Fast Front Transients in Transformer Connected to Gas Insulated Substations: (White+Black) Box Models and TDSF Monitoring

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Abstract — **Protection to fast front transients of power transformers connected to Gas Insulated Substations (GISs) requires not only detailed model of the GIS but also of the power system components connected to it including the power transformers themselves. Transformer models with different degree of modeling detail have been proposed in the literature. However, there is no single model able to represent at the same time the transient performance both outside and inside transformer when connected to the power system. This paper reports an investigation that shows the valuable information obtained when a white+black box representation is used to model the transformer in fast front transient simulations. Precisely, transient overvoltages will be simulated and the time domain severity factor (TDSF) will be monitored in an actual GIS model in the ATP/EMTP program.**

Keywords — **Fast Front Transients, Gas Insulated Substations, Transformer Models, Time Domain Severity Factor**

I. Introduction

Protection to Fast Front Transient (FFTs) [1] of power transformers connected to Gas Insulated Substations (GISs) requires not only detailed model of the GIS but also of the power system components connected to it including the power transformers themselves. An appropriate model of the transformer should therefore be applied in transient simulations to determine not only the overvoltages in its terminal but also in each coil. There are several approaches with different levels of sophistication for obtaining such models [2] [3].

Generally speaking, mathematical models of dynamic systems can be of two types: white-box (or physical) models and black-box models.

The white-box model allows assessing the internal transformer dielectric stress. However, it is based on information normally only available to manufacturers [4]. Hence, the use of white-box model is not feasible in simulation of fast front transients.

An alternative model is the black-box models. Such models have no physical meaning, since its structure is just a mathematical equation that matches the model output with the observed data. These models reproduce the transformer behaviour as seen from its terminals, over a wide frequency band. Black-box models are particularly suitable for studying the high-frequency interaction between a transformer and the network such as insulation coordination studies and the analysis of transferred overvoltages between transformer winding terminals.

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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 in certain a range of frequencies. This range is chosen depending of the desired application. It can be viewed between white and black as a kind of gray-box model 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), suitable and sufficient for a first transient analysis in the substation.

The International Electrotechnical Commission (IEC) has developed modelling guidelines of power system components for FFT simulations [5] . There are recommendations for modelling transformers by simplified models with their winding capacitances to ground and the capacitances between windings. A simplified approach is proposed in [6] to obtain and use a reduced capacitances transformer model developed from the node capacitance matrix provided by the manufacturer instead of using the measured capacitances.

The utility on its side could need to make evaluation studies on interaction between the transformer and the power system in case of fast front transients to monitor the severity of the risks. Such monitoring can thus help to analyse and prevent failures due to upon incoming transients from the system to transformer either design review stages or manoeuvres, change of grid topologies, protection coordination, etc. This paper proposes to monitor the mentioned situations via the time domain severity factor (TDSF), which assesses the severity supported by transformer windings due to transient events occurring in the power system [7].

The TDSF can be considered as tool in substation design studies, complementary to standard insulation coordination analyses, as well as information to the manufacturer of the transient electrical environment of the substation.

This paper presents a new approach for interactive protection system simulation. In this approach, the power system network is modeled in the ATP/EMTP program while the “compiled foreign model” mechanism of MODELS language is employed to implement the transformer in a White+Black box package. This permits to monitor the interaction between power system network and transform model in a ATP/EMTP environment. A case study is included to demonstrate the protection system simulation against overvoltages [8] in a GIS and the transformer subjected to a lightning impulse using the proposed new approach. It shows the capabilities of reproducing the internal transformer behaviour for high frequency in simulations within ATP/EMTP program. A prominent advantage of this approach is the easy interfacing between the power system network models and the transformer model because the MODELS are inherently embedded in ATP/EMTP program.

II. SIMPLIFIED TRANSFORMER MODELS

Traditionally, in very fast transients, such as lightning surge studies into the network, only the capacitive behaviour of the power transformer is consider relevant as first approach. So, the mutual capacitive coupling between phases is ignored, leaving only a capacitive per-phase equivalent. Such a model could be used for representing the impact of a transformer on an incoming wave on a cable or overhead line, but it is a way too simple for capturing the detailed high-frequency interaction between the transformer and the network, or the transfer of overvoltages between inner windings.

