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A HIGH FREQUENCY POWER TRANSFORMERS MODEL FOR NETWORK STUDIES AND TDSF MONITORING

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SUMMARY

In this paper a high frequency power transformer model for network studies is presented. The model combines white and black box representations in a package implemented as "compiled foreign model" of MODELS language of EMTP/ATP program. This approach allows modelling all network components in EMTP/ATP environment. The time domain severity factor (TDSF) monitoring is integrated into the white+black box model package, which offers valuable information to figure out the risk level supported by inner points of power transformer windings when the unit interacts with the network during fast transient conditions. The proposed white+black box model of a 50/50/16.67 MVA transformer is illustrated while simulating the lightning overvoltages when it is connected to a 220 kV gas insulated substation (GIS).

KEYWORDS

High frequency modelling, Power transformers, Network studies, Time Domain Severity Factor.

1. INTRODUCTION

Field experience has shown that even when transformers had previously passed all standard tests and complied with all quality requirements a significant number of them suffered dielectric failures [1]. Such failures may be caused by transient events, which are not necessarily related to any system condition at the time of the failure. The analysis of the failures and their prevention requires characterizing the transients due to the interaction between the transformer and the power system network even during early design review process [2].

An effort to gain better knowledge of these transient phenomena in the aforementioned context has motivated the commissioning of different international working groups. One to be highlighted is the Cigré JWG A2/C4-39 named "Electrical Transient Interaction between Transformers and Power Systems", whose conclusions and recommendations are collected in a technical brochure published in 2014 [3]. Two of those recommendations state that i) "some specific evaluation (transient measurement, system studies, etc.) should be carried out as part of transformer failure analysis when transients may be involved" and ii) "it is highly desirable that the manufacturer provides the utility with an appropriate high frequency model of the transformer to allow for system transient studies". Such recommendations stimulated to continue the work by going deeper into different transformer modelling approaches for application in system transient studies, creating the Cigré JWG A2/C4.52 named "High-frequency transformer and reactor models for network studies" active from 2014 to 2018. Also, a remarkable conclusion from JWG A2/C4.39 is that the utility can make voltage stress evaluation in a unit upon incoming transients from the system employing severity factors. The time domain severity factor (TDSF) is one of the proposed indicators suitable to implement in online monitoring for evaluating the severity supported by the insulation of the transformer windings both in factory and in service [4] [5].

To pursue in this direction, this paper intends to contribute proposing a high frequency power transformer modelling for power system network studies and the monitoring of TDSF into EMTP environment. The proposed model for the transformers is a combined white+black box representations in a package implemented in a "compiled foreign model" of MODELS language inherently embedded in EMTP/ATP program. This strategy permits to model all components of the power system in EMTP/ATP [6]. The TDSF monitoring is integrated into the white+black box model package, which offers valuable information to figure out the risk level supported by inner points of power transformer windings when the unit interacts with the power system during fast transient conditions [7]. The proposed white+black box model of a 50/50/16.67 MVA transformer is illustrated while simulating the lightning overvoltages when it is connected to a 220 kV gas insulated substation (GIS) as practical example.

2. TRANSFORMER MODELS FOR NETWORK STUDIES

Generally speaking, mathematical transformer transient modelling can be classified into two types: white-box (or physical) approach and black-box (terminal) approach.

The white-box representation is the classical way to assess the level of the internal transformer dielectric stress. This type of modelling is based on detailed information (transformer geometry and material properties) according to design criteria [8]. Hence, the modelling by white-box is not practical in simulation of transient interaction between transformer and power systems, because the huge number of elements needed requiring a considerable computation time.

An alternative model is the black-box representation. This type of modelling has no direct physical meaning, since its structure is just a mathematical approach that matches the model output with the observed data (measurements and/or simulations) [9]. The modelling by black-box reproduces the transformer behaviour as seen from its terminals, over a certain frequency range, but it does not provide information about the internal overvoltages.

