High-Frequency Model of the Power Transformer Based on Frequency-Response Measurements

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***Abstract*—In this paper, a new high-frequency black-box model of the power transformer is presented for the calculation of transferred lightning overvoltages. The model is based on frequency-response analysis measurements and the application of four-terminal network theory. The computational verification of the presented model was successfully performed on a white-box transformer model in Electromagnetic Transients Program-Restructured Version software. The experimental verification was carried out on 130-kVA and 36-MVA three-phase power transformers. The presented calculation and measurement results confirm the validity of the proposed model for full and chopped lightning impulse voltages.**

***Index Terms*—Fast Fourier transform (FFT), four-terminal network, frequency-response measurements, high-frequency transformer model, transfer function, transferred lightning overvoltages.**

I. Introduction

LIGHTNING overvoltages propagating along transmission lines and entering substations are transferred from the high-voltage (HV) winding of the power transformer to the low-voltage (LV) winding and vice-versa by inductive and capacitive coupling. The capacitive transfer depends on the surge capacitance and increases with the rate of rise of the applied overvoltage. The inductive transfer of the overvoltage depends on the flow of surge current in the HV winding and it is less sensitive to the rate of rise of the applied voltage [1].

Transferred overvoltages can endanger winding insulation or the insulation of equipment in a substation. Transferred lightning overvoltages may be particularly harmful for generator step-up transformers which have a large voltage ratio and transformers with an LV tertiary winding [2]–[4].

So far, extensive research has been performed regarding the investigation of high-frequency transients in power transformers. High-frequency transformer models for the calculation of internal overvoltages that occur inside windings are described in [5]–[7]. Lumped and distributed parameter transformer models have been used for the analysis of transferred overvoltages [8]–[16]. It is shown that the lumped parameter model can give adequate results for fast transients (up to 1 MHz). However, for very fast transients (above 1 MHz), a distributed-parameter model provides better results.

In [17]–[19] it is shown that a transformer can be modeled by considering turns as conductors of a multiconductor transmission line while lightning overvoltages transferred through distribution transformers are investigated in [20]–[22]. The analysis of transferred overvoltages can be of importance at the design stage of winding insulation for the determination of dielectric stresses and selection of the appropriate overvoltage protection. Therefore, a high-frequency power transformer model for accurate calculation of lightning overvoltages transferred through the power transformer is preferred. The electromagnetic-field approach [23], [24], based on the finite-element method (FEM), is used to establish the elementary parameters of a lumped parameter transformer model. This approach requires constructional details of the transformer and is, in general, complex and highly case dependent. An important issue in the parameter determination for high-frequency transformer models used for the calculation of internal overvoltages is that they require very detailed information of the transformer geometrical configuration [25] which is only available to manufacturers. However, if overvoltages generated within the windings are not required and only external overvoltages are of interest, parameters can be obtained from transformer terminal measurements.

For the calculation of external transferred overvoltages, black-box-type models are usually suitable since they do not require information about the transformer geometry and because they can reproduce the transformer terminal behavior. Therefore, a transient interaction between the transformer and the network can be analyzed. A transformer model based on the measured admittance matrix of the transformer is described in [26]–[29]. In this way, a general representation of the transformer in a wide frequency range can be done by applying vector fitting [30]. In [31], an accurate and simplified high-frequency model of the distribution transformer under lightning strokes is presented, which is based on experimental frequency-response analysis (FRA) measurements.

This paper presents a new high-frequency transformer model for the calculation of lightning overvoltages transferred through power transformers. The main advantage of the model is its simplicity and the fact that it can be derived from widely used FRA measurements.

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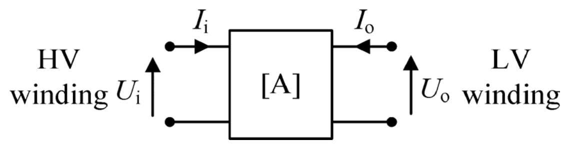

Fig. 1. Four-terminal network.

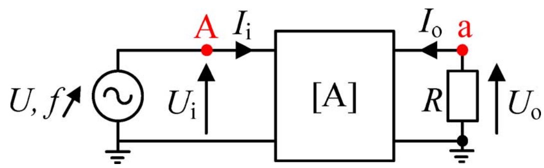

Fig. 2. FRA measurement between input and output terminals.

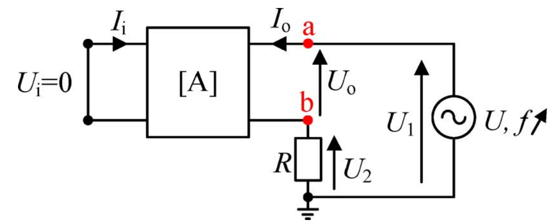

Fig. 3. FRA measurement between output terminals while input terminals are short-circuited.

II. High-Frequency Transformer Model

A. Model Description

In order to calculate the transferred overvoltages, the transfer function of the four-terminal network has to be determined. In the presented approach, the input voltage is expressed as a sum of sine and cosine functions of varying frequency and the frequency-dependent network transfer function is formed from the FRA results. The transferred overvoltage is calculated as a sum of products of input voltage and transfer function for each frequency. FRA is widely used in the industry today, mainly to detect winding displacements after overcurrents and inter-turn winding faults [32]. Therefore, it is highly convenient to apply FRA results for high-frequency modeling of power transformers.

