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Measurements for validation of manufacturer's white-box transformer models

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Abstract

The transformer manufacturers make use of electromagnetic transient calculations by detailed white-box models to ensure that the transformer will withstand the lightning impulse test during the factory acceptance test. In principle, such models could be used in general electromagnetic transient simulation of overvoltages in the system. One of the objectives of CIGRE JWG A2/C4.52 is to assess the accuracy of the manufacturer's white-box models in the context of general transient overvoltages that can occur in the system. As part of this activity, extensive measurements have been performed on two three-winding transformers: one three-phase unit and one single-phase unit. The measurements involved voltage transfer between external terminals and from external terminals to three points in the regulating winding. The measurements were performed with alternative points of voltage excitation, grounding conditions and alternative tap settings, giving 64 cases for each transformer. Some admittance measurements were also performed. This paper gives an overview of the measurements that were performed, the measurement procedure, and some initial results. The voltage transfer measurements were mostly performed in the frequency domain and transferred to the time domain via rational function approximation and recursive convolutions. That way, voltage transfer functions have been generated for well-defined excitations, e.g. the standard 1.2/50 μs voltage wave. In addition, initial results for black-box modeling of the three-phase unit is shown. The measurements are currently being used within CIGRE JWG A2/C4.52 for benchmarking of white-box models.

Keywords: Transformer; model; white-box, black-box; grey-box; measurement; overvoltages; electromagnetic transients

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1. Introduction

This paper is presented on behalf of CIGRE JWG A2/C4.52 "High-frequency transformer and reactor models for network studies". One of the pursued objectives of the JWG is to make the detailed white-box models [1]-[8] used by transformer manufacturers available for use in general electromagnetic transient simulations. This would permit calculation of the transient interaction between the transformer and the system, giving the overvoltages on the transformer terminals. In principle, overvoltages inside the transformer windings could be calculated as well. The need for such model is high since the currently applied high-frequency transformer models for system studies are primitive [2], often being just one or a few lumped capacitors whose values are in any case not well known.

As the white-box models are primarily targeted at calculating the voltage response due to the standard lightning impulse test voltage (1.2/50 µs), their accuracy for use in general transients studies remains to be clarified. It was already observed in a previous WG (JWG A2/C4.39) that the calculation programs by manufacturers give quite different results when applied to the same geometry [9]. One example of such comparison is given in Fig. 1 which shows the node-ground voltage at one internal point inside the transformer when a lightning impulse voltage is applied to an external terminal. It is clear that the simulation by the various contributors differ substantially regarding the frequency components and their damping. These deviations are particularly worrisome if the model is to be used in simulations involving resonant overvoltages as the natural frequencies must then be quite accurate to obtain reliable results.

In order to validate the various white-box models and their parameter determination, it is necessary to compare simulations against measurements on a complete transformer whose geometry is known in detail. Such combination of measurements and detailed geometry description has not been available. In A2/C4.52, WEG Transformers Mexico therefore offered to release the detailed design information of one three-phase unit and one single-phase-unit. Measurements of transient waveforms were performed by the WG on the two transformers to permit direct comparison between white-box simulations and measurements. This paper gives an overview of the measurements that were performed and the adopted measurement principles. The possible use of such measurements for modeling purposes is also discussed.

