Mansoura Engineering Journal

Volume 49 | Issue 5 Article 4

2024

The Transformer Modelling for VFTOs Calculation - A Comprehensive Review Mohamed Salah

Mohamed Salah
Demonstrator, Electrical Engineering Department, Faculty of Engineering, Mansoura University, mohamedwaheeb@mans.edu.eg

Ebrahim A. Badran
Professor of Electrical Power Electrical Engineering Department, Faculty of Engineering, Mansoura University Dean, HIET Mansoura Collage

Mansour H. Abdelrahman
Professor of Electrical Power Electrical Engineering Department, Faculty of Engineering, Mansoura University

Recommended Citation

Salah, Mohamed; Badran, Ebrahim A.; and Abdelrahman, Mansour H. (2024) "The Transformer Modelling for VFTOs Calculation - A Comprehensive Review Mohamed Salah," *Mansoura Engineering Journal*: Vol. 49 : Iss. 5 , Article 4.
Available at: https://doi.org/10.58491/2735-4202.3226

REVIEW

Analysis of the Transformer Winding Under Very Fast Transient Overvoltages: A Comprehensive Review

Mohamed Salah*, Ebrahim A. Badran, Mansour H. Abdelrahman

Department of Electrical Engineering, Faculty of Engineering, Mansoura University, Mansoura, Egypt

Abstract

The transformer is exposed to very fast transient overvoltages originated from the switching operations in the gas insulated switchgears, these overvoltages may damage the transformer insulation and result in catastrophic failures. Consequently, the transformer should be modeled to handle the transient state. In this work, the methods published in the literature to illustrate the very fast transient overvoltages in gas insulated switchgears are reviewed, and then an overview of the transformer modeling techniques is presented with the contribution and shortcomings of each technique. The determination methods of the parameters required for the modelling of the transformer are also reviewed. In addition, the contributions of utilizing the frequency response analysis as a diagnostic tool of the transformer condition are summarized.

Keywords: Fault, Frequency response analysis, Gas insulated switchgears, Transformer, Transients, Very fast transient overvoltage

1. Introduction

The power transformer is considered as one of the most vital pieces in the power system as it is an essential link in the chain of power system components. The transformer failure may result in catastrophic failures to the other system devices, and economic consequences, incorporating proceeds decrease and market backlash (Abbasi, 2022). Hence, the reliability of the power system relies significantly on the reliability of the transformer. A significant amount of transformer failures is due to the fast and very fast transient overvoltage (VFTO) (Taikina-aho, 2010). As this overvoltage results in a dielectric stresses degrading the insulation between the turns and this leads to hazardous short circuit between the turns, therefore the transformed insulation should be designed well to withstand such overvoltages.

Most of the transient overvoltages in the power system result from the switching operations in the gas-insulated switchgears (GIS) (Vinod Kumar et al., 1999; Lu and Zhang, 2005; Yu et al., 2009). When the disconnector in the switchgear is being opened or closed, arc strikes occur between the contacts, so VFTOs are generated and propagate into the power system. These overvoltages may damage the devices connected to GIS, especially the transformer, as the frequency of the VFTO may match one of the resonant frequencies of the transformer winding, consequently this results in an inter-turn fault as the insulation between the turns is vulnerable to the high-frequency oscillations.

The transformer may pass the standard tests, and in the same time the failure occurs due to overvoltage. To reduce the failure, the system is to be modeled to monitor and assess the state of the system various devices, and to clarify the mutual effect between the transformer and the other system components (Yang et al., 2011).

The transformer modeling is not an easy process for many reasons among them: the transformer behavior is non-linear, frequency dependent, and affected by the variations in the winding and the core construction. In addition to the presence of physical attributes which have to be considered. Many

Received 8 February 2024; revised 22 May 2024; accepted 7 June 2024.
Available online 19 July 2024

* Corresponding author.

https://doi.org/10.58491/2735-4202.3226

achievements for transformer winding have been published in the literature which can be categorized into: multi transmission line (MTL) model, the lumped parameter models, and the hybrid models. The MTL models are utilized for fast and VFTO, the voltage distribution along the winding can be driven from these models. They require the construction details of the transformer winding and are time-consuming (Shibuya and Fujita, 2002; Popov et al., 2007; Wang et al., 2018). The lumped parameter models depend on the geometrical data of the transformer (Yang et al., 2011; CIGRE, 2014; Colqui et al., 2019). They are used to simulate the lightning impulse and the fast transient overvoltage and to clarify the interaction between the transformer and the neighboring equipment. The hybrid model is a compromise between the aforementioned two models, where the winding is represented by a single transmission line to compute each disc voltage, and then the coil of interest is studied so as to obtain the voltage on each turn (Shintemirov et al., 2009a).