B. Determination of the Transfer Function From FRA Results

Commercially available frequency-response analyzers measure input voltage and output voltage with an output terminal grounded through the matching resistor. The ratio of output voltage and matching resistance gives output current, and the ratio of input voltage and output current gives transfer impedance. So the ransfer function cannot be determined from a single measurement. However, it can be obtained from the results of two independent measurements. Fig. 1 shows a part of a transformer represented by a four-terminal network. Input voltage U_i is applied to the HV winding and output voltage U_o is transmitted to the LV winding.

The relationship between input and output voltage is defined by the transference matrix $\mathbf{A}(j\omega)$ as follows:

$$\begin{bmatrix} U_i \\ I_i \end{bmatrix} = \begin{bmatrix} A_{11}(j\omega) & A_{12}(j\omega) \\ A_{21}(j\omega) & A_{22}(j\omega) \end{bmatrix} \cdot \begin{bmatrix} U_o \\ I_o \end{bmatrix}. \tag{1}$$

When measuring the transferred overvoltages, only the measuring system is connected to output terminals. This approximately corresponds to the no-load condition and, therefore, $I_o \approx 0$. Then, from (1), the voltage transfer function (2) is calculated

$$H(j\omega) = \frac{U_o(j\omega)}{U_i(j\omega)} = \frac{1}{A_{11}(j\omega)}. \tag{2}$$

$H(j\omega)$ can be determined from the results of two FRA measurements. In the first measurement shown in Fig. 2, frequency response is measured between the input terminal "A" to which the voltage U_i of variable frequency is applied and the output terminal "a" grounded through the matching resistor R.

The output current is calculated as

$$I_o(j\omega) = -\frac{U_o(j\omega)}{R}. \tag{3}$$

U_i is derived from (1):

$$U_i(j\omega) = A_{11}(j\omega)U_o(j\omega) - A_{12}(j\omega)\frac{U_o(j\omega)}{R}. \tag{4}$$

The ratio of output and input voltage for this case is

$$H_1(j\omega) = \frac{U_o(j\omega)}{U_i(j\omega)} = \frac{R}{R \cdot A_{11}(j\omega) - A_{12}(j\omega)}. \tag{5}$$

Ratio $H_1(j\omega)$ can be measured with frequency-response analyzers and the result is given in a form of magnitude A and phase angle Θ

$$A(dB) = 20\log|H_1(j\omega)|, \tag{6}$$
$$\Theta = \tan^{-1}(H_1(j\omega)). \tag{7}$$

$H_1(j\omega)$ can be derived from (6) and (7) as

$$|H_1(j\omega)| = 10^{A/20}, \tag{8}$$
$$angle\ (H_1(j\omega)) = \Theta. \tag{9}$$

In the second measurement shown in Fig. 3, the FRA is measured between the output terminals "a-b" while the input terminals are short-circuited.

Expressions for the output voltage (10) and current (11) are derived from (1) for $U_i = 0$

$$U_o(j\omega) = \frac{-A_{12}(j\omega)}{A_{11}(j\omega)A_{22}(j\omega) - A_{12}(j\omega)A_{21}(j\omega)} I_i(j\omega) \tag{10}$$
$$I_o(j\omega) = \frac{A_{11}(j\omega)}{A_{11}(j\omega)A_{22}(j\omega) - A_{12}(j\omega)A_{21}(j\omega)} I_i(j\omega). \tag{11}$$

The ratio of the output voltage and current gives the short-circuit impedance $Z_{SCI}(j\omega)$

$$Z_{SCI}(j\omega) = \frac{U_o(j\omega)}{I_o(j\omega)} = -\frac{A_{12}(j\omega)}{A_{11}(j\omega)}. \tag{12}$$

$Z_{SCI}(j\omega)$ is the impedance between terminals "a-b" and can also be expressed as

$$Z_{SCI}(j\omega) = R \cdot \frac{U_1(j\omega) - U_2(j\omega)}{U_2(j\omega)} = R \cdot \left(\frac{1}{H_2(j\omega)} - 1\right) \tag{13}$$

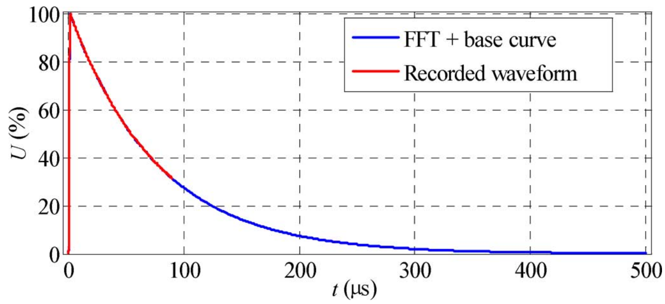

Fig. 4. Recorded lightning waveform approximated by FFT up to 90 μs and extended with the base curve to its complete attenuation.

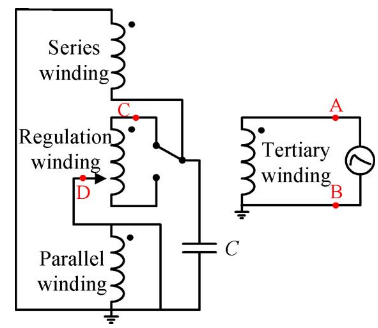

Fig. 5. Autotransformer representation for the lightning impulse test.