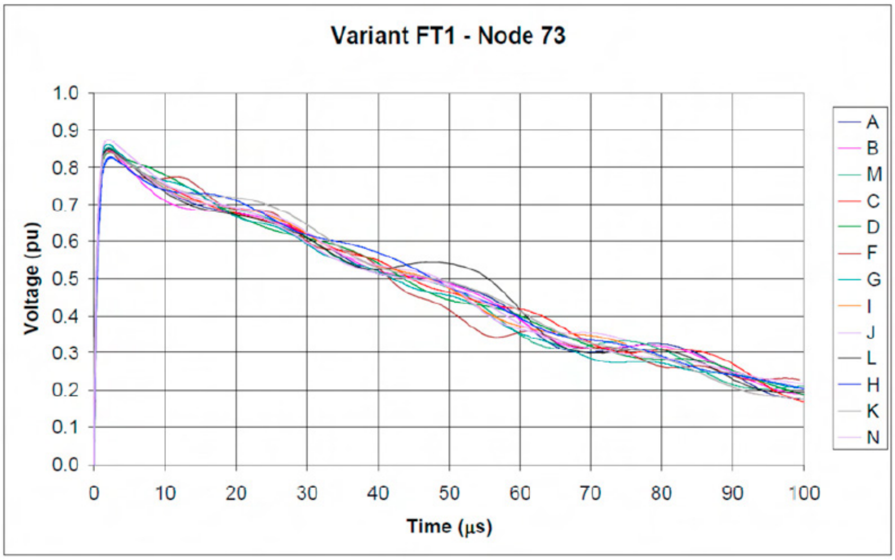

Fig. 1. Comparison of calculation results for the "Fictitious Transformer 1" [9].

2. Transformers

The three-phase unit is a 92/92/30.67 MVA three-winding transformer with rated voltages 115/34.5/13.8 kV at 60 Hz with internal connections shown in Fig. 2, left. The transformer is of variable induction, as the on-load tap changer (OLTC) is in the high voltage winding, to regulate the voltage in low voltage winding (+9/-11 Taps), with a total of 21 tap positions. The stabilization tertiary winding is connected in series with a reactor to limit the short circuit current.

The single-phase unit is a 50/50/16.67 MVA three-winding transformer with rated voltages 230/69/13.8 kV at 60 Hz with internal connections shown in Fig. 2, right. The on-load tap changer (OLTC) has 11 tap positions with reversible polarity, giving a total of 21 tap positions.

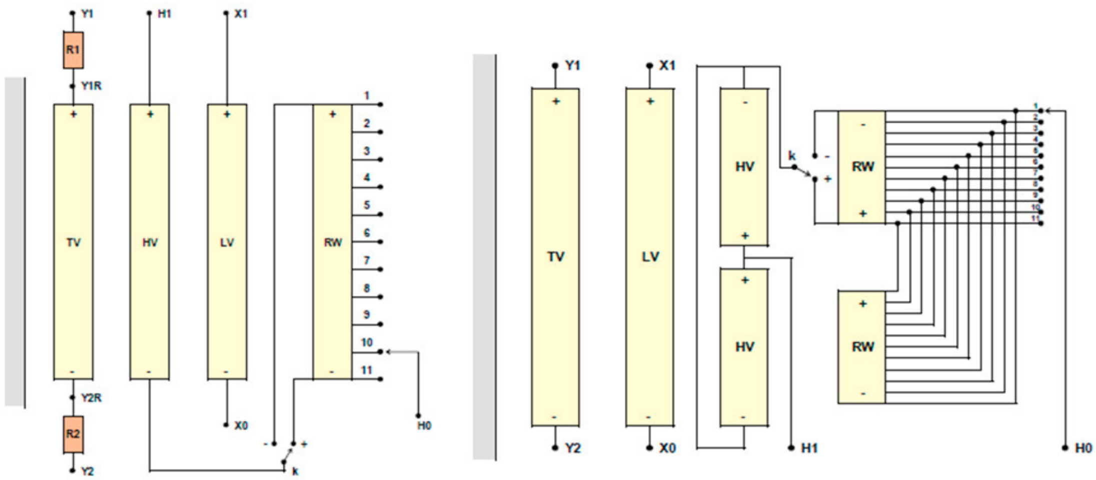

Fig. 2. Left: three-phase transformer (one leg of); Right: single-phase transformer.

3. Measurement setup

The measurements were performed with the transformer active parts inside the tank, but without oil and bushings. A flat braided wire was clamped to the tank rim and used as ground reference in the measurements. The winding terminals were brought to the rim and connected to suitable test fixtures which permitted easy grounding, connection of voltage probes, and connection of shielded cables for admittance measurements. In addition, unshielded cables were connected to three points in the regulating winding (extreme ends and close to mid-point) that were brought to the tank rim. The setup is shown in Fig. 3, in the case of voltage transfer measurements on the single-phase transformer. In the photo one can observe two voltage probes and the supplied voltage via a shielded cable.

