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TDSF-Based Evaluation of Transformer Interactions with VCB, Cable Length, and Neutral Grounding

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***Abstract* – This paper presents a TDSF-based evaluation of dielectric severity in transformer windings, focusing on transient overvoltages induced by cable–transformer interactions during vacuum circuit breaker (VCB) closing. Unlike prior approaches limited to terminal voltages, this study investigates the highest both spatial and temporal dielectric stress across all combinations of winding nodes and their reference to ground. A hybrid white–black box transformer model implemented in ATP/EMTP is presented and used for high-frequency transient analysis within the transformer. Three case studies on a 50 MVA single-phase, multi-winding transformer validate the model and assess the impact of cable length and neutral grounding resistance. Results show that certain cable lengths increase dielectric stress due to resonance effects, though without exceeding critical thresholds. In contrast, grounding conditions at the LV terminal significantly affect the vulnerability of the winding neutral point. The findings underscore the effectiveness of TDSF-based evaluation in identifying critical stress locations and supporting insulation coordination strategies.**

***Index Terms*--Dielectric severity factor, Dielectric tests, Insulation system, High frequency modelling, Network studies Power transformers, Time Domain Severity Factor, Switching operation, Vacuum circuit breaker.**

I. Introduction

FIELD experience has shown that even when transformers have successfully passed all standard tests and complied with all quality requirements, a significant number of them have suffered dielectric failures [1]. Such failures may be caused by transient events resulting from interactions between transformers and the power system network [2]. These events can lead to high-frequency overvoltages at transformer terminals and within the transformer itself, potentially causing dielectric breakdowns [3].

In recent years, there has been significant interest in the electrical transient interaction between power systems and power transformers. Working groups from both IEEE and CIGRE have been actively investigating these interactions [2][4]. These groups have identified the need for transient studies as part of transformer failure analysis, since transformers may fail in certain configurations due to dielectric stress [5].

A notable conclusion from JWG A2/C4.39 is that utilities can evaluate the voltage stress on transformers caused by incoming transients from the power system by employing severity factors [4]. The Frequency Domain Severity Factor (FDSF) is one of the proposed indicators. It evaluates dielectric severity at transformer terminals but cannot assess severity along the windings to localize dielectrically weak points [1]. The Time Domain Severity Factor (TDSF) is another proposed indicator, suitable for implementation in monitoring systems to evaluate the insulation stress supported by transformer windings [6]. This factor provides a location-specific severity index for transients, based on voltage magnitudes observed during factory Basic Insulation Level (BIL) tests, and has been promoted in [6–9]. The first pilot integration of TDSF monitoring for power transformer field measurements under service conditions is presented in [10] and is illustrated in Fig. 1.

Fig. 1. TDSF monitoring in a 230 kV/20 kV, 60 MVA distribution substation transformer.

In this work, a TDSF-based evaluation of dielectric severity along transformer windings is carried out, focusing on overvoltages caused by cable–transformer interactions during vacuum circuit breaker (VCB) closing operations. The evaluation is implemented using a time-domain white–black box transformer model compatible with the Electromagnetic Transients Program (EMTP) environment [7–9]. This model enables the investigation of internal overvoltages in transformer windings at high frequencies through transient network simulations. It is incorporated into the ATP/EMTP program [11] as a package in a “compiled foreign model” within a MODELS module, using the ATP/MODELS language [12]. This strategy allows time-domain transient simulations of the transformer interacting with all components of the electrical system within ATP/EMTP. Case studies are conducted on a system configuration comprising a 50 MVA transformer, a circuit breaker, one transmission line, and two cable sections. Particular attention is paid to the influence of varying cable lengths and the neutral grounding resistance at the LV terminals on the dielectric stress experienced by transformer windings.

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This work aims to advance the understanding of insulation system stress induced by transient phenomena through a TDSF-based evaluation. It considers the practical interaction between power transformers and the surrounding power system, accounting for internal transformer design features, VCB operating behavior, cable length variations, and the impact of neutral grounding configurations.

II. BACKGROUND

According to the literature, one of the most severe stresses in power systems is caused by switching transient overvoltages that interact with transformers and cables [13]. The prestrike and re-ignition phenomena in vacuum circuit breakers (VCBs) generate high-frequency oscillations that can adversely affect both cables and transformers [4]. These transient effects associated with VCB switching have been extensively investigated [14–19].