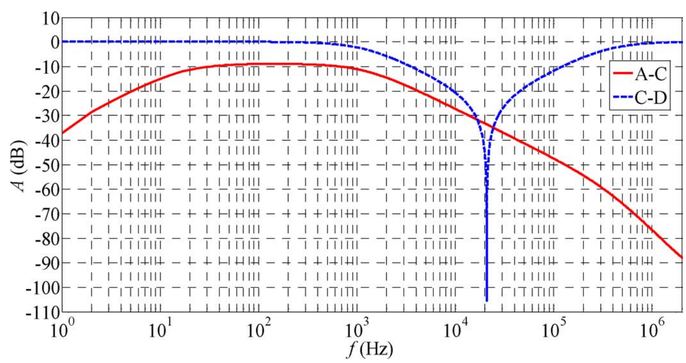

Fig. 6. Frequency response between terminals "A-C" and "C-D".

where $H_2(j\omega)$ is equal to ratio $U_2(j\omega)/U_1(j\omega)$ and can be derived from FRA results in the same way as $H_1(j\omega)$ (8)-(9). Substituting $A_{12}(j\omega)$ in (5) with (12) gives

$$H_1(j\omega) = \frac{R}{R \cdot A_{11}(j\omega) + Z_{SCI}(j\omega) \cdot A_{11}(j\omega)}. \tag{14}$$

Transfer function is determined by (14)

$$H(j\omega) = \frac{1}{A_{11}(j\omega)} = \frac{(R + Z_{SCI}(j\omega)) \cdot H_1(j\omega)}{R}. \tag{15}$$

Finally, substituting $Z_{SCI}(j\omega)$ in (15) with (13) gives

$$H(j\omega) = \frac{H_1(j\omega)}{H_2(j\omega)}. \tag{16}$$

C. Approximation of Input Lightning Impulse Voltage and Calculation of Output Voltage

The input lightning impulse voltage waveform $U_i(t)$ can be expressed as a sum of sine and cosine functions of varying frequency

$$U_i(t) = \sum_{k=1}^{M} (a_k \cos(kf_0t) + b_k \sin(kf_0t)) \tag{17}$$

where M is the total number of harmonics considered; f_0 is the fundamental frequency; and a_k, b_k are coefficients of the Fourier series computed using the MATLAB built-in fast Fourier transform (FFT) function.

The lighting impulse voltage waveform is usually recorded up to around 100 μs and during this period, voltage does not decay to zero value. If a waveform of such duration is expressed by Fourier series, an error in approximation is introduced, and the frequency of the first harmonic is relatively high. As a consequence, errors are introduced in the calculation of transferred overvoltages. Therefore, the recorded lightning impulse waveform is approximated by the corresponding function and extended until it decays nearly to zero value.

Lightning impulse voltage is approximated from the last recorded point to its almost complete attenuation with the base curve whose construction is given in [33]. Fig. 4 shows an example of recorded waveform and its approximation. This approach gives a very accurate approximation of input voltage even for waveforms with strong superimposed oscillations or chopped lightning-impulse voltages.

After the impulse voltage $U_i(t)$ is approximated and the transfer function $H(j\omega)$ is determined, the transferred overvoltage $U_o(t)$ can be calculated

$$U_o(t) = \sum_{k=1}^{M} |H_k| \cdot (a_k \cos(kf_0t + \Theta_k) + b_k \sin(kf_0t + \Theta_k)) \tag{18}$$

where H_k is the amplitude and Θ_k is the angle of transfer function kth harmonic.

III. Comparison with EMTP-RV White-Box Model

The purpose of this section is to check the proposed approach in controlled conditions. Prior to the experiment on a real transformer, the calculation of the transferred overvoltage was carried out on a single-phase model of a three-phase autotransformer 250 MVA, 400/231/22 kV. The model consists of series winding, parallel winding, regulation winding, and tertiary winding. The parameters shown in the Appendix for a simplified Electromagnetic Transients Program-Restructured Version (EMTP-RV) model were provided by the manufacturer. The transferred overvoltage across the regulation winding during the lightning impulse test is analyzed. Voltage is applied on the tertiary winding while the HV and medium-voltage (MV) terminals are grounded (Fig. 5).

The autotransformer is represented by a four-terminal network ABCD according to the previously described procedure. The lightning impulse voltage 1.2/50 μs, a double exponential function in EMTP-RV, is applied between input terminals "A-B", and the transferred voltage is calculated at output terminals "C-D". Then, frequency response is calculated (using the frequency scan option in EMTP-RV; $f_{\min} = f_0 = 1$ Hz,

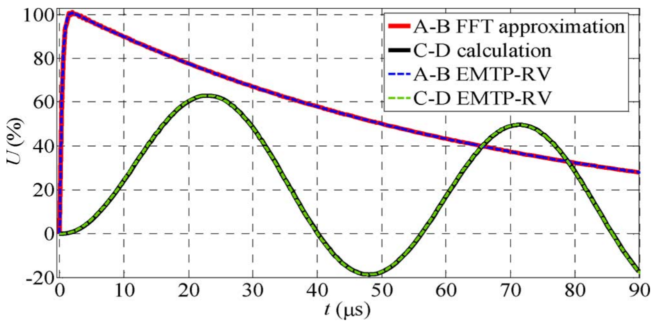

Fig. 7. Comparison between the results of the proposed model and EMTP-RV.