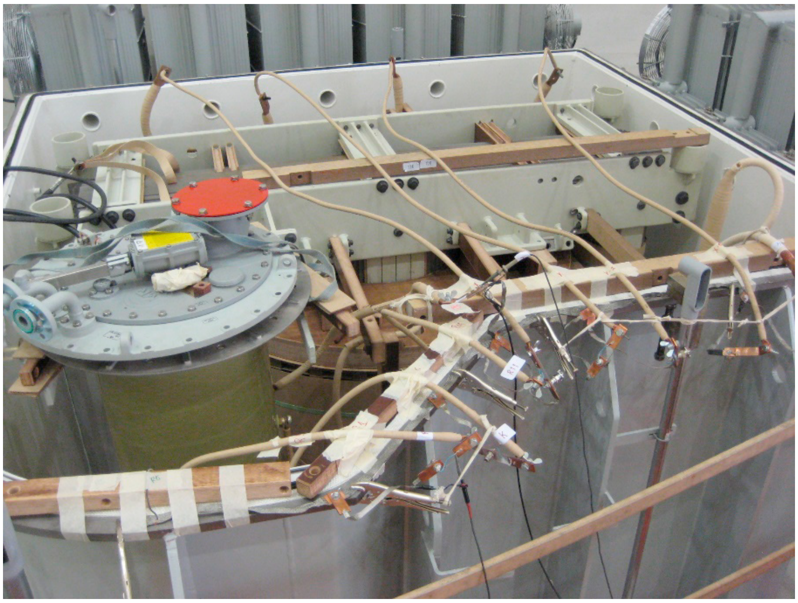

Fig. 3. Connections to single-phase transformer.

4. Measured quantities

4.1. Voltage transfer

With both units, a large set of measurements of node-ground voltages were performed, representing voltage transfer between external terminals. In addition, the voltage transfer from external terminals to three points (R1, R5, R11) inside the tap changer was measured. Fig. 4 shows in the first four rows the basic measurement cases. These four cases were performed with four alternative tap settings (Max, Nom+, Nom- and Min), and with the excitation in either H1, H0, X1 or X0, giving a total of 4×4×4=64 cases for each transformer. Y1R and Y2R denotes voltage on internal reactors terminals in the three-phase unit, see Fig. 2 (left).

Case	Tap	k	Moving	H1	H2	H3	H0	X1	X2	X3	X0	Y1	Y2	Y3	Measurements									
	Position	Connection	Contact H0												H1	H0	X1	X0	Y1	Y2	Y1R	Y2R	R1	R11
1	Max	+	R1	Applied	Grounded	Grounded	Grounded	Grounded	Grounded	Grounded	Grounded	Grounded	Grounded	Grounded	Yes						Yes	Yes	Yes	Yes
2	Max	+	R1	Applied	Open	Open	Grounded	Open	Open	Open	Grounded	Open	Open	Open	Yes		Yes		Yes	Yes	Yes	Yes	Yes	Yes
3	Max	+	R1	Applied	Grounded	Grounded	Grounded	Open	Grounded	Grounded	Grounded	Grounded	Grounded	Grounded	Yes		Yes				Yes	Yes	Yes	Yes
4	Max	+	R1	Applied	Grounded	Grounded	Grounded	Grounded	Grounded	Grounded	Grounded	Open	Open	Grounded	Yes				Yes	Yes	Yes	Yes	Yes	Yes
5	Nom+	+	R11	Applied	Grounded	Grounded	Grounded	Grounded	Grounded	Grounded	Grounded	Grounded	Grounded	Grounded	Yes						Yes	Yes	Yes	Yes
6	Nom+	+	R11	Applied	Open	Open	Grounded	Open	Open	Open	Grounded	Open	Open	Open	Yes		Yes		Yes	Yes	Yes	Yes	Yes	Yes

Fig. 4. Terminal conditions and measurements for three-phase transformer (six out of 64 cases).