Numerous studies have examined transformer overvoltages resulting from cable–transformer interactions [20–25]. For instance, the work performed in [20] analyzes the influence of VCB parameters and cable length on transformer terminal voltages during energization in offshore wind farms. Resonance overvoltages caused by cable–transformer interaction during switching operations are explored in [21], although the comparison is made only against nominal voltages, not dielectric withstand limits. Study [22] evaluates terminal overvoltages for various cable lengths using a black-box modeling approach, with the analysis restricted to terminal responses. An experimental and theoretical frequency-domain severity analysis of dry-type transformers during VCB switching by—considering various cable lengths and load conditions—is presented in [23]. However, the study is limited to measurements performed at the transformer terminals. The Time Domain Severity Factor (TDSF) is applied in [24] to assess voltage stress during transformer energization, accounting for transformer–cable interaction, but only between HV winding nodes. Transformer overvoltages due to resonance with quarter-wave cables are investigated in [25], with the analysis again confined to terminal voltages.

Based on the reviewed literature, this paper focuses on transient overvoltages occurring inside the transformer, beyond its external terminals. Specifically, it evaluates the peak dielectric severity, —both spatially and temporally— for all combinations of winding nodes with respect to ground. The assessment is conducted using a TDSF-based approach, which incorporates internal transformer design features, VCB operating behavior, cable length variations, and highlights the influence of winding neutral grounding configurations.

III. TRANSFORMER MODEL FOR ATP/EMTP

The Alternative Transient Program (ATP), a widely adopted implementation of the Electromagnetic Transients Program (EMTP), enables the simulation of electromagnetic transients with detailed models of transmission lines, vacuum circuit breakers, system components, and control elements [11].

This work employs a hybrid white- and black-box transformer model compatible with ATP/EMTP, previously proposed by the authors for transient power system studies and TDSF monitoring [7–9].

The model is implemented using the "foreign model" function available in the MODELS language embedded in ATP/EMTP [12].

This modeling approach enables dynamic interaction between the transformer and the surrounding power system network during simulations, providing comprehensive insights into the transformer's internal transient behavior and enhancing the accuracy of overall system analysis.

A. Modal White Box Model in Frequency Domain

The hybrid white+black box model employed in this work is based on a frequency-dependent modal white-box transformer model [7–9]. Its parameters are derived from the transformer's physical geometry and material properties. The model incorporates electrostatic coupling and shunt capacitance between adjacent winding turns. Inductive coupling is represented through the self and mutual inductances of all winding turns, including core effects. Additionally, it accounts for dielectric losses, DC copper losses, and eddy-current-induced copper losses due to skin and proximity effects [26].

The white-box approach discretizes each winding into multiple blocks, each modeled by an equivalent frequency-dependent π-circuit with lumped RLCG parameters. Through modal analysis, the transformer behavior in the frequency domain is described by the following equations [26][27],

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

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

where $\boldsymbol{g}$ and $\boldsymbol{\zeta}$ are diagonal matrices characterizing the modal voltage and admittance transfer functions associated with high-frequency resonance modes. $\boldsymbol{Y_b}$ and $\boldsymbol{Y''_{BB}}$ represent nodal admittance matrices for low-frequency inductive and capacitive couplings, respectively. $\boldsymbol{Y_B}$ is the total nodal admittance matrix between terminals. The matrices $\boldsymbol{P}$, $\boldsymbol{P^t}$, $\boldsymbol{C_H}$, $\boldsymbol{Q}$ c and further details on the derivation of (6) and (7) are provided in [26].

Equation (7) defines the transformer's terminal behavior via a *2W*-terminal nodal admittance model in the frequency domain, relating terminal voltages and input currents. Equation (6), based on modal transfer matrices, enables internal node overvoltage estimation from terminal voltages.

B. Conversion Modal White Box Model into Time Domain

Equations (6) and (7) can be converted to the time domain to ensure compatibility with standard EMTP packages. The matrices g, ζ, Y_b, Y''_{BB}, P, P_t, C_H and Q are fitted using least squares and interpolation techniques [26]. The g, ζ, Y_b and Y''_{BB} matrices are approximated to the RLCG branches, which are implemented in the time domain using the trapezoidal rule and Norton equivalent circuits composed of conductances and controlled current sources [11][25][27]. Further implementation details are provided in [26].