The above models depend significantly on the capacitance and the inductance matrices, consequently, these matrices have to be calculated precisely. These matrices can be calculated either by analytical expressions or by finite element method (FEM). In the analytical method, the turns are treated as parallel plates (de leon et al., 2009) to calculate the capacitance, Analytical expressions are used to compute self and mutual inductance as given in (Miki et al., 1978). The authors in (Portillo et al., 2020) reviewed the basics of parameters computation for high frequency transients. There are three approaches to calculate the capacitance matrix by FEM: forced voltage, fixed charge and energy method (de leon et al., 2009), while the inductance matrix can be calculated by flux linkage method or energy method.

Condition monitoring, based on the transformer modelling, is an efficient method to reduce the failures, and help in detecting the deformation in earlier stages which prevent the occurrence of catastrophic failures (Zhang et al., 2015). The FRA introduced in (Dick and Erven, 1978) is an efficacious approach to detect mechanical deformations such as buckling and tightening. In the FRA, sinusoidal voltages containing different frequencies are applied to one terminal then the magnitude and phase of selected winding terminal are plotted as a function of frequency. The instrumentation required for this method is commercially available and can be set up to give repeatable results easily. This approach is considered as simple and cheap which allows the analysis of the transformer in wide frequency range.

Abbreviation

AI	artificial intelligence
BEM	boundary element methods
EMD	empirical mode decomposition
FDTD	finite difference time domain
FE	finite element
FEM	finite element method
FRA	frequency response analysis
GIS	gas insulated switchgears
IF	impulse frequency
STLM	single transmission line model
TF	transfer function
VFTC	very fast transient current
VFTO	very fast transient overvoltage

In this work, first the methods employed to depict VFTOs of GIS are examined. Then the transformer modelling techniques are reviewed in section 3 showing the pros and cons of each model. Section 4 shows the determination methods of the parameters required for the modelling of the transformer. The contributions of utilizing the FRA as a diagnostic tool of the transformer condition are summarized in section 5. Finally, the recommended research issues and conclusions are given in sections 6 and 7, respectively.

2. The VFTOs of GIS

The majority of transient overvoltages in the power system result from the switching operations in the GIS (Vinod Kumar et al., 1999; Lu and Zhang, 2005; Yu et al., 2009). When the disconnector in the switchgear is being opened or closed, arc strikes occur between the contacts, so VFTOs are generated and propagate into the power system.

An early trail to calculate the transient over voltage was introduced by Lovass-Nagy and Szendy in 1964 (Lovass-Nagy and Szendy, 1964). The study outlined a matrix method to derive relatively straight forward expressions for calculating transient-voltage distribution in a system. The differential equations governing the transient voltages were combined to create a unified matrix equation, the solution of which was obtained through the application of the Laplace transform and the matrix-inversion technique. An algorithm incorporating also the numerical inversion of the Laplace transform, accounting for frequency-dependent parameters, was introduced in (Ahmad et al., 1992). This algorithm was applied to transient calculations with good accuracy. The numerical results exhibited agreement with the measured values.