Due to the large number of voltage transfer measurements, it was considered impractical to do the measurements in the time domain. It was foreseen that the voltage excitation would vary from case to case due to the difference in transformer input impedance at the excited terminals. It was therefore decided to perform the voltage transfer measurements in the frequency domain and afterwards calculate time domain voltage waveforms for alternative excitations using convolution. That way, the members in the WG could perform their calculations using a single (or a few), well-defined excitations that could be communicated by email. One relevant case of excitation is the standard lightning impulse wave. Another advantage of frequency domain measurements is small measurement files and a high signal-to-noise ratio.

The voltage transfer measurements were performed using two identical passive voltage probes in combination with a vector network analyzer (VNA).

- A coaxial cable was connected from the VNA output to the transformer terminal to be excited, with the shield grounded on the tank rim ground reference (in addition to the VNA ground).
- One voltage probe was connected from the VNA reference to the excited terminal, with the ground clip connected to the ground reference.
- The other voltage probe was connected from the VNA input to the terminal where the voltage response was to be measured, with the ground clip connected to the ground reference.

The VNA then performed a frequency sweep measurement of the input voltage divided by the reference voltage, directly giving the voltage transfer function.

In addition, a few time domain measurements with voltage step excitation were performed, for validation purposes.

4.2. Admittance

The admittance matrix with respect to the transformer's external terminals was measured in the frequency domain. These measurements provide additional validation for the white-box model, and they also serve as input for the black-box and grey-box modelling activities in the WG.

- In the case of three-phase transformer. The admittance matrix was measured with respect to the HV and LV terminals (six terminals), with the tertiary terminals left open (and ignored), and H0 and X0 grounded.
- In the case of the single-phase transformer, the measurements were performed with respect to all (four) external terminals (H1, X1, Y1, Y2) with H0 and X0 grounded. Due to the presence of the ungrounded tertiary, special measurements [10] were needed to achieve high accuracy at lower frequencies.

The admittance measurements were performed using a connection box which includes a wide-band current sensor and shielded cables between the connection box and the transformer external terminals, see Fig. 5.

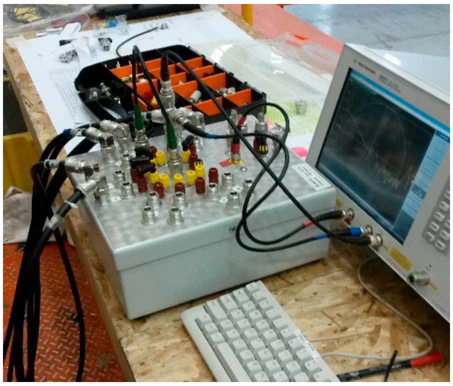

Fig. 5. Connection box and VNA used in admittance measurements (left), and connection to transformer using shielded cables (right).

5. Conversion of measurements from frequency domain to time domain

The frequency domain measurements were performed from 50 Hz to 10 MHz using K=601 logarithmically spaced samples. Each response $h(\omega)$ was fitted by a pole-residue type rational model (1) using the method of vector fitting [11]. The coefficients (a_i, r_i) are real or complex conjugate (causal function), and all poles (a_i) are in the left half-plane (stable).

The response $y(t)$ due to an excitation $u(t)$ can now be calculated as

$$h(\omega_k) \cong r_0 + \sum_{i=1}^{N} \frac{r_i}{j\omega_k - a_i} \quad , k = 1, \ldots, K \tag{1}$$

