Generic and Automated Simulation Modeling Based on Measurements

Martin Tiberg, Dierk Bormann, Bjørn Gustavsen, Christoph Heitz, Olaf Hoenecke, Gheorghe Muset, Jean Mahseredjian, and Peter Werle

Abstract-- SoFT is a new method and tool which measures and models linear electrical network components in a wide frequency band with unprecedented accuracy. This is achieved by a special modal based measurement technique in combination with suitable rational fitting and passivity enforcement methods. The models are easily imported into most commonly used simulation software.

This paper demonstrates the SoFT tool computations in a comparison between A) time-domain measurements of a lightning impulse test of a power transformer, B) simulation of the test results using a SoFT model, and C) simulation of the test results using a lumped-element circuit simulation model based on geometrical transformer design information.

Keywords: Transformer, wide band model, electromagnetic transients, EMTP-RV, measurement

I. Introduction

THE modeling of power system components for electromagnetic transient simulations is becoming increasingly more sophisticated due to advances in modeling capability and computing resources. One of the remaining difficulties is the modeling of complex devices that are characterized by a pronounced frequency dependency at the ports (terminals) of the device. Typical examples are the modeling of motors and transformers over a wide frequency band. The modeling of transformers can be done starting from detailed geometrical data [1–3] but this information is usually of proprietary nature. And even with this information known, it is still very difficult to obtain a sufficiently accurate model. In many simulation studies it suffices to use only a terminal equivalent of the transformer, e.g. when simulating the voltage transfer between windings and in studies of transformer resonant overvoltages. An attractive way of dealing with such situation is the black box approach where a model is identified that reproduces the observed (measured) behavior at the ports as closely as possible. In two important situations, however, detailed transformer modeling is mandatory: (A) during the design stage, i.e., when the transformer is not yet physically available for measurements, and (B) for studies of resonant overvoltages *within* transformer windings, stressing its insulation between turns or to ground.

A systematic approach for the wide band black box modeling of transformers was introduced in [4] where the terminal admittance matrix Y was measured by its columns, one-by-one. Since the ratio between the largest and smallest eigenvalue of Y (eigenvalue spread) is usually large at low frequencies, it is difficult to accurately represent the smallest eigenvalues. This can result in that the model behaves inaccurately if the transformer is used in a simulation with many open terminals. In the case of a transformer with ungrounded windings, the eigenvalue spread can become quite extreme at low frequencies due to a vanishingly small zero sequence current. In [5] it was proposed to overcome this problem by measuring and modeling the zero sequence system separately, but the procedure results in an undesirable perturbation of the model.

The present paper presents results from a fully general modeling procedure. The procedure named SoFT relies on exciting the transformer by the eigenvectors of the admittance matrix, with the eigenvectors obtained from the measurements in an iterative way [6]. This allows revealing even the smallest eigenpairs, thereby overcoming the problem of small eigenvalues vanishing in the measurement noise. The subsequent rational modeling is based on Vector Fitting [7] with relaxation [8]. Passivity checking is done via the eigenvalues of the Hamiltonian matrix [9,10], and any passivity violations are removed by perturbing the residues of the obtained model [11]. In order to retain the accuracy of the smallest eigenvalues, the Modal Vector Fitting approach (MVF) [12] as well as the Modal Perturbation approach for passivity enforcement [13] have been implemented. Finally, the resulting model is exported to a file for use with the state-space component of EMTP-RV [14].

The main emphasis of this paper is to compare the results of a direct time domain measurement with those of a black box model (created from low-voltage measurements on the transformer, using SoFT) and those of a geometrical model (a detailed lumped-element circuit model generated from the transformer design information), in order to assess and compare the accuracy of both modeling approaches.

II. Overview

The objective of the paper is to compare the different

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approaches to high-frequency transformer modeling with measurements in an industry setting outside the laboratory.

Previous evaluations have never included both theoretical and measurement-based models of transformers for the high frequencies which are relevant in lightning studies.

As test object was selected a 250 MVA, 400/120/33 kV, YN/yn0/d5 transformer manufactured by ABB (see Fig. 1).