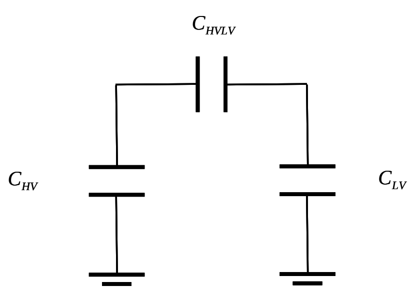

Figure 1. Simplified transformer model representation (two terminals).

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A typical simplified transformer model is shown in Figure 1. The parameters C_{HV}, C_{LV} and C_{HVLV} are the surge capacitances and will depend upon the range of frequencies considered. The parameter C_{HV} can be provided by the manufacture or calculated from impedance frequency response measurements. If these values are not available from measurements or from manufactures typical values are suggested in the literature. For example see Table 4.1 in [9]. Typical capacitance values for auto-transformers can be found in Table 4.2 in [10]. This subject is also discussed in [11] and in [12] where a list of typical values are also provided.

Also IEC [5] recommends to represent transformers in FFT simulations by the winding capacitances to ground and the capacitances between windings as shown in Fig. 1.

Reference [6] has obtained and used a reduced capacitances transformer model developed from the node capacitance matrix provided by the manufacturer instead of using the measured capacitances. The capacitance transformer model can be written in the frequency domain as:

$$j\omega \mathbf{C}\mathbf{V}_n = \mathbf{I}_n \tag{1}$$

The reduced capacitance matrix $\mathbf{C}_R$ is firstly obtained by performing the Kron reduction to the high and low voltage terminals of the transformer. The windings capacitances are obtained from the reduced capacitance matrix $\mathbf{C}_R$ according to:

$$\mathbf{C}_R = \begin{bmatrix} C_{R11} & C_{R12} \\ C_{R12} & C_{R22} \end{bmatrix} \tag{2}$$

$$\left.\begin{aligned} C_{R11} &= C_{LV} + C_{HVLV} \\ C_{R12} &= -C_{HVLV} \\ C_{R22} &= C_{HV} + C_{HVLV} \end{aligned}\right\} \begin{aligned} C_{HVLV} &= -C_{R12} \\ C_{HV} &= C_{R22} - C_{HVLV} \\ C_{LV} &= C_{R11} - C_{HVLV} \end{aligned} \tag{3}$$

III. WHITE+BLACK BOX TRANSFORMER EMTP/ATP PACKAGE

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 the most widely used version 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 the transformer model is based on simplify one usually without option to analyze the performance inside in the windings excited by a transient voltage. That is the reason that this work proposed a white+black box for the transformer as a package easy to use in the ATP/EMTP environment connected to the all components of the substation. A demonstrative case was implemented in ATP/EMTP, since it offers the option of programming function through MODELS. By recompiling the ATP/EMTP program, it is possible to create sub-routines and function programming models by foreign programming languages.

The white+black box ATP/EMTP package proposed in this work is constructed from a white-box model. Their parameters are frequency dependent and calculated from transformer geometric dimensions and material physical of the transformer. Series capacitances interturns, earth capacitances of the turn to core, to tank and to yoke, and shunt capacitances between turns of adjacent windings have been included for modeling the electrostatic couplings. Self-inductance of each turn and mutual inductance between turns of all windings has been considered for taking all inductive couplings into account. The dielectric losses and copper losses caused by the eddy currents (skin and proximity effects) have also been included. The white+black box ATP/EMTP package can simulate any type of multi-phase, multi-winding transformer.

This approach is particularly useful for enhancing the understanding of the internal transformer transient behavior connected to the power system, since the transformer model and the network model of the power system 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 simulation more powerful.

IV. TIME DOMAIN SEVERITY FACTOR (TDSF) MONITORING

To take decisions on the risk level supported by power transformer, in this work focused to overvoltages, when connected in the grid an evaluation tool is necessary to manage capable to bring the internal transformer voltages stress information. The guide published by Cigre JWG A2/C4.38 [2] recommends the time domain severity factor (TDSF) [13] which 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 of 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 further 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 [13] :

$$TDSF(i) = \frac{\Delta V_{sw}(i)}{\Delta V_{env}(i)} \tag{2}$$

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, it implies that each of those combinations is characterized by a TDSF. To obtain the TDSF implies the use of two different models of the transformer under consideration. First, a terminal model (black box model) of the transformer is built 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 is used to compute the internal transient voltage distribution along transformer windings.