C. Modal White+Black Box in ATP/EMTP in MODELS

The model is integrated into the ATP/EMTP environment through the MODELS module, utilizing the Type-94 Norton block. Within the power system network model in ATP/EMTP, the Type-94 Norton block serves as the interface to the transformer, enabling access to the "foreign" model via its associated "foreign" functions, as described in [12].

IV. VACUUM CIRCUIT BREAKER MODEL

The simulation of high-frequency currents during multiple prestrikes and re-ignitions in VCB switching is performed using a refined VCB model, as described in [18]. This model features an ideal switch controlled by logic implemented in MODELS [12], considering the chopping current, dielectric strength, and quenching capability of the VCB, all of which affect the breaker's state during simulation, as outlined in [14-19].

V. TDSF COMPUTATION

To monitor the internal transient response of transformer windings subjected to voltage disturbances caused by power system events—such as the interaction between the transformer and the grid during VCB switching operations—we propose a metric called the Time Domain Severity Factor (TDSF). This factor enables a TDSF-based evaluation of dielectric stress along the transformer windings by comparing the internal transient response induced by such events with the response observed during standard time-domain dielectric tests [6–10].

The TDSF between two adjacent winding nodes at each time step is given by [7],

$$TDSF(i,j,t) = \frac{\Delta V_{tra}(i,j,t)}{\Delta V_{env}(i,j)} \tag{11}$$

where $\Delta V_{tra}(i,j,t)$ is the voltage drop between the i-th and jth node due to the transient event at t instant time and $\Delta V_{env}(i,j)$ is the maximum voltage drop between the i-th - and j-th node for all standards dielectric tests of the transformer. The case when $i = j$ corresponds to the voltage drop between the i-th node and the grounded core. Expression (11) is used to determined the severity of the dielectric path between two adjacent nodes [6].

In time domain, the maximum TDSF at each transformer node is expressed by,

$$TDSF(i,t) = \max_{j=1,\dots,N}[TDSF(i,j,t)] \tag{12}$$

where N is the total number of nodes into which the transformer windings are discretized. Expression (12) defines the maximum level of dielectric stress sustained by each transformer node at any given time. For safe operating conditions, this value should remain below unity.

Using a TDSF-based evaluation, the severity of dielectric stress can be mapped along the geometry of the transformer windings, enabling the estimation of voltage stress levels and the identification of internal locations subjected to elevated stress. When implemented under field conditions, TDSF monitoring provides valuable insight into the risk levels at specific locations within power transformer windings during interactions with the power system under transient conditions.

VI. PRACTICAL APPLICATION

This section presents case studies (CSs) based on a TDSF-based evaluation, focusing on the interaction between a transformer, VCB, and cable. The system under consideration consists of a single-line representation of the substation described in [9]. The transformer is a single-phase, three-winding unit rated at 50/50/16.67 MVA and operating at 60 Hz, with high-voltage (HV), low-voltage (LV), tertiary (TV), and regulation (RW) windings rated at 230/69/13.8 kV, as illustrated in Fig. 2. Complete design specifications are provided in [29].

A. CS 1: Validation

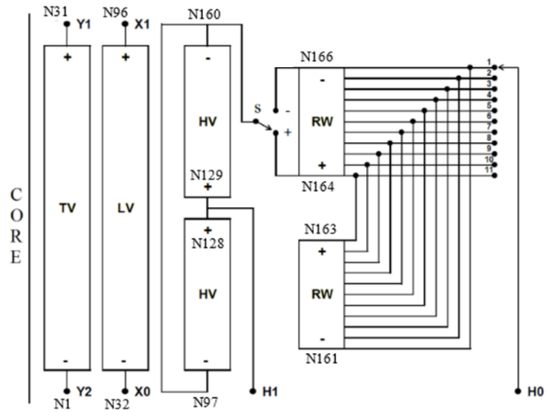
This case aims to validate the white-black model by comparing simulated results with measurements. A standard lightning wave (1.2/50 µs) is applied to H1, with terminal X1 open and other terminals grounded. The voltage-time profile p.u. at various transformer nodes are shown in Fig. 3. The model's accuracy at maximum voltage values is acceptable for this study. The FRA of the calculated admittance matrix elements between transformer terminals is shown in Fig. 4.