The evaluation consists of comparing simulated results with measurement results from a lightning impulse test of the transformer in both frequency and time domain. For the simulated results, three different models have been used:

1. a model based on measurements with SoFT technology ("SoFT model"),
2. a lumped-element circuit model [1] based on geometrical design data ("geometrical model"),
3. a model based on standard transformer model in EMTP-RV ("standard model").

III. Experimental Setup

The lightning impulse measurements were performed according to IEC 60076 (part 3) standard. A high voltage with a fast rise time of about 1 µs (see Fig. 5) was applied to one of the HV windings and the current response of the MV winding was measured. The current response was measured as the voltage drop across a 2 Ohm shunt resistor that connects all three MV phases to ground as shown in Fig. 2. The remaining terminals and neutral were connected to ground. The HV and MV neutrals, all three phases of the LV winding, and two HV windings (where the voltage was not applied) were all connected to ground.

Fig. 1. 250 MVA transformer.

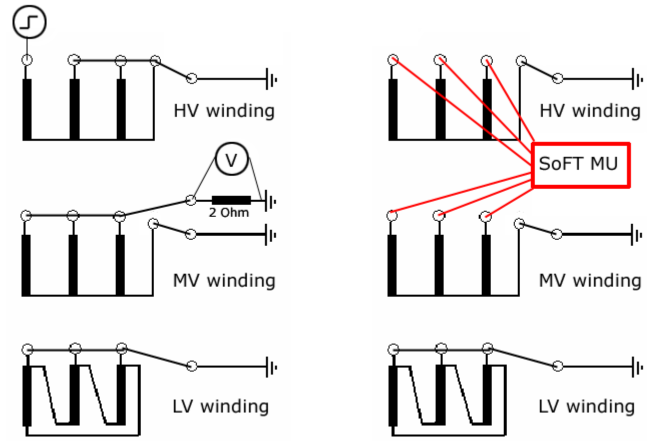

Fig. 2. Experimental setup for lightning impulse test and SoFT measurement.

IV. Methods for Modelling

In this section we briefly describe the different modeling approaches for creating a simulation model. The simulation itself is described in the following section.

A. SoFT approach

The general idea of the SoFT approach is to measure and model the complete dynamic behavior of the transformer as an electrical N-port over a wide frequency band. It consists of two steps: first a measuring step, and second a modeling step.

For the measurement, a specifically designed measuring system is used which has the following characteristics [15,16]:

- Seven independent but synchronized voltage ports that are connected to the object simultaneously allow to apply arbitrary voltage combinations to the N-port
- Measurement is made via frequency sweeps over a frequency range from 10 Hz to 10 MHz.
- The applied voltage vector (combination of these 7 voltages) is chosen in an optimum way such that the system is excited exactly at its frequency dependent eigenmodes [15]. The eigenmodes are determined by prior test measurements and refined in two iteration steps. With this approach, the acquired data has maximum precision.

For the present study, we measured at 400 frequencies in the range of 20 Hz – 2 MHz, where half the points were spaced logarithmically and the other half linearly spaced.

As a by-product, from the measured data, one can calculate the frequency dependent admittance matrix Y(ω) which is used as a reference for describing the dynamic behavior of the system in the frequency domain.

For the modeling, we used the relaxed version [8] of the pole relocating, vector fitting (VF) method [7]. The VF method generates a state-space model that approximates the port characteristics of the data. For use in simulation studies, passivity of the model is a necessary condition in order to avoid unstable simulation results. Since the obtained model is not necessarily passive, a perturbation is calculated that ensures passivity while minimizing the change to the model behavior. For passivity enforcement, we use a modified version of [11]. Currently, the authors are implementing more powerful approaches that can retain the relative accuracy of the modes, both in the fitting step [12] and in the passivity enforcement step [13].

After these steps, a passive state-space model is obtained that can be used directly in EMTV-RV.