The impulse response (1) is in the time domain given as a sum of exponential functions,

$$h(t) = r_0 \delta(t) + \sum_{i=1}^{N} r_i e^{a_i t} \tag{2}$$

The response $y(t)$ due to an excitation $u(t)$ can now be calculated as

$$y(t) = h(t) * u(t) \tag{3}$$

By discretizing the relation (3) with a fixed time step length Δt using the frame of recursive convolution [12], the response at a time point n can be calculated as

$$\mathbf{x}_n = \boldsymbol{\alpha} \mathbf{x}_{n-1} + \boldsymbol{\beta} u_n \tag{4a}$$

$$y_n = \mathbf{c}^T \mathbf{x}_n + \gamma u_n \tag{4b}$$

where $\boldsymbol{x}_n$ is a state vector of length N. $\boldsymbol{\alpha}$ is a diagonal matrix, $\boldsymbol{\beta}$ is a column vector and $\mathbf{c}^{\mathrm{T}}$ is a row-vector. The details of the determination of coefficients in (4) are given in [13].

As an example we consider measurement Case 1 for the three-phase transformer.

- Fig. 6 shows with blue trace the measured voltage transfer from H1 to internal point R11. The dashed red trace shows the calculated rational function approximation (1).
- Fig. 7 shows a direct time domain measurement of the voltage response on R11 when a step voltage is applied to H1. The applied voltage is next applied to the model (1) in Fig. 6 and the response is calculated by convolution (3). The result by the convolution (dashed red trace) is seen to closely resemble the measured result.

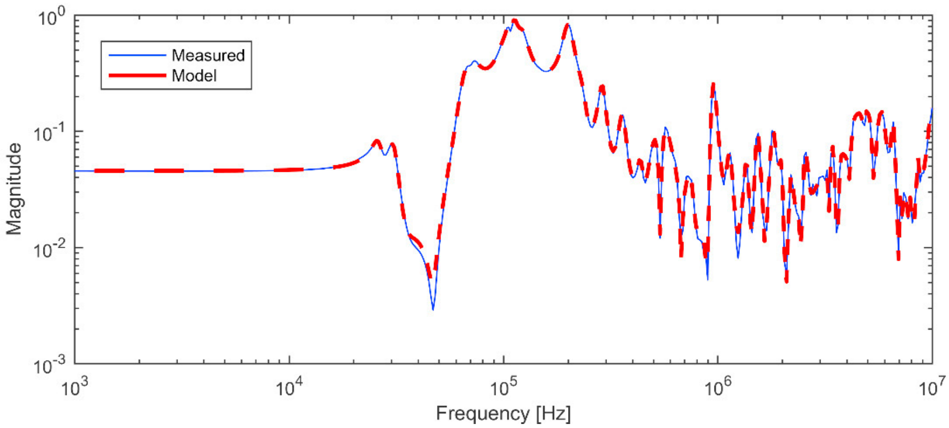

Fig. 6. Measured voltage transfer function and its rational approximation.

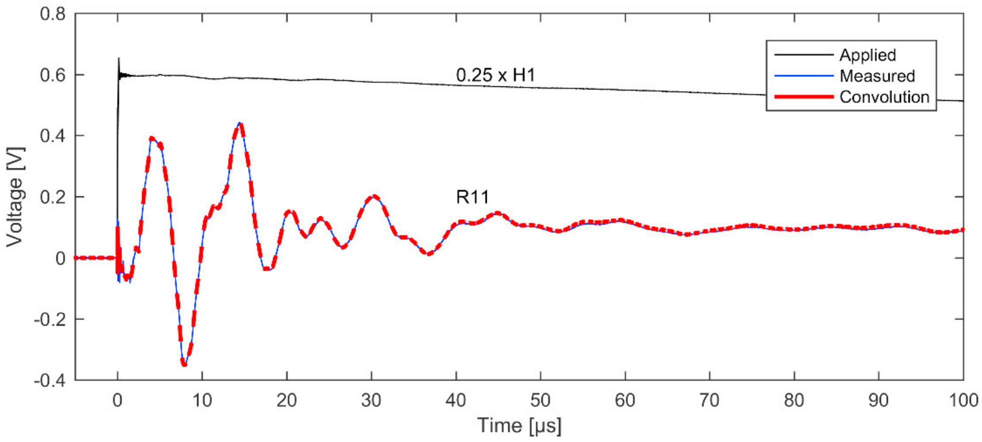

Fig. 7. Convolution: validating the rational approximation against direct time domain measurement.