On the other hand, there are many examples in the literature and in the engineering practice describing simplified models for representing power transformers. Generally, such practice uses models valid only at certain range of frequencies. This range is chosen depending on the desired application. The simplified models can be placed between white and black models as a kind of gray-box model [10] since the structure is built primarily on the equipment physic and the parameters obtained by calculation or measurement tests. The advantage of these simplified models is that they are easy to implement in electromagnetic transient programs (EMTP) for network studies.

Methodologies for reduction of RLC elements are commonly used for reduction of power system full model or transformer detailed model [11]. A method similar to Kron’s reduction technique on the transfer function for constructing reduced order transformer model for system studies with not complex networks was proposed by Degeneff [12]. Recently, members of the Cigré JWG A2/C4.52 have published a procedure for interfacing transformer manufacturer's white box models with EMTP-type circuit simulators via rational function-based model obtained by nodal analysis and curve fitting [13]. That procedure is based on constant-parameter model frequency-independent what may involve loss of accuracy. Also, a general approach for evaluation of transformer resonance EMTP-based environment is presented in [14].

Authors of this paper are also members of Cigré JWG A2/C4.52. They are contributing in the high frequency power transformer modelling for power system network studies and the monitoring of TDSF [7]. The followed modelling procedure of white-black box proposed in this paper incorporates the RLCG frequency-dependent lumped parameters and based on frequency domain modal theory developed by Wilcox [15]. That offers advantages comparable with time domain since the parameters can be taken into account in an easy and rigorous way [16]. Here, it is implemented in a package “compiled foreign model” of MODELS language inherently embedded in EMTP/ATP program [17].

2.1 Modal white box model

The modal white-box modelling followed in this paper consists in discretizing the transformer windings into several blocks [8]. Each block is represented by means of an equivalent π-circuit with RLCG lumped parameters frequency-dependent in the frequency domain [18].

For a given frequency, the elements of the impedance and admittance matrices ***Z*** and ***Y***, are calculated from elements of the ***R***, ***L***, ***C***, ***G*** matrices as [8][19],

$$\mathrm{Z}_{ij}(r,m) = R_{ij}(r,m) + j\omega\, L_{ij}(r,m) \tag{1}$$

$$Y_{ij}(r,m) = G_{ij}(r,m) + j\omega\, C_{ij}(r,m) \tag{2}$$

where $R_{ij}(r,m)$, $L_{ij}(r,m)$, $C_{ij}(r,m)$, $G_{ij}(r,m)$, $Z_{ij}(r,m)$ and $Y_{ij}(r,m)$ are the resistance, inductance, capacitance, conductance, impedance and admittance between the *r*th and *m*th blocks (branches) of the *i*th and *j*th windings of the transformer, respectively.

Considering the transverse electromagnetic waves theory, the transformer modal modelling with *W* lossy windings can be expressed by following matrix form [8][20],

$$\begin{bmatrix} \boldsymbol{I_B} \\ \boldsymbol{V'} \end{bmatrix} = \begin{bmatrix} \boldsymbol{A} & \boldsymbol{B} \\ \boldsymbol{C} & \boldsymbol{D} \end{bmatrix} \begin{bmatrix} \boldsymbol{V_B} \\ \boldsymbol{V'} \end{bmatrix} \tag{3}$$

where $\boldsymbol{V_B}$ represents the set of voltages at the winding terminals, $\boldsymbol{I_B}$ represents the set of currents entering them, and ***V’*** the voltages in the internal nodes as defined in [8][20],

$$\boldsymbol{V'} = (\boldsymbol{1} - \boldsymbol{D})^{-1}\boldsymbol{C}\boldsymbol{V_B} \tag{4}$$

$$\boldsymbol{I_B} = (\boldsymbol{A} + \boldsymbol{B}(\boldsymbol{1} - \boldsymbol{D})^{-1}\boldsymbol{C})\boldsymbol{V_B} \tag{5}$$

More details about the derivation of (4) and (5) and corresponding submatrices ***A, B, C,*** and ***D*** can be found in [19].