B. Geometrical modeling

Based on the (proprietary) geometrical design information of the tested transformer (Fig. 1), self and mutual inductances and capacitances of a detailed lumped-element circuit representation [1–3,17] are derived. The resulting system of dynamic equations in time or frequency domain is then decomposed into normal modes and solved with MATLAB. Resonance damping is included by an empirical frequency dependent modal damping function which has led to good results in previous comparisons between measurements and simulations, and is not specific to the transformer studied here.

We do not describe the procedure in more detail here since it is relatively standard and its details are not central to the message of this paper.

C. Standard model

As a reference, we also used a standard transformer model of EMTP-RV that uses transformer name-plate data as input.

V. Simulation

The SoFT model was included in the EMTP-RV simulation environment using the available state-space block. The circuit representation is shown in Fig. 3. The state-space block can be simultaneously solved with any number and configuration of surrounding network devices.

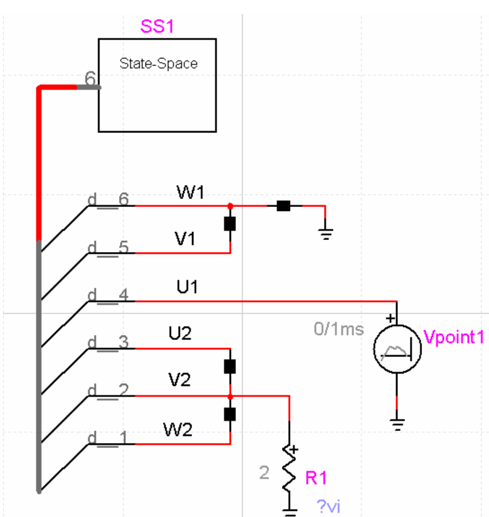

Fig. 3 EMTP-RV simulation case.

The measured voltage is applied in the circuit by an ideal voltage source (Vpoint1) while the current flowing through the shunt resistor (R1) is recorded.

As mentioned above, the matrix equations describing the detailed geometrical model (including the measurement circuit) were simulated with separate time and frequency domain solvers implemented in MATLAB.

VI. Simulation Results

A. Frequency domain comparison

Using the three alternative modeling approaches described previously, the current through the shunt resistor (Fig 2) due to a sinusoidal voltage application is calculated in the frequency domain (frequency scan). In addition is calculated the current response using the measured Y (SoFT) via the nodal admittance method (tagged as SoFT meas.), and the response deduced by Fourier transformation from the measured time domain impulse response. The result is shown in Fig. 4.

- All models agree well up to about 10 kHz where the result by the standard model departs. This departure is caused by the fact that the standard modeling lacks resonant branches.
- The response obtained by SoFT measurement and SoFT model agree, implying a correct modeling from the measurement. A local deviation occurs around 20 kHz. The deviation is probably caused by a missing inverse magnitude weighting in the current implementation.
- The SoFT responses (measurement/model) agree well with the impulse measurement up to about 500 kHz. The main cause of the deviation at higher frequencies is differences in the measurement cables used in the SoFT measurement and the impulse measurement.
- The geometrical model has similar characteristics as the SoFT responses, but there is still a quite large deviation in the frequency responses, both in number of resonance peaks and their size.

The comparison with the standard (non-frequency dependent) transformer model is rather irrelevant here, but it is included to highlight the importance of advanced modeling.

B. Time domain comparison

Fig. 5 compares the measured and simulated waveforms for the current response. The applied voltage (also included in Fig. 5) was taken as a known quantity in the simulation.

- The SoFT response agrees closely with the measured response, except for an offset value.
- The response of the geometric model shows a less good agreement. It is recalled that the main application of detailed geometrical modeling is to calculate internal winding stresses, for which SoFT is not applicable.
- The standard transformer model produces an incorrect result. This was to be expected, due to the poor agreement in Fig. 4.