B. CS 2: VCB Closing Maneuver and TDSF-Based Evaluation

This case aims to simulate voltage transients during the closing operation of a VCB, in order to recreate the TDSF-based evaluation of transient voltage propagation along the transformer windings over time, as detailed in the next section. The studied system, shown in Fig. 5, consists of a simplified setup with one overhead line, two cable sections, a VCB in between, and the transformer. It includes four 300-meter overhead line segments modeled using the Bergeron method, and two cables characterized by R = 0.27 mΩ/m, Z = 22.35 Ω, and a propagation speed of 179,237,000 m/s. The source-side cable length is fixed at 500 m, while the load-side length varies depending on the scenario. VCB parameters are defined by a dielectric strength rate of 40 kV/ms, a maximum strength of 1050 kV, quenching current capability from 300 A/µs to 500 A/µs, and a chopping current of 1 A. The closing time is set at 9.5 ms. To account for stray effects, a branch is connected in parallel with the VCB, as described in [17], [18]. The simulation time step is 0.2 µs. The transient response of the VCB for a 224 m load-side cable is shown in Fig. 6, overvoltages at transformer terminals in Fig. 7, and internal node responses in Fig. 8.

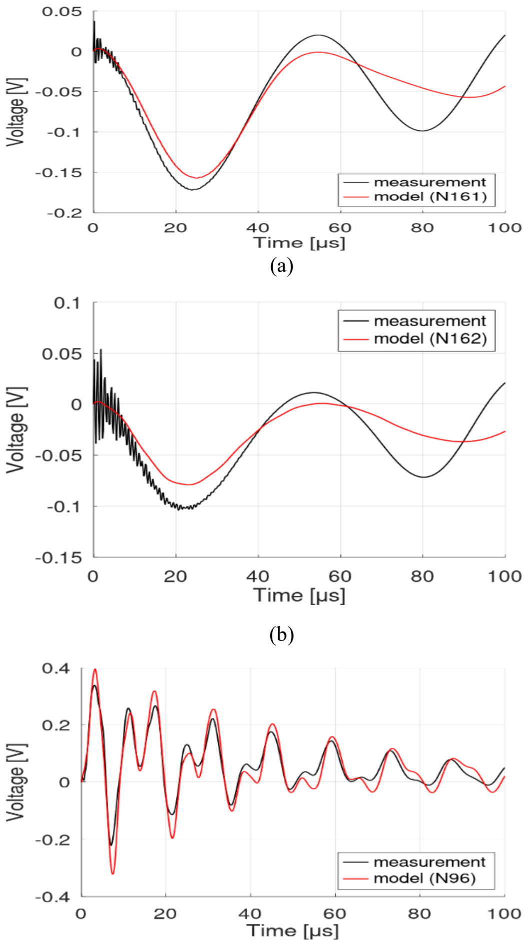
C. CS 3: TDSF-Based Evaluation Voltage Transient Propagation

In this case, transient overvoltages propagate through transformer windings during VCB closing, following the simulation strategy described in the previous section. The objective is to assess dielectric stress using a TDSF-based evaluation. As shown in Fig. 9, the maximum TDSF value reaches 0.46 at the TV and LV windings, indicating that the transformer remains within safe dielectric limits. Figure 10 illustrates how load-side cable length affects TDSF, with longer cables increasing stress due to voltage wave reflections at the transformer terminal, where impedance mismatch leads to oscillations. The oscillation frequency can be estimated as $f_{osc} = v/4l$, where v is the wave propagation speed (approximately 60% of the speed of light) and l is the cable length. By varying the load-side cable from 224 m to 45 km, a frequency sweeps from ~1 kHz to 200 kHz is applied. Figure 10 shows that the maximum TDSF values align with resonance peaks in the transformer winding identified through FRA (see Fig. 4). TDSF peaks occur when oscillation frequencies coincide with resonance modes, notably at 2.5 km and 5.5 km (18 kHz and 8 kHz, respectively). For the worst-case scenario (5.5 km cable), the influence of grounding the X0 terminal is assessed using a variable resistance ranging from short circuit (0 Ω) to open circuit (10 kΩ). As shown in Fig. 11, TDSF remains below the failure threshold until the grounding resistance approaches open-circuit conditions (~6 kΩ), at which point the X0 terminal effectively floats and the transformer may become dialectically vulnerable.