2.2 Modal black box model in frequency domain

According to [20], the expressions (4) and (5), are converted in the following frequency domain modal expressions,

$$\boldsymbol{V'} = \boldsymbol{C_H}\boldsymbol{V_B} + \boldsymbol{Q}\boldsymbol{g}\boldsymbol{P}^t\boldsymbol{V_B} \tag{6}$$

$$\boldsymbol{I_B} = \boldsymbol{Y_B}\boldsymbol{V_B} = \left(\boldsymbol{Y_b} + \boldsymbol{Y''_{BB}} + \boldsymbol{P}\boldsymbol{\zeta}\boldsymbol{g}\boldsymbol{P}^t\right)\boldsymbol{V_B} \tag{7}$$

where $\boldsymbol{g}$ and $\boldsymbol{\zeta}$ are diagonal matrices related with the modal voltage and admittance transfer functions of the transformer resonance modes, respectively, and $\boldsymbol{Y_B}$ is the nodal admittance matrix between transformer terminals.

The equation (7) describes the behaviour of the transformer from modal black box modelling with *2W* terminals in frequency domain, defined by the nodal admittance matrix between terminals. This black box brings the transferred voltages and input currents at the terminals. While, the equation (6) expressed in terms of modal transfer matrices gives the overvoltage at transformer internal nodes from the terminals voltages.

More about derivation of (6) and (7) and corresponding matrices $\boldsymbol{P}$, $\boldsymbol{P}^t$, $\boldsymbol{C_H}$, $\boldsymbol{Q}$ can be found in [19].

3. WHITE+BLACK BOX MODEL FOR EMTP

3.1 Conversion modal black box model in frequency domain into time domain

The later modal black box modelling equation (6) and (7) can be implemented in time domain for being compatible with standard EMTP packages. Therefore, the $\boldsymbol{Y_b}$, $\boldsymbol{Y''_{BB}}$, $\boldsymbol{P}$, $\boldsymbol{g}$, $\boldsymbol{\zeta}$, $\boldsymbol{Q}$ and $\boldsymbol{C_H}$ matrices are fitted applying process of least squares and interpolation [21].

The $\boldsymbol{g}$ and $\boldsymbol{\zeta}$ matrices are approximated to the RLC series resonant circuits and the three terms of the $\boldsymbol{Y_B}$ matrix are approximated to RLCG of parallel branches. These RLC series circuits and RLCG parallel branches are implemented in time domain using the trapezoidal numerical rule and the corresponding Norton equivalent circuits with a fixed conductances and controlled current sources [22].

Considering time domain equation in standard EMTP form, described by Dommel [23][24], the adjustment of (7) in time domain results as

$$\boldsymbol{i}_{\mathbf{B}}(t) = \boldsymbol{i}_{\mathbf{B}_{\boldsymbol{his}}}(t - \Delta t) + \boldsymbol{G}_{\mathbf{B}}\boldsymbol{v}_{\boldsymbol{B}}(t) \tag{8}$$

where, $\boldsymbol{G_B}$ is the sum of all conductance matrices, and $\boldsymbol{i_{Bhist}}$ historic currents (previous time step Δt) of each term of equation (7). Once all conductances and sources of the Norton equivalent circuits are obtained in each time step, the currents and voltages at the terminals are calculated applying (8) and the voltages at the internal nodes are determined applying the adjusted representation of (6) as [21],

$$\boldsymbol{v}'(t) = \boldsymbol{Q}_{\boldsymbol{apx}}\boldsymbol{v}_{\boldsymbol{c}}(t) + \boldsymbol{C}_{\boldsymbol{H,apx}}\boldsymbol{v}_{\boldsymbol{B}}(t) \tag{9}$$

where $\boldsymbol{v'}$ is the column vector of the voltages at internal nodes in time domain, $\boldsymbol{v_c}$ is the column vector of the voltage drop at the modal capacitances, $\boldsymbol{Q_{apx}}$ and $\boldsymbol{C_{H,apx}}$ are the approximated matrices of $\boldsymbol{Q}$ and $\boldsymbol{C_H}$ calculated in previous section, respectively.

More details about the derivation of (8) and (9) can be found in [21].