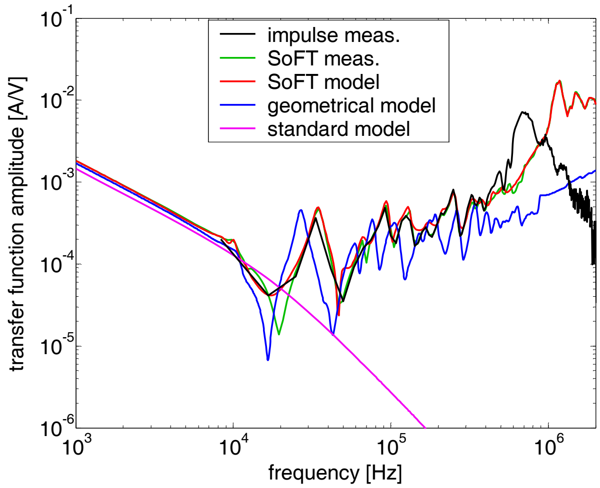

Fig. 4 Frequency-dependent transfer functions between applied voltage and measured current. Black line: behavior derived by Fourier transformation from the time domain impulse measurement data. Green line: theoretical behavior calculated from admittance matrix. Red line: behavior of SoFT model calculated with EMTP-RV. Blue line: behavior of geometrical model. Magenta: behavior of EMTP-RV standard transformer model.

- At short times (< 10 μs) both impulse measurement and SoFT model simulation display transient oscillations, albeit with different frequencies of about 1 MHz and 0.7 MHz, respectively. This difference is also reflected in corresponding maxima in the transfer function plot, Fig. 4. In contrast, the geometrical model does not display oscillatory behavior, corresponding to the absence of a pronounced high-frequency maximum of the transfer function.

C. Discussion

Some of the results were as expected: the standard model used for power frequency studies is clearly inadequate for high frequency simulations. The geometrical model based on design data shows well the general trends of the response of the lightning impulse. The SoFT model based on complete fingerprint measurements refines the agreement of the lightning impulse response further.

The SoFT model does however not portray the 700 kHz oscillations of the measured impulse response. This oscillation occurs in the initial transient (Fig. 5) and is also observed in the frequency response in Fig. 4. The resonance is probably caused by the usage of very long measurement cables (50 m) in the time domain measurement, while the SoFT measurement setup made use of 5 m long cables. This conclusion is supported by the fact that a close agreement has previously been reported [4,5] when using identical cables for frequency domain and time domain measurement.

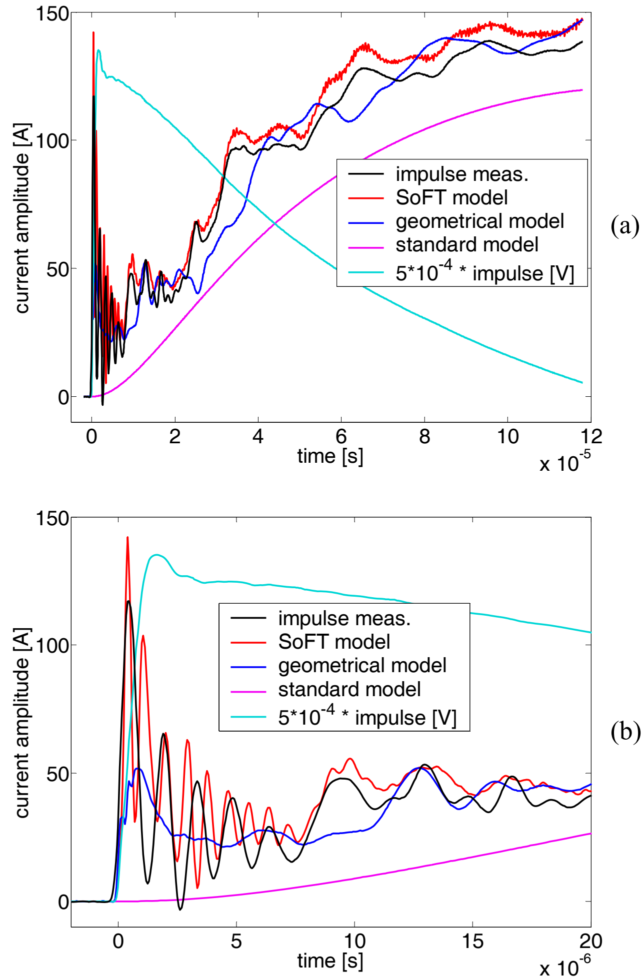

Fig. 5. Time domain responses. Same line colors as in Fig. 4 for impulse measurement and SoFT, geometrical and standard models. For comparison, the impulse voltage is shown on the same time scale. (a) full time interval of the impulse measurement, (b) blow-up of the first 20 μs.