(a) (b)

Fig. 2. Outline of a single-phase of the modelled transformer: Terminals, internal connections, and identification of the transformer nodes.



(a)

(b)

(c)

Fig. 3. Transient voltage (p.u.) measurement vs. simulation under lightning impulse excitation at: (a) N161, (b) N162, (c) X1.

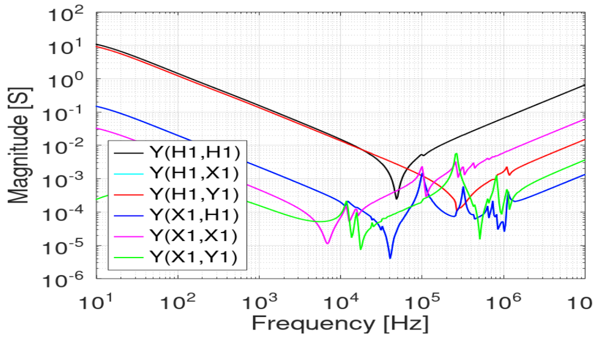


Fig. 4. FRA of the admittance matrix elements between transformer terminals obtained from model.

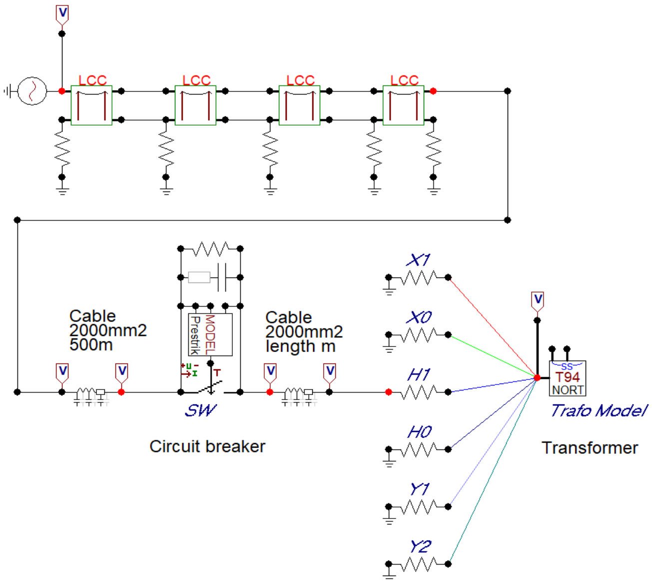


Fig. 5. System configuration implemented in ATP/EMTP to evaluate transformer transient voltages in the practical application.

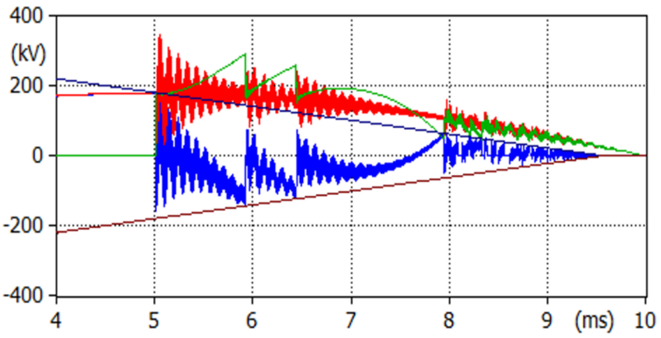


Fig. 6. Transient response of the VCB during the closing operation for a load-side cable length of 224 m: (red) Transient voltage on the source side; (green) Transient voltage on the load side; (blue) Transient voltage drop across the circuit breaker contacts.

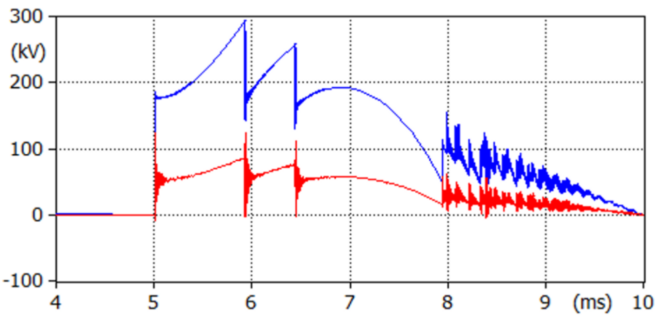


Fig. 7. Transient voltage at the H1 and X1 terminals of the transformer during the VCB closing operation, for a load-side cable length of 224 m: (blue) H1 terminal; (red) X1 terminal.