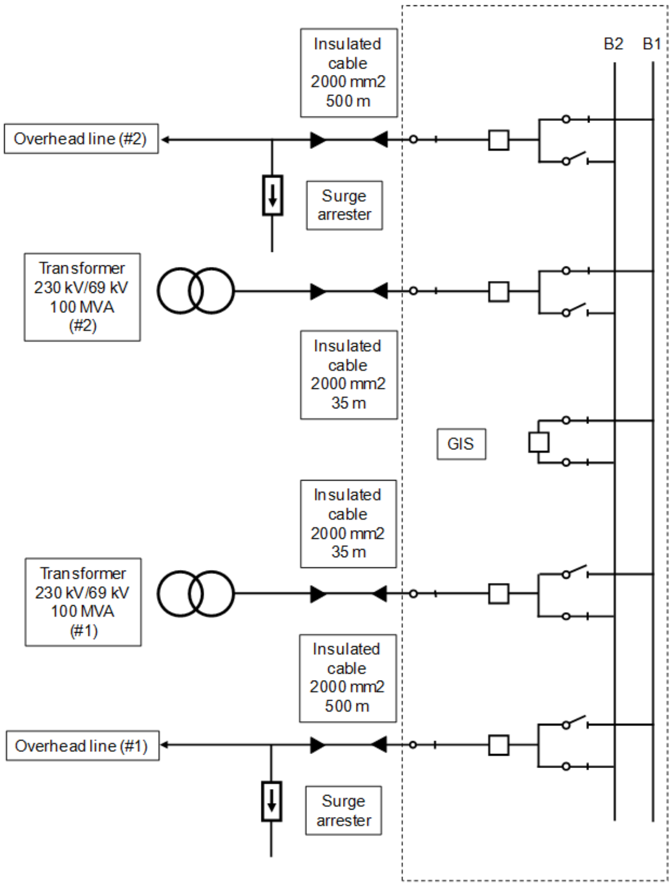

Figure 2. Substation layout.

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V. TIME DOMAIN SIMULATIONS. CASE STUDY

The performance of the white+black box EMTP/ATP package and the simplified model have been compared using them for modelling a 220 kV/66 kV transformer in an actual substation equipped with 220 kV GIS with five bays (two overhead line bays, two transformer bays and a bus bar coupling bay) and simulating a direct lightning stroke in a phase conductor of one of the two overhead lines (#2) [8] . The layout of the substation is shown in Figure 2. The ATP/EMTP model of the GIS and the power system components connected to it is displayed in Figure 3. The white+black box ATP/EMTP package has been used to represent transformer #2.

