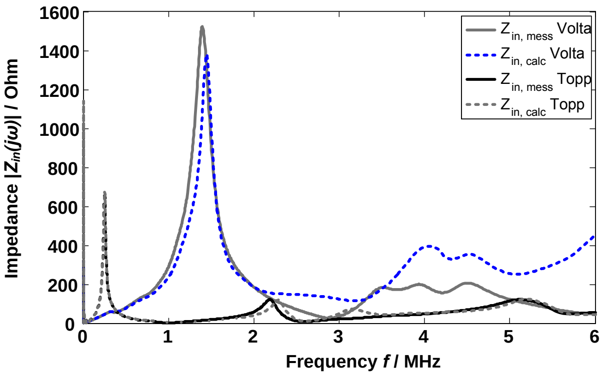

Figure 10: Measured impedance $\underline{Z}_{in}$ and estimated impedance $\underline{Z}_{in,calc}$ based on end-to-end measurements up to 6 MHz.

For the 160 kVA transformer, the approximation is acceptable up to 6 MHz, the estimation for the 400 kVA transformer can be regarded as valid up to 2 MHz. This simple example demonstrates that the accuracy of the impedance approximation depends on the transformer impedance in relation to the 50 Ohm measurement impedance. The shunt capacitance of the winding influences the result, too. Hence the size, voltage level type and internal design of the transformer will have an effect result.

6 CONCLUSION

This paper gives an overview about the various approaches and techniques for power transformer high frequency modelling for transient simulation purposes. The simulation principle of transient interaction between a transformer and the power system is described in several steps discriminating between internal and external aspects of simulation and analysis.

The three main approaches of transformer high frequency modelling, black box, white box and grey box are described. For the black box approach, the modelling process is explained in detail analysing its necessary steps. The white box model is discussed together with two different approaches for lumped element parameter determination, FEM simulation and analytical calculation. The grey box model was introduced as a simple lumped element model of reduced complexity reflecting the main features of the frequency dependent admittance. All three modelling techniques are compared with each other in terms of their practically relevant characteristics.Two different measurement strategies were described together with their pros and cons. The first measurement type referred as short circuit method is suitable for the black box approach but has drawbacks in the low frequency range. The second method uses an impedance estimation which is based on standard frequency response measurements. This approach was successfully tested with two distribution transformers.

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