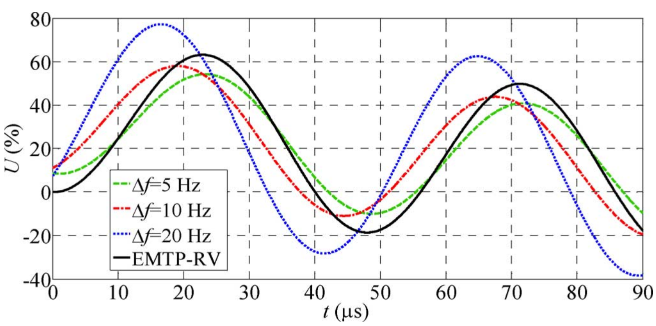

Fig. 8. Influence of Δf on the calculated transferred overvoltage at terminals "C-D".

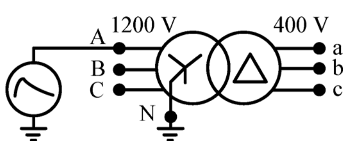

Fig. 9. Test circuit for the measurement of the transferred overvoltages in case of the Yd connection.

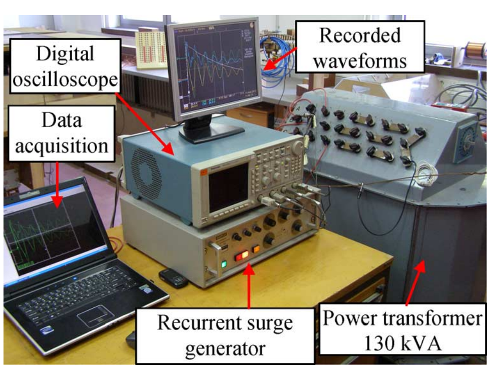

Fig. 10. Test setup for the measurement of transferred overvoltages.

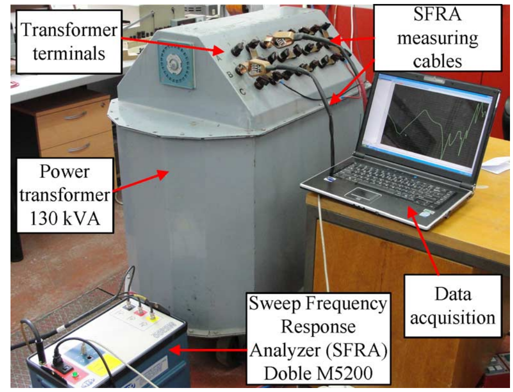

Fig. 11. Test setup for the FRA measurement.

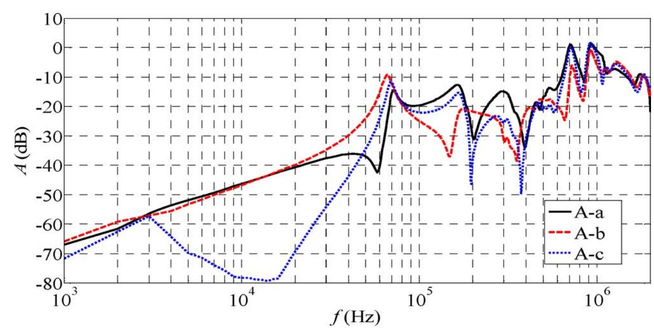

Fig. 12. Measured magnitude between terminals "A-a", "A-b", and "A-c" for the Yd connection.

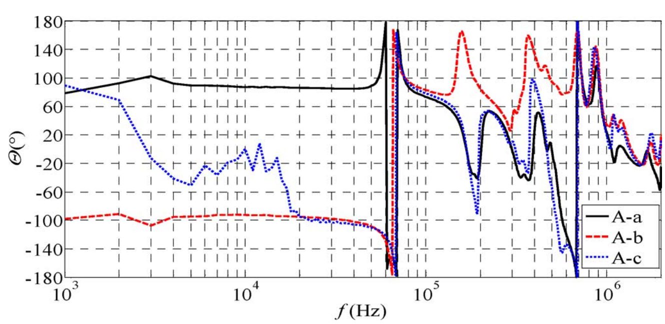

Fig. 13. Measured phase angle between terminals "A-a", "A-b", and "A-c" for the Yd connection.

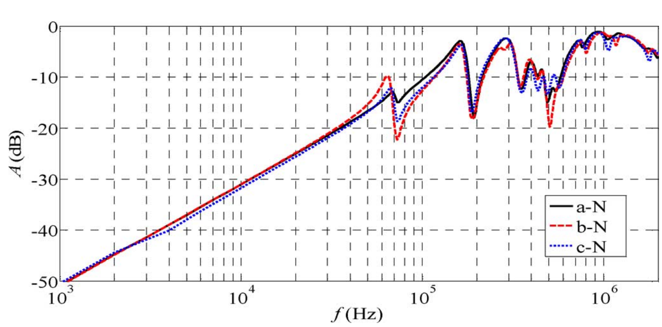

Fig. 14. Measured magnitude between terminals "a-N", "b-N", and "c-N" for the Yd connection.

