# External and Internal Overvoltages in a 100 MVA Transformer During High-Frequency Transients

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Abstract— This paper presents results from time domain transient simulations using a wide band black-box model of a 100 MVA transformer. Unlike in other studies, a modified transformer model is used which also allows investigating voltage transfers from external terminals to chosen nodes along the windings. The severity of voltage stresses on transformer's insulation is assessed using the Time Domain Severity Factor. Several cases of transformer energization from the HV side are presented with focus on transformercable interaction. It is shown that connecting a cable to the LV terminal reduces the maximum overvoltages due to cabletransformer resonance; however, the overvoltages in internal nodes can still exceed the winding's BIL level at external terminals.

*Keywords:* transformer, wide band model, EMTP, electromagnetic transients.

#### I. INTRODUCTION

High frequency interactions between transformer and the system can result in overvoltages of considerable magnitude not only at the terminals of a transformer, but also internally. In extreme cases, transformers can fail due to the resulting dielectric stresses.

Many studies can be found in literature investigating overvoltages at transformer terminals due to, e.g. excitation of transformer resonance by cable-transformer interaction [1-4]. Typically, a wide band linear terminal equivalent, or black-box model of a transformer, is used [5]. These models are often based on short circuit admittance measurements [6, 7], since suitable medium- and highfrequency models are in general not provided by manufacturers. Therefore, it is not possible to investigate internal overvoltages in a winding, e.g. caused by excitation of winding resonance frequency.

In this paper, we present the results of time domain transient simulations using a wide band black-box transformer model of a 100 MVA transformer. However, unlike other studies, here a modified transformer model [8] is used, which also allows investigating voltage transfers from external terminals to chosen nodes along the winding. Therefore, the paper presents investigations of both external and internal overvoltages due to cable-transformer interactions by means of time domain studies performed in an electromagnetic transient program, EMTP-RV [9]. Several case studies of cable energization and ground fault initiation are presented. Multi-run simulations are used to present dependency of magnitude of the resulting overvoltages on the cable's length.

#### II. TRANSFORMER MODEL

The investigated transformer is a three-phase two winding 100 MVA unit, consisting of three single-phase transformers connected in wye-delta. The technical data is shown in TABLE 1. In this work we consider only one of the single-phase units, see Fig. 1.

TABLE 1. TRANSFORMER DATA

Power	Vector	Voltage	Voltage	Ratio	BIL (IL)	BIL (IL)
[MVA]	group	HV [kV]	LV [kV]		HV [kV]	LV [kV]
100	YNd11	218.5	69	1.82	1050	325

The unit is a "fictitious transformer" designed within Cigré JWG A2-C4.39 for benchmarking of white-box modeling software, but it has not been constructed;



Fig. 1. Transformer with investigated connection points and internal nodes.

therefore the design is realistic but not optimized. low-voltage The (LV)winding is designed as a 'continuous disk' type while the high-voltage (HV)winding is of 'interleaved disk' type. Details of the transformer's construction are presented in [10].

This manufacturer's detailed white-box model was used to calculate a black-box terminal model, plus a transfer model for the voltage transfer from external nodes to a set of internal nodes [8]. The two external nodes are the

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high-voltage and low-voltage terminals, shown as nodes 47 and 70 in Fig. 1. The neutrals are assumed solidly grounded.

The voltage transfers are from the external nodes (47, 70) to selected internal nodes: 24, 58, 59, 68, 69, 72, 73, 82, 83.

The two models were established as follows [8]. Using the white-box model, as defined by its R, L, C, G matrices, the terminal admittance matrix  $\mathbf{Y}_{ext}$  was calculated as function of frequency. A rational model (1) was obtained by subjecting the admittance matrix to vector fitting and passivity enforcement. Using the white-box model, the voltage transfer matrix  $\mathbf{H}_{transfer}$  was calculated in the frequency domain and subjected to vector fitting, giving a rational model (2). Thus, the transformer becomes represented by two state-space models (1) and (2):

$$\mathbf{Y}_{ext}(s) = \mathbf{C}_{Y}(s\mathbf{I} - \mathbf{A}_{Y})^{-1}\mathbf{B}_{Y} + \mathbf{D}_{Y} + s\mathbf{E}_{Y}$$
(1)

$$\mathbf{H}_{transfer}(s) = \mathbf{C}_{H}(s\mathbf{I} - \mathbf{A}_{H})^{-1}\mathbf{B}_{H} + \mathbf{D}_{H} + s\mathbf{E}_{H}$$
(2)

Only  $\mathbf{Y}_{ext}$  needs to be subjected to passivity enforcement, since  $\mathbf{H}_{transfer}$  does not interact with the system.