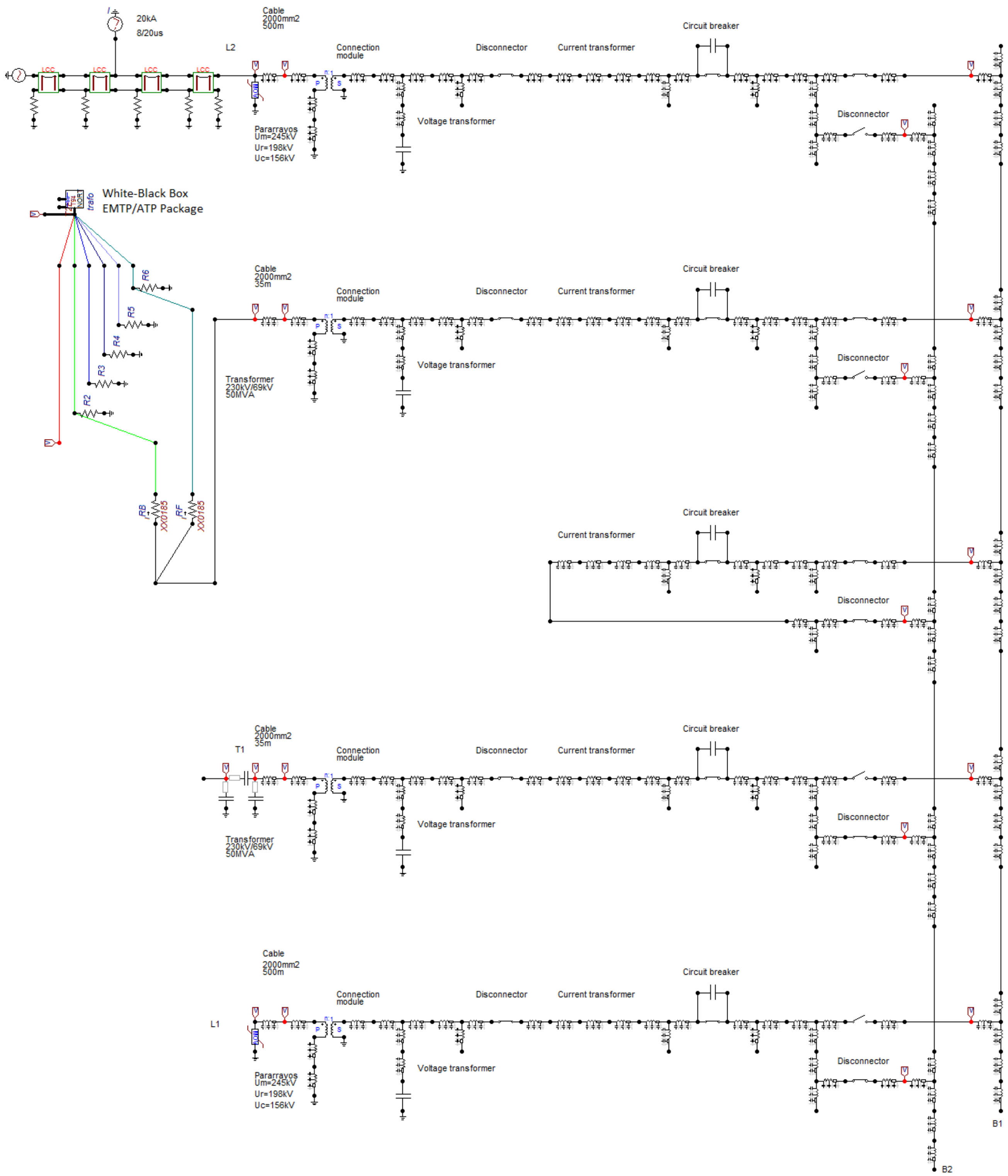

Figure 3. Substation EMTP model with transformer white+black box package.

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Results were obtained running the substation EMTP model simulating a direct lightning stroke in a phase conductor of one of the two overhead lines (#2).

Figure 4 compares the high voltage (HV) terminal voltages provided by both the white+black box package and the simplified model when surged arrested is connected. Voltages provided by both model agree. It confirms the value of the simplified model. Moreover, as the maximum voltage is below the transformer BIL (850 kV). Figure 5 compares the low voltage (LV) terminal voltages provided by both the white+black box package and the simplified model. It must be noted the great difference between the voltages of provided by the white+black box package and the simplified model. However, the voltage provided by the white+black box package is below the BIL of the low voltage winding (325 kV).

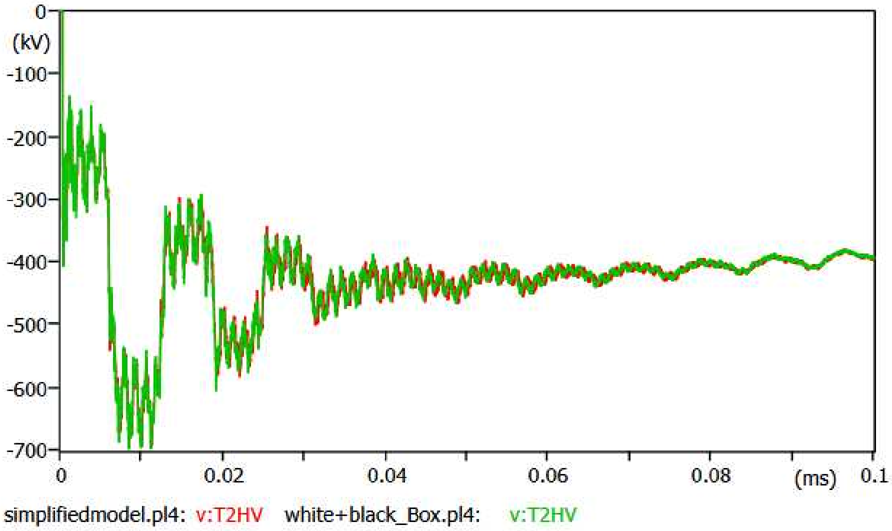

Figure 4. Comparison between white+black box EMTP/ATP package and simplified: HV terminal.