$f_{\max} = 2$ MHz, frequency scan step $\Delta f = 1$ Hz) between terminals "A-C", voltage is applied on "A" while "C" is grounded through the 50-Ω resistor. Afterwards, the response between terminals "C-D" with "A-B" short-circuited is calculated, voltage is applied on "C", while "D" is grounded through the 50-Ω resistor (Fig. 6).

Results of the EMTP-RV simulation and the proposed model are given in Fig. 7 and show good agreement. EMTP simulation results are represented by dashed curves. The lightning impulse voltage is approximated by FFT (red curve), the transfer function is calculated from the results of frequency responses, and the transferred overvoltage (black curve) is calculated by (18).

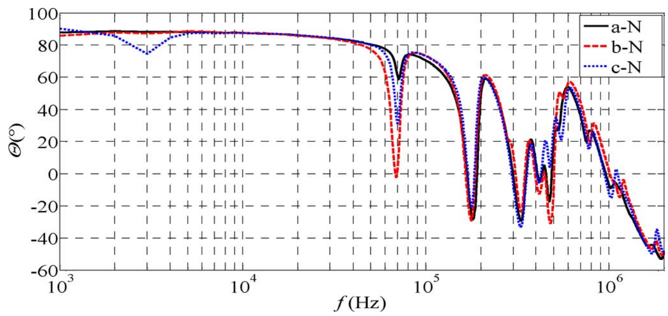

Fig. 15. Measured phase angle between terminals "a-N", "b-N", and "c-N" for the Yd connection.

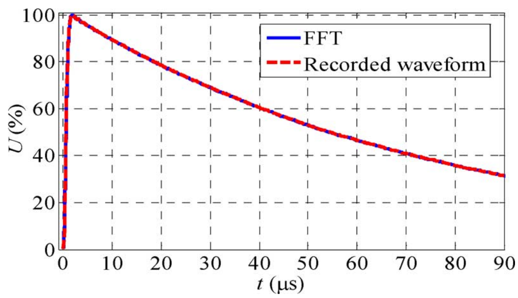

Fig. 16. Recorded full lightning impulse voltage approximated by FFT.

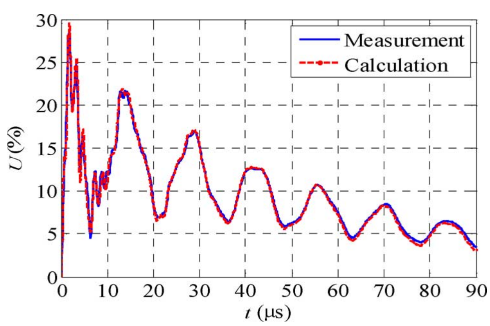

Fig. 17. Transferred overvoltage on terminal "a-N" when a full lightning impulse voltage is applied to terminal "A".

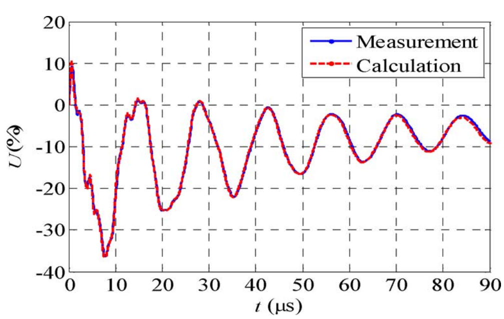

Fig. 18. Transferred overvoltage on terminal "b-N" when a full lightning impulse voltage is applied to terminal "A".

The accuracy of the proposed model depends on Δf and upper limit $f_{\max}$ frequency. For $f_{\max} = 2$ MHz, satisfactory approximation of lightning impulse voltage is achieved. In this case, the calculated transferred overvoltage is very sensitive to Δf as shown in Fig. 8.

Enlargement of Δf results in larger deviations from the accurate result. Influence of Δf is significant because the frequency response between terminals "C-D" changes rapidly at a very narrow frequency range around a resonant frequency of approximately 21 kHz (Fig. 6). Nevertheless, the calculation results for $\Delta f = 1$ Hz confirm that the proposed method gives accurate results for the simple transformer model shown in Fig. 5.

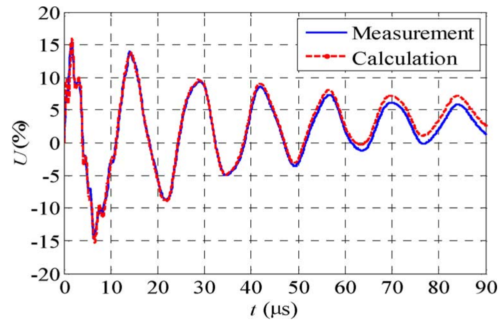

Fig. 19. Transferred overvoltage on terminal "c-N" when a full lightning impulse voltage is applied to terminal "A".