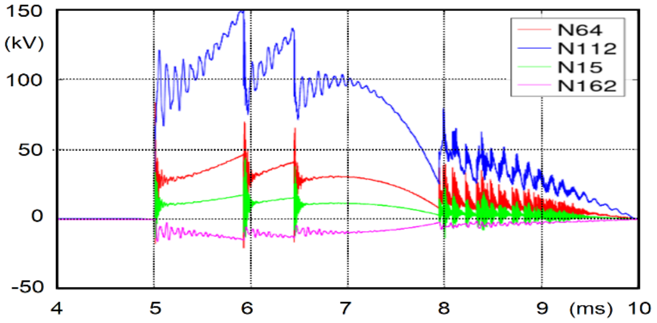
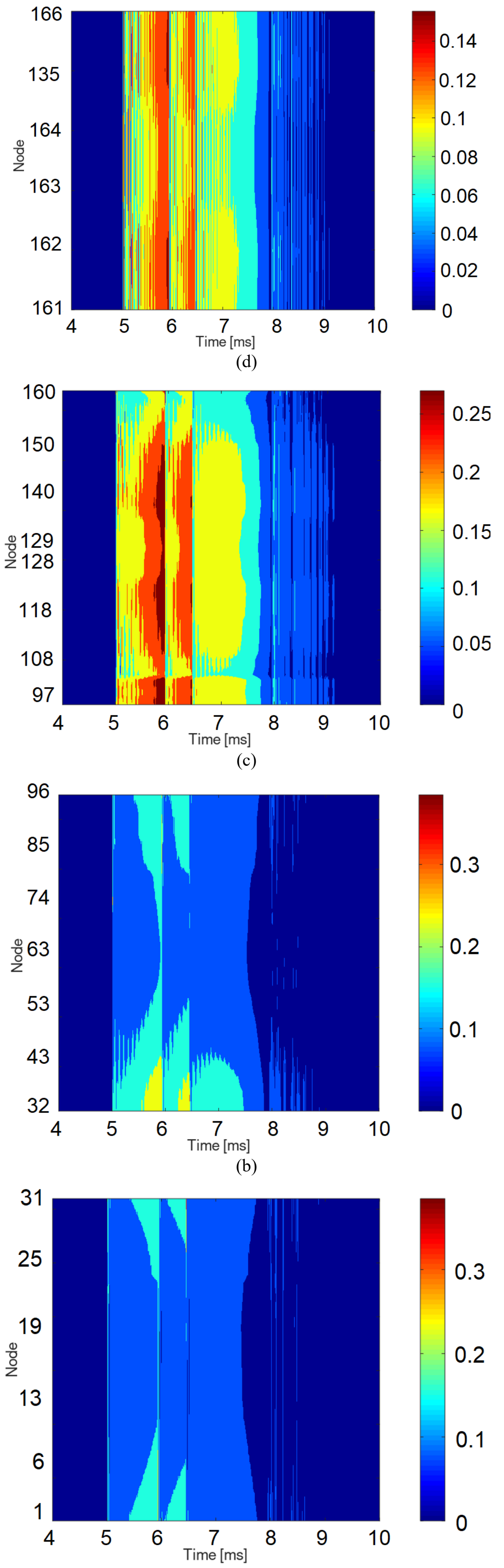


Fig. 8. Transient voltage at various internal nodes of the transformer during VCB closing operation, with a load-side cable length of 224 m.



(d)

(c)

(b)

(a)

Fig. 9. Monitoring of the TDSF at each node and time instant during VCB closing operation, with a load-side cable length of 224 m: (a) TV winding nodes, (b) LV winding nodes, (c) HV winding nodes, (d) RW winding nodes.

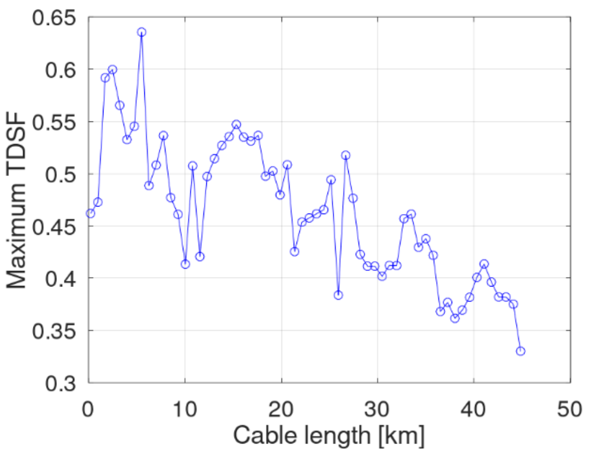


Fig. 10. Maximum TDSF of the transformer during the VCB closing operation for different load-side cable lengths.