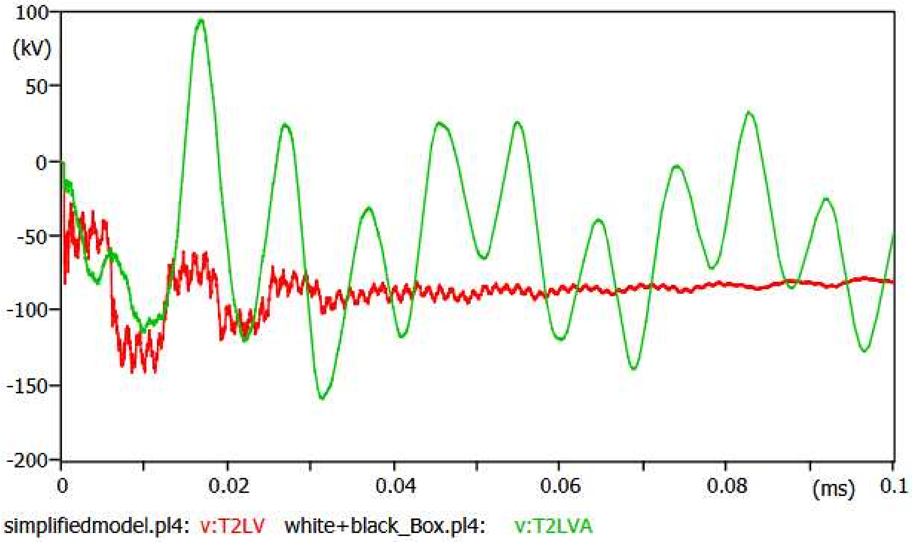

Figure 5. Comparison between white+black box EMTP/ATP package and simplified model: LV terminal.

The distribution of voltages within the high voltage winding provided by the white+black box package are displayed in Figure 6. The internal node voltages are scaled with respect to the terminal node voltage. The distribution of voltages within the low voltage winding provided by the white+black box package are shown in Figure 7. No node exhibit voltage higher than the low voltage transformer winding BIL (325 kV).

The TDSF monitoring both with and without surge arrester protection (MOV) are shown in Figure 8 and Figure 9 respectively. It is remarkable that without protection the TDSF goes to near unit value, which means that the transformer is close to potential risk.

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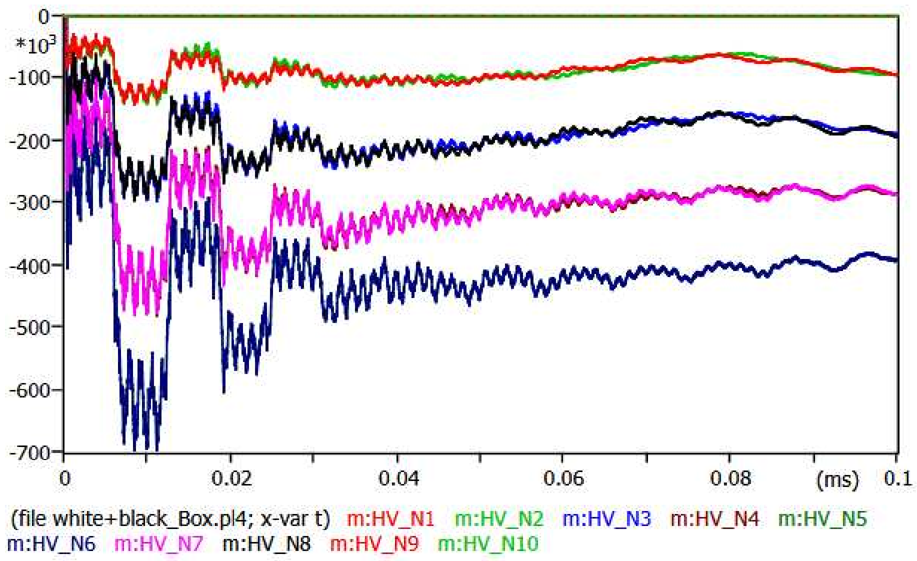

Figure 6. White+black box package: HV winding voltages.