3.2 Implementation of the white-black box model in EMTP/ATP interface using MODELS

The ATP (Alternative Transient Program) is the public domain version of EMTP (Electromagnetic Transient Program). It is based on the original version of the EMTP program and it is one of the most widely used versions of EMTP. This software allows simulating electromagnetic transient phenomena, taking into account, among other features, sophisticated models for transmission lines, circuit components and control elements. However, there is no still a well stablished methodology with option to analyze the performance inside the transformer windings when excited by a transient voltage. That is the reason why this paper tries to contribute describing a white+black modelling procedure for the transformer as a package easy to use in the EMTP/ATP environment connected to the all components of the power system network.

The transformer time domain model described in previous sections was implemented in a "foreign" model written in Fortran 90, which is introduced into the environment of ATP using a MODELS module called Type-94 Norton block with "foreign" functions. In the power system network model implemented in ATP, the Type-94 Norton block is used for building the interface of the transformer, as a component of the power system, and to access the transformer "foreign" model through of the "foreign" functions, as described in [17].

4. MONITORING THE TIME DOMAIN SEVERITY FACTOR (TDSF)

The guide published by Cigre JWG A2/C4.38 [3] recommends the TDSF to evaluate the risk level supported by transformer insulation focused to overvoltages when connected to network [4]. It is useful when combined with “online” monitoring either in the simulation stage or physically implemented in the real network, as indicator of increased transient risks for a unit.

A severity factor assesses the dielectric stress on a transformer winding considering the incoming transient overvoltage. It determines the safety margin regarding the standard acceptance tests either in the frequency or time domain.

In the case of the TDSF gives detailed information in the time domain on the severity supported by the transformer windings due to the transient event coming from the power system, regarding the internal transient response due to dielectric tests in the time domain. The TDSF is formulated as [5],

$$TDSF(i) = {}^{\Delta V_{sw}(i)}\!\big/_{\Delta V_{env}(i)} \tag{10}$$

where $\Delta V_{sw}(i)$ is the maximum voltage drop along the ith dielectric path due to the transient events and $\Delta V_{env}(i)$ is the maximum voltage drop along the same ith dielectric path for all standards dielectric tests.

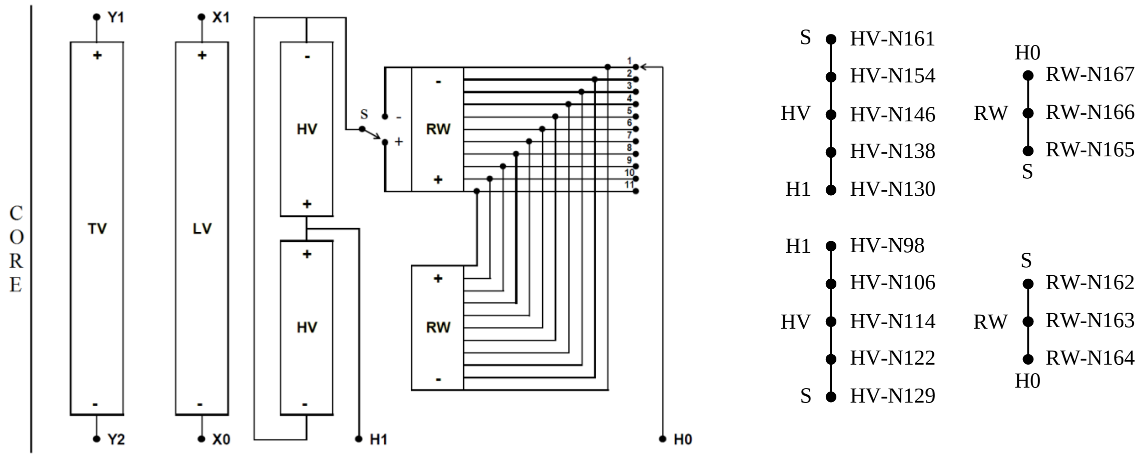
Since each transient waveform depends on the electrical interaction between transformer and the power system network, it implies that each of those combinations is characterized by a particular TDSF. In order to obtain the TDSF, the use of two different models of the transformer under consideration is needed. First, a terminal model (black box model) of the transformer used to compute the transient voltage waveform at the transformer terminals during the transient event that occurred in the power system where the transformer is connected. Then, a detailed model (white box model) of the transformer used to compute the internal transient voltage distribution along transformer windings. The TDSF was integrated in white+black box EMTP/ATP package proposed using the MODELS module.