The two models are interfaced with EMTP-RV using built-in standard modules, i.e. the model  $Y_{ext}$  (1) was incorporated using the *State-Space Equations* block, while the model  $H_{transfer}$  (2) was included using the *State-Space* block. In a simulation, the voltages at nodes 47 and 70 are used as input signals to the *State-Space* block, whose output signals represent voltages at investigated internal nodes. That way, the complete time-domain analysis is performed within the EMTP-RV software. This modeling approach allows the unique opportunity of assessing transformer's internal overvoltages during surges without having access to the manufacturer's full white model.

Fig. 2 shows the elements of  $2\times 2$  admittance matrix of the transformer model. The first anti-resonance is at approximately 10 kHz at the HV side and 22 kHz at the LV side, which are typical values for large transformers [11, 12]. The behavior of self-admittance of the HV winding at frequencies above the first resonance frequency is almost purely capacitive and dominated by winding's series capacitance.



Fig. 2. Elements of transformer's admittance matrix.  $Y_{47,47}$  and  $Y_{70,70}$  are self-admittance elements while  $Y_{47,70}$  and  $Y_{70,47}$  are mutual admittances.

# III. CHARACTERIZING TRANSFORMER VOLTAGE STRESSES USING SEVERITY FACTORS

The dielectric withstand capability of the transformer insulation system against transient overvoltages is verified using standardized tests, i.e. the lightning and switching impulse tests. These tests aim to ensure that a given transformer withstands lightning and/or switching impulses of specific shape and magnitude. In the case of the lightning impulse, this implies the standard voltage shape with front time of 1.2  $\mu s$  and time to half-value of 50  $\mu s$ .

Below, two factors are briefly described which allow to compare the insulation stresses resulting from an impinging overvoltage of arbitrary shape against that by the standard wave shapes.

#### A. Frequency Domain Severity Factor

Frequency Domain Severity Factor (FDSF) compares spectral energy density of a voltage waveform at transformer terminals during a given transient and during excitation with the standard wave shape:

$$FDSF = \frac{\left|\widehat{X}_{Transient}(j\omega)\right|^2}{\left|\widehat{X}_{test-wave}(j\omega)\right|^2}$$
(3)

In this way, the FDSF quantitatively describes how well a given transient phenomenon measured or simulated at a transformer's terminals is described by standard transformer tests. If FDSF is less than unity at all frequencies, the voltage stress during a surge is covered by the factory tests and as such should not constitute a danger to the transformer. It is remarked that the FDSF does not utilize the phase information in the two wave shapes and so it is not a 100% solid metric.

In this study, we will however focus on internal overvoltages and therefore FDSF will not be used. Example of multivariate analysis of energization of a wind farm's radial using FDSF can be found in [13].

#### B. Time Domain Severity Factor

Time Domain Severity Factor (TDSF) was introduced in [14]. The idea is similar to the FDSF, namely to compare transformer conditions during tests with the specific conditions during surges. However, TDSF performs the comparison in time domain and compares magnitudes of voltage drop between the corresponding discs of a transformer, as given by (4):

$$TDSF = \frac{\Delta V_{\max(transient)}}{\Delta V_{\max(test-wave)}}$$
(4)

where  $\Delta V_{max(transient)}$  is the maximum voltage drop between consecutive disks along the winding during transient condition at the terminals of the transformer.  $\Delta V_{max(test-wave)}$  is the maximum voltage drop between corresponding disks during tests.

In this way, the TDSF allows finding points along the winding with potentially dangerous voltage stress. Until recently the TDSF could only be used with detailed whitebox models, which are often confidential and difficult to obtain. The type of black-box models, as the one used in this study, allows using TDSF and at the same time protects manufacturers proprietary design information.

# IV. SIMULATIONS

#### A. Multivariate Analysis in EMTP-RV

The simulations were performed in EMTP-RV (EMTPWorks v.2.4). This software allows programmatic control over the simulation as well as most of the parameters of components using JavaScript. The extraction of data was done in post-processing stage using scripting functions of MPLOT, which is a standard plotting program for EMTPWorks.