IV. Experimental Verification–Measurement and Calculation of Transferred Overvoltages

The experimental verification was carried out on a three-phase 130-kVA intermediate reconnectable power transformer. Measurements of FRA and transferred overvoltages were performed for YNd1 and YNyn0 transformer connections. Fig. 9 shows the test circuit arrangement for the measurement of transferred overvoltages in the case of the Yd connection. Full and chopped lightning impulse voltage with an amplitude of 300 V are applied on HV terminal "A" while transferred overvoltages are measured between the LV terminals "a", "b", "c" and neutral point "N".

A recurrent surge generator, a low-voltage single-stage equivalent of a high-voltage impulse generator, was used as a lightning impulse voltage generator. The impulse voltages were recorded using a digital oscilloscope (500 MHz, 1 GSamples/s) connected to a PC. Fig. 10 shows the test setup for the measurement of transferred overvoltages.

The transformer is observed as a four-terminal network with input terminals "A-N" and output terminals "a-N". In order to obtain the transfer function between "A-N" and "a-N", two frequency responses have to be measured. The first response is measured between terminals "A-a" while terminal "N" and transformer tank are grounded the same way as when measuring transferred overvoltages. The second response is measured between "a-N" with "A", "N" and the transformer tank short-circuited and grounded through a 50-Ω matching resistor.

Fig. 11 shows the test setup for the FRA measurement. FRA measurements were performed within the frequency band 1 kHz to 2 MHz, $\Delta f = 1$ kHz, by the Doble SFRA M5200 instrument. The accuracy guaranteed by the manufacturer for FRA measurement is $\pm$ 1 dB down to -80 dB. Figs. 12–15 show the measured magnitude and phase angle of the frequency response for the Yd connection.

Fig. 16 shows the recorded full lightning impulse waveform applied on HV terminal "A" and its FFT approximation.

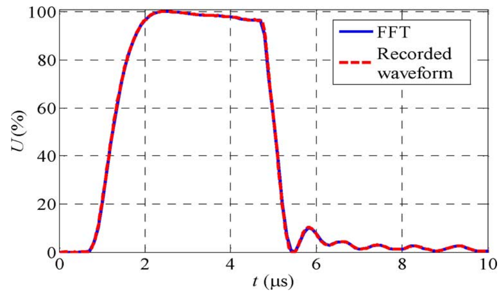

Fig. 20. Recorded chopped lightning impulse voltage approximated by FFT.

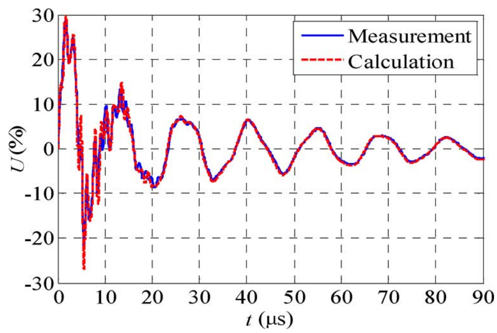

Fig. 21. Transferred overvoltage on terminal "a-N" when chopped lightning impulse voltage is applied to terminal "A".

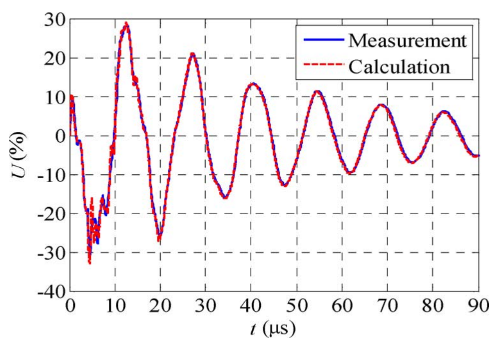

Fig. 22. Transferred overvoltage on terminal "b-N" when chopped lightning impulse voltage is applied to terminal "A".

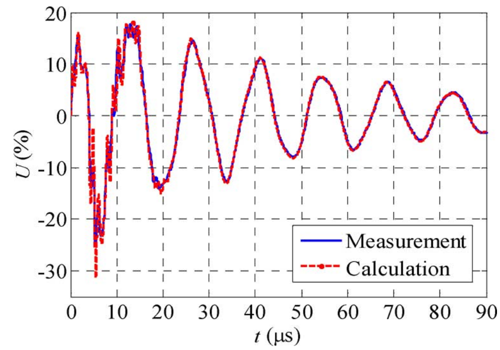

Fig. 23. Transferred overvoltage on terminal "c-N" when chopped lightning impulse voltage is applied to terminal "A".

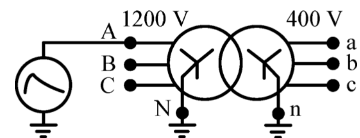

Fig. 24. Test circuit for the measurement of transferred overvoltages in case of the Yy connection.

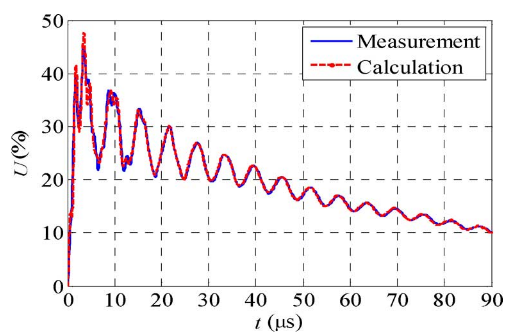

Fig. 25. Transferred overvoltage on terminal "a-n" when full lightning impulse voltage is applied to terminal "A".