Experiences from FRA measurements show that 5 m long cables could start influencing frequencies above 500 kHz. It is remarked that SoFT makes use of a cable compensation approach [4] that subtracts a shunt capacitance term from the diagonal elements of the measured Y, thus in principle producing a model of the transformer alone. This approach is correct up to frequencies where internal resonance effects in the cable become significant.

The SoFT and impulse measurements underlying this evaluation were carried out as part of the final testing of a very large power transformer before it was delivered to the customer. This fact put restrictions on the measurements, because they were carried out once and under time constraints and they could not be repeated. Such restrictions are typical for real industrial out-of-the-lab experiments. In this case, they led to the situation that not all discrepancies could be re-checked with new measurements.

When measured and modeled correctly, the SoFT simulations should portray the first high-frequency oscillations as accurately as the rest of the impulse response. In the frequency domain (Fig. 4), a i) comparison of the simulated SoFT results based on the SoFT model, and ii) the results computed directly from the SoFT measurements without the modeling step show a very good/perfect agreement. Thus, the SoFT modeling is done highly accurately and the discrepancies between the SoFT simulations and the impulse response must be due to inaccuracies in the measurements rather than the modeling.

As to the the geometrical model, it is well know that its finite spatial resolution limits the bandwidth of the resulting lumped-element circuit model (in the present case, it has an upper limit frequency of some 200–300 kHz). Also, no attempt has been made here to include the effect of measurement cables in the geometrical model. As a consequence, the time domain simulation does not display the transient oscillation in the MHz range during the first 10 µs (Fig. 4b). In the frequency domain plot of the transfer function amplitude, this is represented by a much lower amplitude around 1 MHz than for both the impulse measurement and the SoFT results. Furthermore, lower-lying resonances do not precisely coincide in frequency with the measured ones, which leads to a phase shift relative to the measured curve of the slow oscillations at later times (Fig. 4a).

VII. Conclusions

This paper describes the first high-frequency transformer modeling evaluation performed in an industrial setting. Previous evaluations have never included both theoretical and measurement-based models of transformers for the high frequencies which are relevant in lightning studies.

The main results of the study are:

1. The overall qualitative behavior of both terminal model (SoFT) and detailed geometrical model is similar to the results from impulse measurements, and both give much more realistic results than a simple standard transformer model.
2. The quantitative agreement of the SoFT simulations with the measurements is clearly better than that of the geometrical model, which was of course expected since no empirical information about the tested transformer is used in the geometrical modeling procedure (only a general empirical damping function).
3. The standard transformer model is not applicable for high frequency simulations. This was also expected since is does not include any resonant branches.

The SoFT model can be directly included in EMTP-RV simulations via the state space block and used in general purpose network simulations.

VIII. Acknowledgement

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X. Biographies

Martin Tiberg holds a Bachelor of Science in Mathematics and in Physics in 2001 from Massachusetts Institute of Technology in Boston, USA. Master of Science in Engineering Physics in 2002 from Royal Institute of Technology in Stockholm, Sweden. From 2002 he has worked at ABB as enterprise-wide technology consultant for ten business units, as project leader, and as product manager for the SoFT technology as described in this paper. He is the author of nine invention disclosures and four patents

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Peter Werle studied Electrical Engineering at the University of Hannover, where he received his PhD at the Schering-Institute for High Voltage Technique and Engineering. Since 2003 he is with ABB AG, Transformers in Halle, Germany, where he is responsible for the departments condition assessment, quality management and high voltage testing. He is member of VDE, IEEE, DKE K 182 insulation liquids and IEC JWG 32 condition assessment derived from oil analysis.