Programmatic change of a cable's parameters (e.g. length) during multivariate analysis is more complicated than in case of other standard components as the cable model is made in several steps. It was decided that the most convenient method was to pre-compute a separate model for each length and use it in multivariate analysis by changing the path to its file in *Attributes* of the cable model block. The cables were modeled using a wideband model, which is an implementation of Universal Line Model (ULM) [15, 16] and is the most accurate line/cable model in EMTP-RV.

#### B. Lightning Impulse Test

The standard lightning test is performed on the model, with crest voltage equal to the transformer's BIL (1025 kV) and standard wave shape of  $1.2/50 \,\mu s$ , represented by a double exponential curve [17]. The voltage is applied to the transformer's HV terminal with the LV terminal grounded, as shown in Fig. 3 (left hand side). The same procedure was also applied to LV side, with the appropriate BIL (325 kV).

Fig. 4 shows clear similarity between pairs of internal nodes: 72-69, 73-68, 82-59, 83-58. This result is due to the symmetric distribution of the pairs on nodes around the HV terminal, which is in the middle of the winding. The shown voltages were computed for duration of 1 ms when calculating the TDSF.



Fig. 3. Lightning test with standard lightning impulse:  $1.2/50\mu s$  applied to HV terminal (left figure). Additional test with lightning impulse applied to LV side (right figure).



Fig. 4. Lightning impulse test at HV winding. LV winding grounded. Current source: 1050 kV, 1.2/50  $\mu$ s. HV and LV denote HV and LV terminals, respectively and nXX, where XX in a number, denotes a number of an internal node.



Fig. 5. Lightning impulse test at LV winding. HV winding grounded. Current source: 325 kV,  $1.2/50 \ \mu s$ . HV and LV denote HV and LV terminals, respectively and nXX, where XX in a number, denotes a number of internal node as indicated in Fig. 3.

# *C. Transformer Energization via a Cable. LV side Open.*

It is known that high overvoltages can occur at the terminals of a transformer during energization due to voltage transfer from the HV side to the LV side. This is especially true when the transformer has a high voltage ratio and the LV side is unloaded, as illustrated in Fig. 6.



Fig. 6. Simulation of transformer energization via a cable.

Fig. 7 shows voltage at the HV terminals when the ideal voltage source in Fig. 6 is represented with parameters 230  $kV_{rmsLL}\cos(\omega t)$  and the CB closes at t = 0. The result is shown for different lengths of the cable, varied from 0.3 km to 10 km in 40 equidistant steps.



Fig. 7. Voltage versus time at HV terminal for different lengths of 230 kV cable. Breaker at HV side is closed at t = 0.

Each color in Fig. 7 represents a time domain voltage waveform at HV terminal of a transformer during energization of a transformer via a cable of different length. For clarity, waveforms for only seven lengths of cables were shown in the figure. It is clear from Fig. 7 that the frequency of oscillations of voltage waveform present at HV terminal of the transformer depends on the length of the cable.

Fig. 8 shows a strong dependency of cable length on the peak value of the transformer's HV terminal. The "peaks" in Fig. 8 can be explained as follows. After closing the breaker, the voltage wave travels along the cable and reflects from the transformer terminal where transformer input impedance is much higher than the cable surge impedance. This gives a voltage doubling at the cable end. The reflections from both ends of the cable result in oscillations in the transformer terminal voltage. The frequency of these oscillations can be approximately described by quarter wave resonance frequency (5) [18]:

$$f_{res} = \frac{v}{4l} = \frac{1}{4\tau} \tag{5}$$

where l is cable's length, v is waveform's propagation speed and  $\tau$  is propagation time. Here, v is approximately sixty percent of speed of light in vacuum.

When systematically changing the length of the cable between 0.3 and 10 km we effectively perform a finiteduration "frequency sweep" on the transformer model, varying the frequency between approximately 1.1 kHz and 150 kHz. Main resonance frequencies are present in this frequency range, both in admittance elements shown in Fig. 2 and in voltage transfers between HV and LV terminals [19]. Fig. 8 shows an increase in voltage magnitude at the investigated terminals (both internal and external), which occurs when the frequency of voltage oscillations corresponds to the transformer's resonance frequencies.