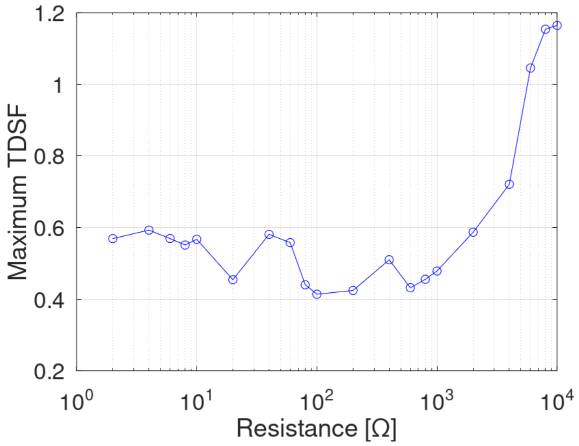


Fig. 11. Maximum TDSF of the transformer during the VCB closing operation for different earth resistances of X0 terminal with the X1 terminal floating and a selected load-side cable length of 5.5 km.

VII. CONCLUSION

This study presents a TDSF-based evaluation of dielectric severity within transformer windings, focusing on transient overvoltages generated during vacuum circuit breaker (VCB) closing maneuvers and their interaction with cable-connected transformers. Unlike previous approaches limited to terminal voltages, the proposed methodology enables the identification of the most critical dielectric stress points across all winding node combinations and their reference to ground.

The evaluation was carried out using a hybrid white–black box transformer model implemented in the ATP/EMTP simulation environment, which proved effective for high-frequency transient analysis within the transformer. Case studies conducted on a 50 MVA single-phase, multi-winding transformer revealed that cable length significantly influences dielectric stress due to resonance effects, although insulation limits were not exceeded under the tested conditions. In contrast, grounding resistance at the LV terminal plays a decisive role in the vulnerability of the winding neutral point, with high resistance values leading to increased dielectric severity and potential risk.

These findings underscore the value of TDSF-based evaluation as both a diagnostic and design-support tool for insulation coordination. By enabling location-specific assessment of transient stress, this approach contributes to improved transformer reliability and supports the development of more resilient power system configurations.

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I. BIOGRAPHIES

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Marjan Popov (M’95–SM’03-F'22) is full professor at the Delft University of Technology, Delft, The Netherlands, in 2002. He is also a Chevening Alumnus and, in 1997, he was an Academic Visitor with the University of Liverpool, Liverpool, U.K., working in the Arc Research Group on modeling SF6 circuit breakers. His major fields of interest are in future power systems, large-scale power system transients, intelligent protection for future power systems, and wide-area monitoring and protection. He is a member of Cigre and actively participated in WG C4.502 and WG A2/C4.39. In 2010, he received the prestigious Dutch Hidde Nijland Prize for extraordinary research achievements. He was the recipient of the IEEE PES Prize Paper Award and IEEE Switchgear Committee Award in 2011 and at present is an Associate Editor for Elsevier’s International Journal of Electrical Power and Energy Systems. In 2017, together with the Dutch utilities TenneT, Alliander and Stedin he founded the Dutch Power System Protection Centre to promote the research and education in power system protection.

Luis Rouco obtained the M. Sc. and Ph.D. degrees from Comillas Pontificial University, Madrid, Spain, in 1985 and 1990, respectively. He is a Full Professor of the School of Engineering (ICAI) of Comillas Pontificial University attached to the Department of Electrical Engineering. He develops his research activities at the Instituto de Investigación Tecnológica (IIT), IC-AI, Universidad Pontificia Comillas. He is a Distinguished Member of CIGRE where he convenes the Advisory Group on Wind Generation and New Technologies of Study Committee Al on Rotating Machines. He has been Visiting Engineer at MIT, Ontario Hydro, and ABB Power Systems. His research interests include modeling, analysis, and simulation of power system.