5. APPLICATION EXAMPLE. FAST FRONT TRANSIENT IN A GIS

An application example to illustrate the proposed white+black model is included in this section considering a three-phase transformer bank. The single-phase unit is 50/50/16.67 MVA three-winding transformer with rated voltages 230/69/13.8 kV at 60 Hz (220/66/13.2 kV at 50 Hz). High voltage (HV), low voltage (LV), tertiary (TV) and regulation windings (RW) with internal connections per phase are shown in Figure 1.

5.1 White box model v.s. White+Black box model

In order to check the modelling methodology proposed, simulation results obtained with white box and also with white+black model in the EMTP/ATP program are compared with measurements carried out as described in reference [25].



(a) (b)

Figure 1. Outline of a single-phase of the modelled transformer: (a) Terminals and internal connections; (b) Identification of some internal nodes at the HV and RW windings.

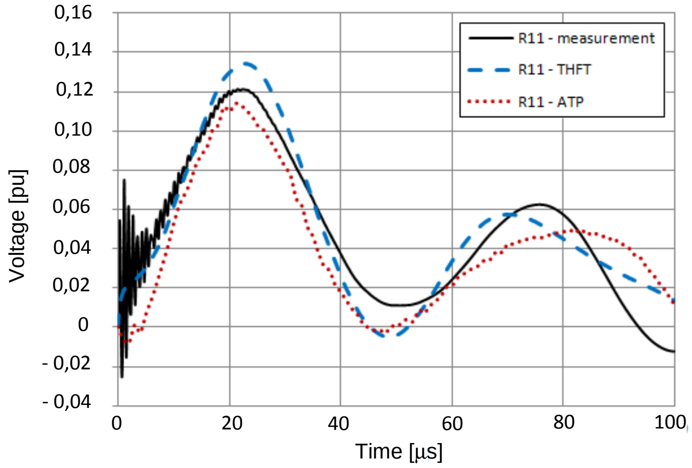


Figure 2. Comparison of the voltages in time at one of the input RW tap.

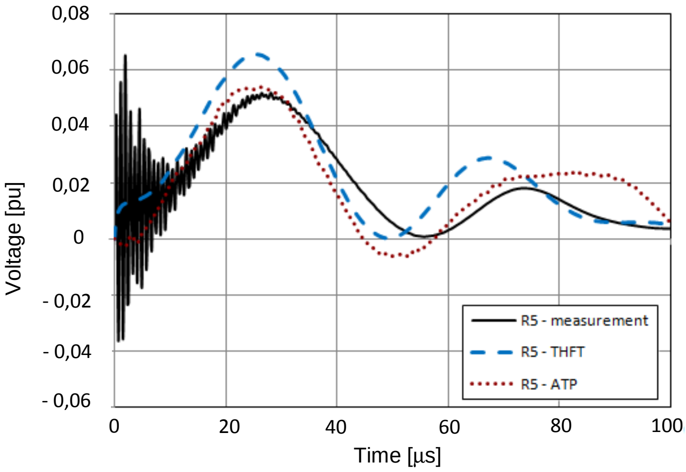


Figure 3. Comparison of the voltages in time at the middle of RW tap.