Using the model together with convolution, the transient waveforms can now be generated for any shape of the applied voltage. For instance, Fig. 8 shows the voltage response when a chopped lightning wave is applied to H1.

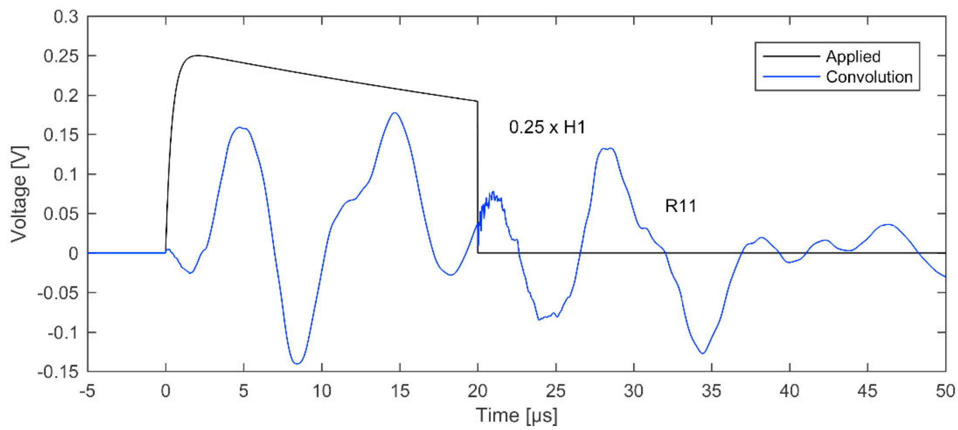

Fig. 8. Calculated voltage response on R11 due to a chopped voltage application on H1.

6. Spot checking using white-box model

A white-box model was created in advance and used for generating time domain voltage waveforms for each of the measurement cases. Spot checks against the calculated waveforms were performed during the measurements as a safety measure against incorrect connections. Fig. 9 shows a result for Case 1 of the three-phase transformer: R11 (regulating winding end point) and Y1R, Y2R (voltage on internal reactors in tertiary winding). It is remarked that the white-box model was created without care for high accuracy as its purpose was only to check for obvious errors in the measurements.

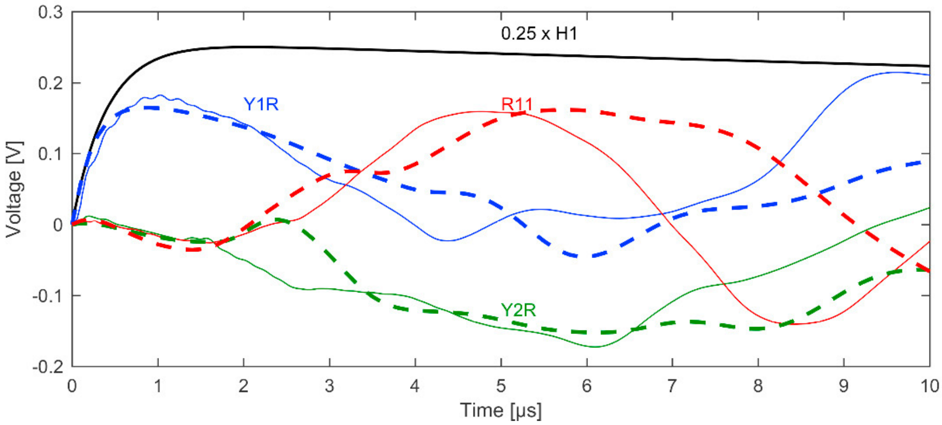

Fig. 9. Checking result against a white-box model. Solid traces: convolution; dashed traces: White-box model simulation.