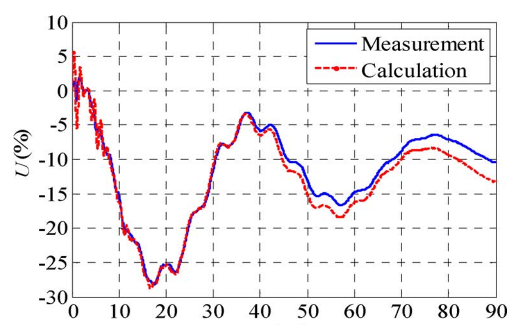

Fig. 26. Transferred overvoltage on terminal "b-n" when full lightning impulse voltage is applied to terminal "A".

Although not shown in Fig. 16, FFT approximation lasts up to 1 ms to match the FRA fundamental harmonic frequency of 1 kHz. Calculated transferred overvoltages are expressed as a percentage of input lightning impulse voltage amplitude (100% corresponds to an amplitude of 300 V). The comparison between measured and calculated transferred overvoltages on the LV side (Figs. 17–19) shows good agreement. Fig. 20 shows the recorded chopped lightning impulse waveform applied on HV terminal "A" and its FFT approximation. Figs. 21–23 confirm very good matching between the calculated and the measured transferred overvoltages. The similar analysis is performed in the case of the Yy connection. Fig. 24 shows the test circuit arrangement for the measurement of transferred overvoltages.

The comparison between measured and calculated transferred overvoltages on the LV side (Figs. 25–28) shows good agreement.

However, disagreements between measurements and calculation can be observed at lower frequencies in Figs. 19, 26, and 27. This is probably caused by high attenuation at lower frequencies (A less than -60 dB) as shown in Fig. 12.

Additional experimental verification was carried out on a three-phase power transformer 96.7/10 kV, 36 MVA, YNd11. Fig. 29 shows the test setup for the measurement of transferred overvoltages.

FRA measurements were performed within the frequency band 1 kHz to 2 MHz, $\Delta f = 1$ kHz. Figs. 30 and 31 show

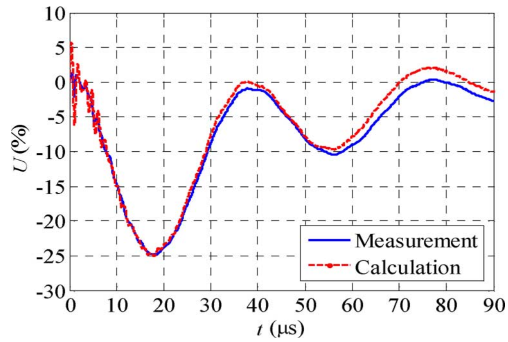

Fig. 27. Transferred overvoltage on terminal “c-n” when full lightning impulse voltage is applied to terminal “A”.

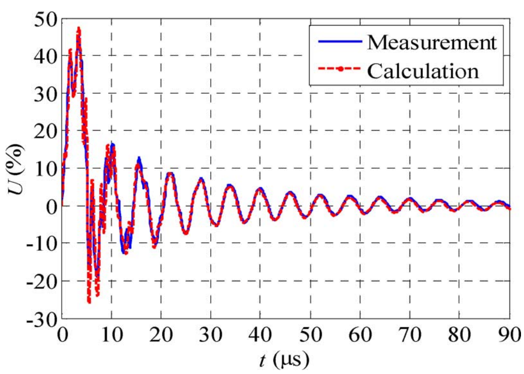

Fig. 28. Transferred overvoltage on terminal “a-n” when chopped lightning impulse voltage is applied to terminal “A”.

Fig. 29. Test setup for the measurement of transferred overvoltages.

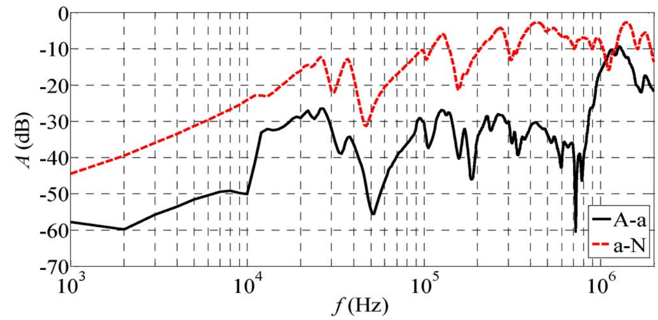

Fig. 30. Measured magnitude between terminals “A-a” and “a-N”.

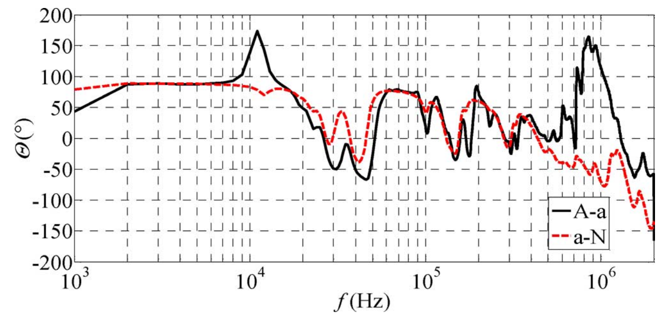

Fig. 31. Measured phase angle between terminals “A-a” and “a-N”.