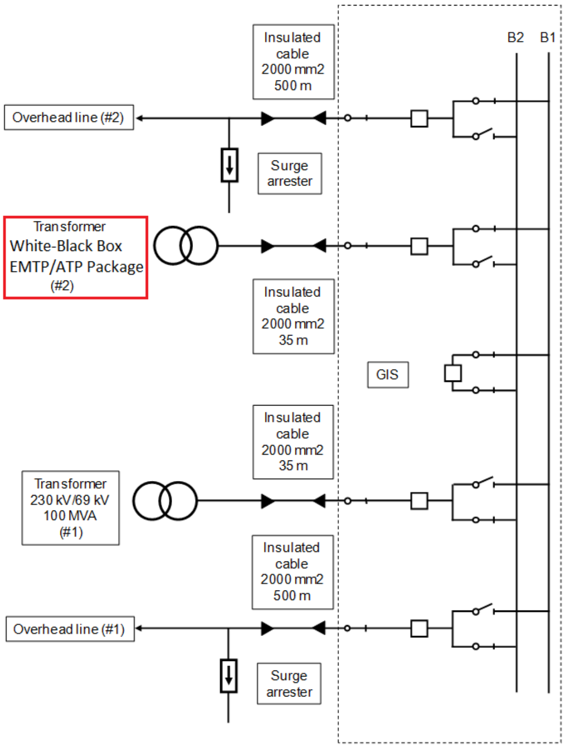


Figure 4. Substation layout.

Figure 2 and Figure 3 shows the voltage in time at two regulation taps (at one of the input RW tap: R11; at the middle of RW tap: R5) computed both by white+black box model (R11-ATP, R5-ATP) and by a pure white box model (R11-THFT, R5-THFT), when a full standard lightning wave (1.2/50 μs) is applied at high voltage H1 with Y1, Y2 terminals open and X0, H0 grounded. Both computation results are compared with experimental measurements.

5.2 Fast Front Transients in a GIS

The proposed white+black box model of the aforementioned 50/50/16.67 MVA real transformer was incorporated to a 220 kV GIS with five bays (two overhead line bays, two transformer bays and a bus bar coupling bay). The layout of the substation is shown in Figure 4.

A portion of the detailed EMTP/ATP model of the GIS, one transformer bay, with all the power system components connected to it is displayed in Figure 5. The white+black box model package has been used to represent transformer #2.

Two different scenarios, with and without surge arrester protection (MOV), were simulated when a direct lightning stroke is applied in a phase conductor of one of the two overhead line (#2) [8]. In both cases the LV secondary transformer terminals were kept unloaded.

The voltages at internal nodes of the transformer HV winding in time, with and without surge arrester protection (MOV), provided by the white+black box model are displayed in Figure 6.a and Figure 6.b, respectively. Particularly, at main HV winding (HV-N98, HV-N106, HV-N114, HV-N122, HV-129) and at regulation winding (RW-N162, RW-N163, RW-N164).

The TDSF monitoring at 30 internal nodes to ground and between those nodes of the HV windings both with and without surge arrester protection (MOV) are shown in Figure 7.a and Figure 7.b, respectively. It is remarkable that without protection the TDSF goes over unit value, which means that the transformer is in dielectric potential risk.