7. Application of voltage transfer measurements in JWG A2/C4.52

From the detailed design information provided by WEG, WG members (including manufacturers) have independently created white-box models of the two transformers using their own calculation program. Using their models, WG members have calculated time domain voltage responses for the 64 cases when applying an ideal voltage source corresponding to the 1.2/50 μs standard test voltage (5) with k=1.0383, a=0.015·10^6, b=2.47·10^6.

$$U_0(t) = k(e^{-at} - e^{-bt}) \tag{5}$$

The calculated results by WG members have been collected and compared against the responses obtained via frequency-domain measurement and subsequent convolution. An analysis is ongoing, trying to explain deviations, improve models, and clarify limitations.

8. Admittance measurements

In addition to white-box modeling activities, JWG A2/C4.52 is involved in black-box modeling [14]-[21] and grey-box modeling [22]-[25]. These activities also require terminal admittance measurements as input. Terminal measurements were accordingly performed on both transformers, but only in a single tap position. The admittance measurements define the relation between terminal voltage and terminal admittance by the admittance matrix **Y**(ω),

$$\mathbf{i}(\omega) = \mathbf{Y}(\omega)\mathbf{v}(\omega) \tag{6}$$

Using the setup in Fig. 5, the elements of the admittance matrix were measured one-by-one.

- Three-phase transformer: The admittance matrix was measured with respect to all external terminals of the HV and LV winding, with H0 and X0 grounded, and Y1, Y2 and Y3 left unconnected. This gives a 6×6 **Y**.
- Single-phase transformer: The admittance matrix was measured with respect to all four external terminals with H0 and X0 grounded, giving a 4×4 **Y**.

The measurements involved 401 logarithmically spaced frequency samples from 5 Hz to 10 MHz. The effect of the 3-m measurement cables (coaxial cables) observed in Fig. 5 were eliminated from the admittance matrix using the transmission line method in [26]. The admittance matrix elements were subjected to rational fitting with a pole-residue model (7) which was refined by enforcement of passivity [27], thereby giving a model which is guaranteed stable in a time domain simulation.

$$\mathbf{Y}(\omega_k) \cong \mathbf{Y}_0 + \sum_{i=1}^{N} \frac{\mathbf{R}_i}{j\omega_k - a_i} \quad , k = 1, \ldots, K \tag{7}$$

Fig. 10 shows the 36 elements of the admittance matrix elements for the three-phase transformer (solid blue traces) together with the admittance elements of the rational model (dashed red traces). The agreement between model and measurement is seen to be excellent.

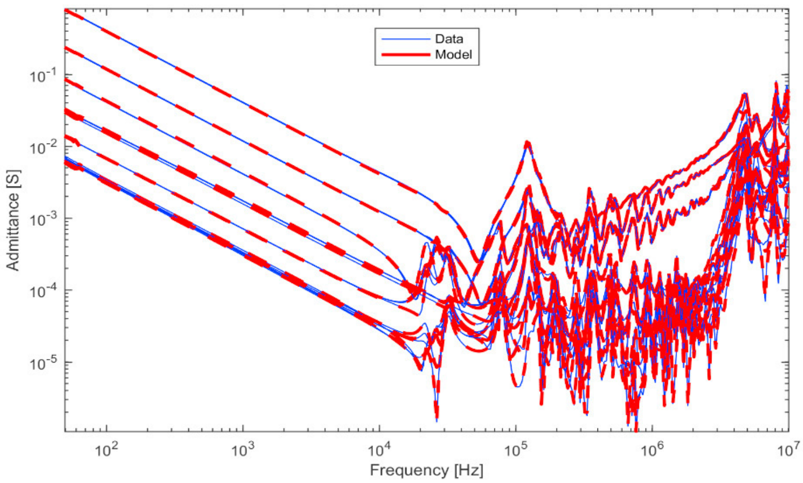

Fig. 10. Admittance matrix elements of measured (blue) and of rational model (dashed red) of three-phase transformer.

It is well known that admittance-based models can be prone to error magnification in applications with high-impedance terminations. To check for this possibility, the obtained model accuracy was assessed in the time domain against voltage transfer measurements by the convolution-based method. Fig. 11 shows the simulated voltage on X1 when applying the voltage on H1 with all other terminals (H2, H3, X1, X2 and X3) open-circuited. It is observed that a quite accurate result has been achieved. Results from black-box modeling of the single-phase transformer are described in detail in [10].