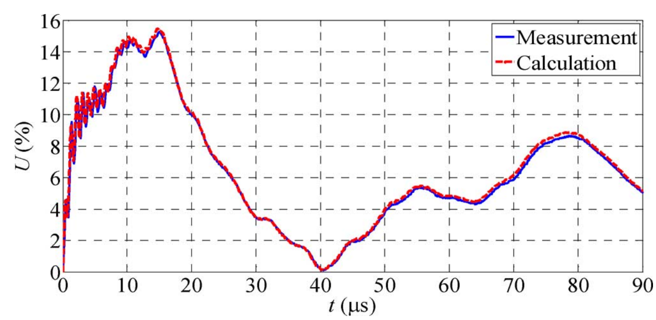

Fig. 32. Transferred overvoltage on terminal “a-N” when full lightning impulse voltage is applied to terminal “A”.

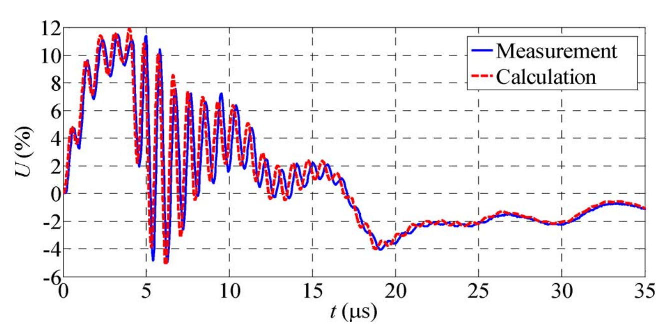

Fig. 33. Transferred overvoltage on terminal “a-N” when chopped lightning impulse voltage is applied to terminal “A”.

the measured magnitude and phase angle of the frequency response.

Both full (1.13/54 μs) and chopped ($T_c \approx 4\ \mu$s) lightning impulse waveforms were applied on HV terminal “A”. The calculated transferred overvoltages on LV terminal “a” are expressed as a percentage of input lightning impulse voltage amplitude (100% corresponds to an amplitude of 300 V). The comparison between measured and calculated transferred overvoltages on the LV side (Figs. 32 and 33) shows good agreement.

The choice of frequency band parameters $f_{\min} = 1$ kHz, $f_{\max} = 2$ MHz, $\Delta f = 1$ kHz is based on preliminary FRA measurements performed within the frequency band $f_{\min} = 100$ Hz, $f_{\max} = 6$ MHz, $\Delta f = 100$ Hz. Analysis showed that approximated impulse voltages and calculated transferred overvoltages change negligibly if Δf and $f_{\min}$ are increased to 1 kHz and $f_{\max}$ is decreased to 2 MHz. However, a more complex FRA response will probably require lower Δf, but it is unlikely that the upper limit frequency will increase significantly.

V. Conclusion

A new high-frequency black-box transformer model for the calculation of lightning overvoltages transferred through power transformers has been presented. The model is based on a frequency-dependent voltage transfer function which is determined from FRA measurements and the application of a four-terminal network theory. The transferred overvoltage is calculated from the voltage transfer function and FFT approximation of input lightning impulse voltage.

The computational verification of the presented model was successfully performed on a white-box model representing a single phase of a three-phase 250-MVA autotransformer. The results of the presented model and EMTP-RV simulations show good agreement. It is shown that the accuracy of the model depends on the frequency scan step and upper limit frequency. The experimental verification of the presented model was carried out on 130-kVA and 36-MVA three-phase power transformers. The comparison between the measured and calculated transferred overvoltages has demonstrated that the proposed model accurately reproduces the high-frequency voltage transfer between the windings when full or chopped lightning impulse voltage is applied. The main advantages and contributions of the presented model are:

- transferred overvoltages can be quickly and accurately calculated;
- its parameters are derived from FRA measurement results obtained with commonly used equipment;
- it is stand alone and does not require EMTP-like tools;
- it could be of interest for power utilities when calculating lightning overvoltages transferred through power transformers and performing insulation coordination studies, or to check the results of transferred overvoltage measurements;
- it could be used by transformer manufacturers to advise their clients about the level of surge-transferred overvoltages.

The presented model is assumed to be linear since its experimental verification was carried out at low voltage. Further research will focus on checking the model validity at HVs and upgrading it in order to be applicable to time-domain simulations.

Appendix

The self and mutual inductance matrix $\mathbf{L}$ of a three-phase 250-MVA, 400/231/22-kV autotransformer

$$L = \begin{bmatrix} 752.26 & 127.26 & 50.08 & 49.77 & 2.36 \\ 127.26 & 752.74 & 50.14 & 49.78 & 2.36 \\ 50.08 & 50.14 & 15.34 & 14.60 & 0.69 \\ 49.77 & 49.78 & 14.60 & 26.96 & 1.52 \\ 2.36 & 2.36 & 0.69 & 1.52 & 0.40 \end{bmatrix} \text{ mH.} \quad \text{(A1)}$$

Matrix elements represent: a series winding which consists of two windings connected in parallel (L_{11} and L_{22}), regulation winding L_{33}, parallel winding L_{44}, and tertiary winding L_{55}. Capacitance of the regulation winding to ground: $C = 8.87$ nF.

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