Fig. 8. Maximum overvoltage at transformer's HV and LV terminals as well as internal nodes for excitation shown in Fig. 6 and different cable lengths.

The main resonance frequencies in voltage transfer from HV side to LV side are at 16 and 43 kHz, which roughly corresponds to the cable length of 2.8 and 1 km, respectively. The TDSF for chosen consecutive disks at HV side for different cable lengths is shown in Fig. 9.



Fig. 9. TDSF for excitation shown in Fig. 6 and different cable lengths. E.g. n83-n82 is a voltage difference between nodes 83 and 82, representing two consecutive disks of HV winding.

TDSFs are calculated from curves shown at Fig. 4 because the excitation of the transformer is done from HV side, as shown in Fig. 6. For example,  $TDSF_{n83-n82}$  at Fig. 9 is calculated by dividing a voltage difference between nodes 83 and 83 during transformer energization by voltage difference between discs 83 and 82 during lightning test at HV side (Fig. 4).

As the TDSF at Fig. 9 is smaller than unity, voltage stress between investigated nodes do not exceed the corresponding voltage stress during lightning impulse  $(1.2/50 \ \mu s)$ .

# D. Transformer Energization via a Cable. LV Side Loaded With a Cable

Next example investigates the case shown in Fig. 10, where the transformer is energized via a cable at HV side, with a LV side loaded with a 66 kV cable. Wide-band model is used to model also the 66 kV cable using the same procedure as with the 230 kV cable.



Fig. 10. Simulation of transformer energization via a cable at HV side, with a LV side loaded with a cable.

Connection of the cable to LV side damps the overvoltages at this side during energization, as shown in Fig. 11. The maximum overvoltage does not exceed the BIL level at the LV side.



Fig. 11. Maximum overvoltage at LV side during energization via a cable at HV side.

The maximum overvoltage is dependent more on the length of the LV cable than HV cable. The resonances due to HV cable are present mostly for short lengths of LV cables.



Fig. 12. Maximum overvoltage at internal node 24 at LV winding during energization via a cable at HV side. Notice changed axis as compared to Fig. 11.

The overvoltages in the middle of LV winding (node 24) are more profound than at LV terminal, with maximum value higher than the winding's BIL.

Cable loading decreased TDSF at observed locations along the HV winding, with maximum value between discs 72 and 73, as shown in Fig. 13.



230kV cable length [km]

Fig. 13. TDSF for discs 72-73, for different cable lengths and excitation shown in Fig. 10.

#### E. Influence of Loading on Overvoltages

The final example shows the influence of the LV loading. The simulated case is shown in Fig. 14.



Fig. 14. Simulation of transformer energization via a cable at HV side, with a LV side loaded with a variable resistance.

A resistor connected to the LV side is varied between 0.1  $\Omega$  and 390.1  $\Omega$  in 40 linearly distributed steps. The range 25  $\Omega$  to 400  $\Omega$  could correspond to cases where infinite-length cables or lines of various characteristic impedances are connected to LV terminal.



Fig. 15. Maximum overvoltage at LV side during energization via a cable at HV side.



Fig. 16. Max overvoltage at internal node 24 at LV winding during energization via a cable at HV side.



Fig. 17. TDSF between nodes 73 and 72 for excitation shown in Fig. 10 and different cable lengths.

Fig. 15 and Fig. 16 show, similarly as in previous example, high overvoltages exceeding BIL of the winding at internal node 24 during resonance. The maximum voltage at the LV terminal does not exceed critical values.

Loading decreased the TDSF values in all investigated locations to below 0.6. An interesting case is shown at Fig. 17, where the TDSF increases sharply for cable lengths of approximately 2.5 and 7 km. The first peak increases with the increase of resistance while the second peak decreases with the increase of resistance.

### V. CONCLUSIONS AND SUMMARY

This paper presents the results of time domain transient simulations using a wide band black-box model of a 100 MVA transformer. Unlike in other studies, here a modified transformer model is used, which also allows investigating voltage transfers from external terminals to chosen nodes along the windings. The severity of voltage stress on the transformer's insulation is measured with Time Domain Severity Factor (TDSF). Several cases of transformer energization are presented with focus on transformer-cable interaction. Connecting a cable to the LV terminal reduces the maximum overvoltages due to cabletransformer resonance; however, the overvoltages in internal node can exceed the winding's BIL level.

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