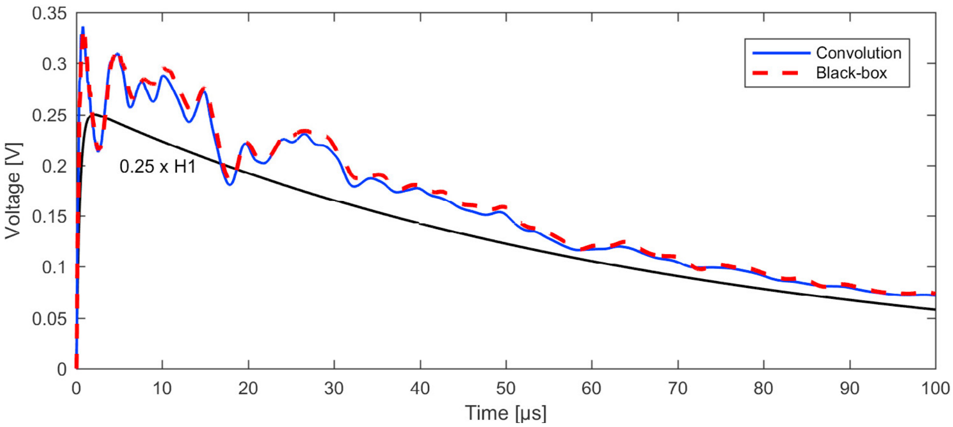

Fig. 11. Checking simulation by black-box model against convolution-based voltage transfer measurement.

9. Discussion

The approach of frequency sweep measurements (Chap. 4) with conversion to time domain measurements by recursive convolution (Chap. 5) was utilized for creating voltage responses that are associated with "clean" excitations, in this case the lightning impulse voltage. Additionally, the approach gives voltage responses that have a very low noise level compared to direct time domain measurements. In principle, the approach can be extended to give an EMTP compatible simulation model for use in general transient simulations, as shown in [10]. It is then necessary to perform the voltage transfer measurements from all external terminals (one-by-one) to the relevant internal nodes, with the non-excited terminals grounded. This defines a MIMO voltage transfer block which gives the voltage on internal nodes by superposition. The input voltages for the transfer block (external terminal voltages) can be obtained by inserting an admittance-based model (Chap. 8) into the EMTP-simulation. Although such approach is feasible and can give very accurate results, it can only provide the transient waveforms at accessible points inside the transformer (tap changer) and not in the insulated parts as invasive measurements are usually not acceptable. One can however also utilize these concepts for making a white-box model compatible with EMTP simulation [28]. From the white-box model, one calculates the admittance matrix with respect to external terminals as function of frequency as well as the voltage transfer function block from external to internal terminals. These two matrices are fitted with rational functions, defining state-space models that can be included in EMTP-type simulation programs for use in general simulations where the transformer is embedded in a power system.

10. Conclusions

CIGRE JWG A2/C4.52 aims at making available wide-band transformer models for use in transient simulation of overvoltages in the system. As part of this work, the WG is comparing simulations by white-, black-, and grey box models against measurements, for two transformers whose design information is available to the group members.

- With both transformers, frequency sweep voltage transfer measurements were performed with alternative points of excitation, terminal grounding, and tap setting. This resulted in a total of 64 cases where each case involved several measurements, including terminal voltages and the voltage on three internal points in the regulating winding. The measurement procedure involved a Vector Network Analyzer (VNA) and voltage probes. The frequency responses were fitted with rational functions, and time domain responses were obtained using convolution between the rational model and a chosen voltage excitation (1.2/50 µs voltage). The resulting voltage waveforms are being used by WG members for white-box model validation.

- Additional measurements of terminal admittance was performed for the two transformers, for the purpose of black-box and grey-box modeling. The admittance measurements are sufficiently accurate for obtaining a rational function-based terminal equivalent of the two transformers.

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