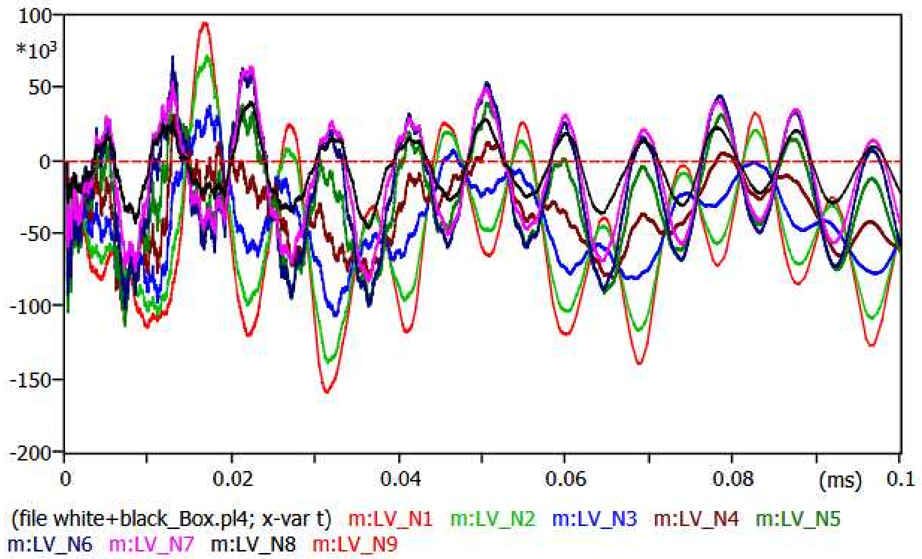

Figure 7. White+black box package: LV winding voltages.

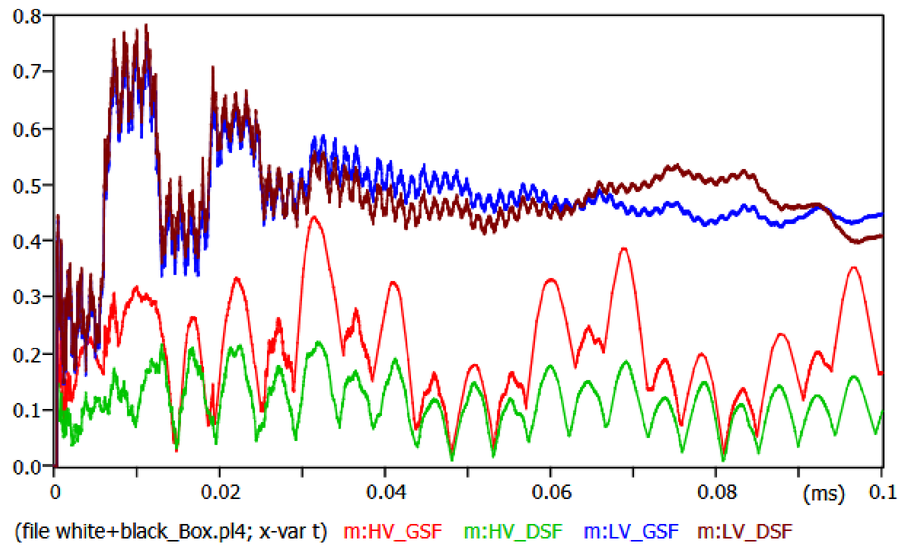

Figure 8. White+black box package: TDSF at HVand LV windings with protection (MOV).

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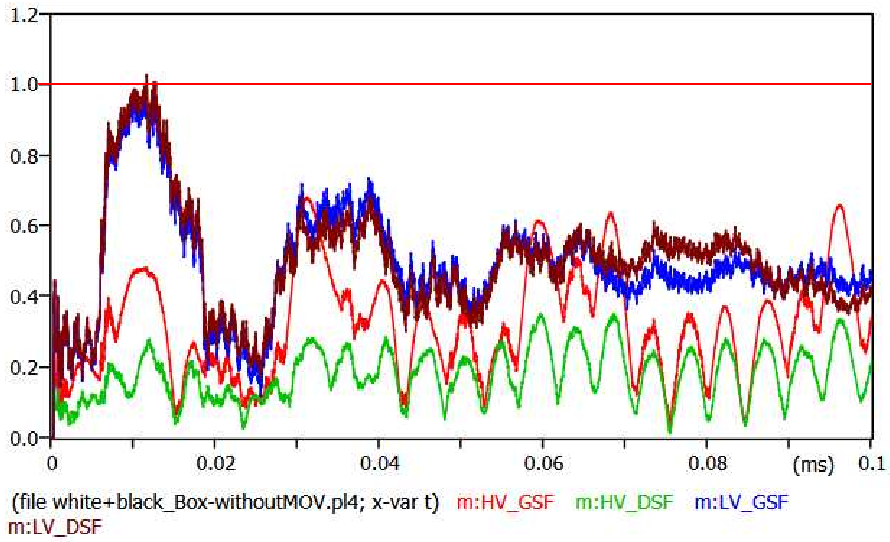