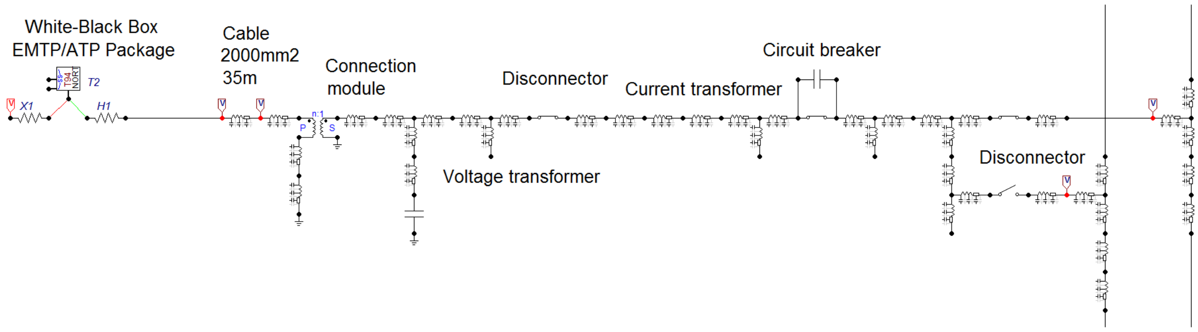
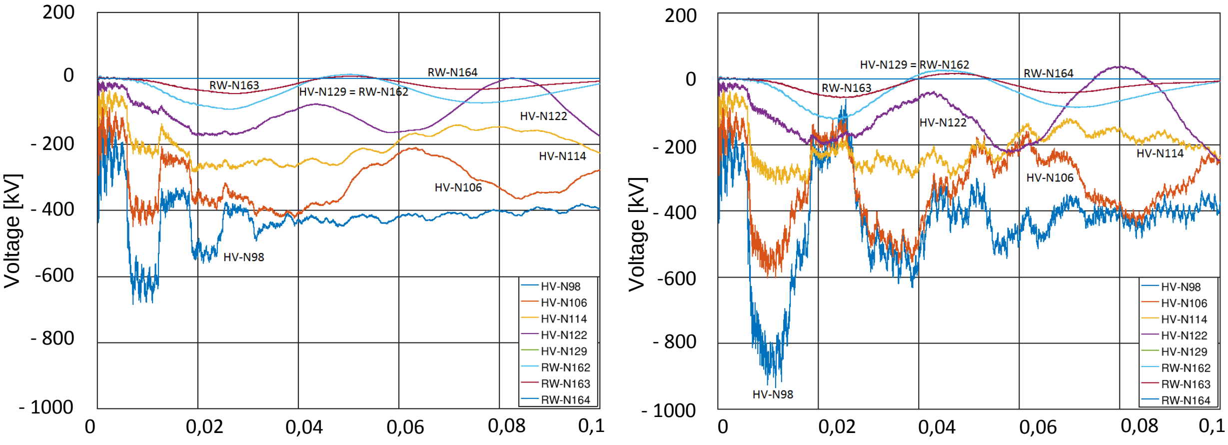
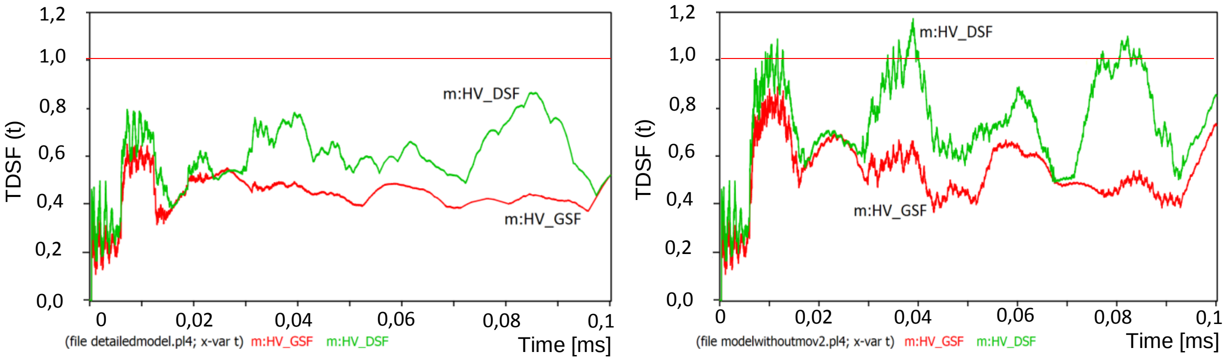


Figure 5. One bay of the substation ATP/EMTP model with transformer white+black box package connected.



(a) (b)

Figure 6. Voltages at internal nodes of transformer HV winding: (a) with surge arrester protection (MOV); (b) without surge arrester protection (MOV).



(a) (b)

Figure 7. TDSF monitoring in time to ground (m:HV_GSF) and between nodes (m:HV_DSF) at HV winding: (a) with surge arrester protection (MOV); (b) without surge arrester protection (MOV).

6 CONCLUSIONS

In this work a white+black box model for power transformer was implemented in the EMTP/ATP program. Results from the proposed model show good concordance with measurements on a real transformer, when a lighting impulse at HV terminal is applied. Also, the model of that transformer implemented in the proposed white+black box model package was successfully incorporate as a component into a 220 kV GIS model.

The proposed approach is particularly useful for enhancing the understanding of the internal transformer transient behaviour connected to the power system, since the transformer model and the model of the power system network can interact during the simulation. As a result, the interaction between the power system network model and the transformer model make the overall power system network simulation more powerful.

The TDSF in time shows in what time instant and what internal point the dielectric failure could occurr. TDSF monitorig offers valuable information as a tool in substation design studies, complementary to standard insulation coordination analyses, as well as information for the utility engineers about environment of power system network.

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