Figure 9. White+black box package: TDSF at HV and LV windings without protection (MOV).

VI. CONCLUSIONS

This paper has investigated the use of white+black box package in simulation of FFT. A white+black box package has been incorporated to a detailed model of a GIS. The terminal voltages provided by both the white+black box package and the simplified model have been compared. High voltage terminal voltage provided by both model agree. In contrast, low voltage terminal voltages provided by both the white+black box package and the simplified model exhibit great differences.

The TDSF monitoring was implanted into the proposed white+black box package, which offers valuable information to take decisions on the risk level supported by power transformer interacting with the power system during fast transient conditions.

REFERENCES

[1] IEC, International Standard IEC 71-1: *Insulation Coordination, Part I: Definitions, Principles and Rules*, 17th Edition, 1993-12.

[2] Joint Working Group SC A2 CIGRÉ, *Electrical Transient Interaction Between Transformers And Power Systems*, Tech. Brochure JWGA2/C439, Part-1 Expertise&Part-2 Case Studies Apr. 2014.

[3] Xose M. Lopez-Fernandez, H.B. Ertan and J. Turowski, Editors, *Transformer: Analysis, Design and Measurements*, CRC Press 2012.

[4] Xose M. Lopez-Fernandez and C. Alvarez-Mariño, *Computation Method for Transients in Power Transformers with Lossy Windings*, IEEE Transactions on Magnetics, Vol. 45, No. 3, p. 1863-1866, March 2009.

[5] IEC, Technical Report IEC TR 600071-4, *Insulation Coordination, Part 4: Computational Guide to Insulation Coordination and Modelling of Electrical networks*, First Edition 2004-06.

[6] L. Rouco, H. Gago and A. Prieto, *Detailed and Reduced Transformers Models in FFT Simulations*, 3rd International Advanced Research Workshop on transformers, ARWtr 2010, Santiago de Compostela, España, 3-6 October 2010.

[7] Xose M. Lopez-Fernandez and C. Alvarez-Mariño, *Induced Transients Voltage Performed Between Transformers and VCB. Severity Factors and Case Studies*, IEEE Transactions on Power Delivery, Vol. 30, No. 3, p. 1137-1144, January 2015.

[8] L. Rouco, L. Sigrist, H. García, E. Palazuelos, J. Bernal, M.A. Jimeno, *Protection of Power Transformers Connected to GIS Against Lightning Overvoltages*, Cigre 2014 Session 45, Paris, France, 24-29 August 2014, Paper C4-205.

[9] CRIEPI, *Lightning Protection Design for Power Stations, Substations and Underground Transmission Lines*, CRIEPI Report T40, 1995 (in Japanese).

[10] IEEE TF Report, *Modeling Guidelines for Fast Front Transients*, IEEE Trans. on Power Delivery, Vol. 11, No. 1, pp. 493-506, 1996.

[11] A. Greenwood, *Electrical Transients in Power Systems*, Second edition, Jon Willy & Sons Inc., ISBN 0-471-62058-0, 1991.

[12] CIGRE WG 33.02, *Guidelines for Representation of Network Elements when Calculating Transients*, CIGRE Technical Brochure 39, 1990.

[13] C. Álvarez-Mariño, X. M. Lopez-Fernandez, A. J. M. Jácomo-Ramos, R. A. F. Castro-Lopes, J. M. Duarte-Couto, Time Domain Severity Factor (TDSF): *Induced Transient Voltage Between Transformer and Vacuum Circuit Breakers*, COMPEL: The International Journal for Computation and Mathematics in Electrical and Electronic Engineering, vol.31 no.2, pp.670-681, 2012.