The VFTO results of a 420 KV GIS calculated using EMTP were proposed in (Vinod Kumar et al., 1999). The pattern of VFTO during the switching operations in the disconnector and the circuit breaker was studied. The formulae of VFTO waveform were deduced in a theoretical manner in (Yu et al., 2009) using the transmission line model. The authors assumed the structure of GIS illustrated in Fig. 1 and its equivalent circuit as shown in Fig. 1. It was assumed that the bus 1 had a trapped voltage of E_1 and bus 2 had initial voltage of E_2 when the switch was closed the amplitude of k th harmonic G_k was deduced as (Yu et al., 2009)

$$G_k = \frac{\sin(\omega_k T_1)\cos(\omega_k T)}{\omega_k T - \sin(\omega_k T)\cos(\omega_k T)}(E_1 - E_2) \tag{1}$$

$$T = T_1 + T_2$$

And the DC component E_0 as (Yu et al., 2009)

$$E_0 = \frac{T_1}{T + z\omega_k}(E_1 - E_2) + E_2 \tag{2}$$

Where T_1, T_2 are the transmission times through bus 1 and bus 2, z is the surge impedance of the buses and ω is the angular frequency of kth harmonic. The analysis involved examining the impact of the length and the characteristic impedance of the bus, and external equivalent capacitance of the transformer on the VFTO waveform. The simulation waveforms obtained by PSCAD software were aligned with the analytical results.

The work in (Wong and Chen, 2009) demonstrated the switching operations in China light and Power Company in Hong Kong. Simulation analysis was performed to evaluate the potential risks of VFTO in GIS substation. The results revealed that the major components of the VFTO cover frequency range from 0.75 MHz to 7 MHz. It was reported that the VFTO surpassed the dielectric strength withstand level of turn-to-turn insulation, particularly for high-frequency components.

Researchers in (Li et al., 2012) discovered a specific category of VFTOs through onsite testing on an 800 kV GIS in commercial operation. The features of this novel VFTO type were examined, encompassing

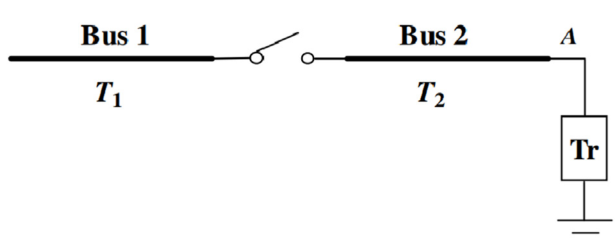

Fig. 1. Structure of GIS system (Yu et al., 2009).

parameters such as the timing of arc restrikes between contacts, rise rate, damping time constant, oscillating frequency, and trapped charge. The results of the work showed that using closing and opening resistors in disconnect switches had the benefit of suppressing VFTO. In (Zhan et al., 2014), a 252 kV GIS circuit and the measurement system for VFTO and very fast transient current (VFTC) were constructed. The relationship between the VFTC and the arc resistance was discussed. Another VFTC model was proposed in (Duan et al., 2015). Tests were conducted on an actual 220 kV GIS. A measurement setup utilizing a Rogowski coil in conjunction with an optical fiber transmission system was employed to measure VFTCs.

A fitting method was introduced in (Almenweer et al., 2018) to derive the mathematical equation describing the SF6 discharge waveform. The aim of this method is to adjust the parameters of a model function to achieve the best fit with a given data set. A typical data set comprises n points (data pairs) (x_i, y_i), where x_i represents an independent variable and y_i represents a dependent variable obtained through observation. The model function is represented as (x), where the vector β holds m adjustable parameters, reflecting the fact that the function model incorporates m parameters. The fit of a model to a data point is assessed by its residual, calculated as (Almenweer et al., 2018):

$$r_i = y_i - f(x_i - \beta) \tag{3}$$

The VFTO waveform resulting from a single SF6 gas discharge was derived from the collected data in (Xixiu et al., 2017). The frequency characteristics were extracted from the time-domain waveforms using the fast Fourier transform (FFT) technique implemented in Matlab. It was determined that the Squares Method was suitable for fitting the VFTO expression due to its transient characteristics. The computed values matched effectively with the results obtained using ATP-EMTP software and the measurements reported in (Xixiu et al., 2017). Utilizing EMTP, disconnector switching operations were simulated in (Haseeb and Joy Thomas, 2018) at different locations in a GIS rated at 1100 kV. In the examination of the specified substation, the highest calculated overvoltage reached 1.76 p.u not accounting for the charge present on the bus bar. However, when considering a trapped charge of 1 p.u, the maximum overvoltage elevated to 2.54 p.u. The research outlined in (Ametani et al., 2018) concentrated on analyzing the oscillating frequencies of VFTOs produced during disconnector and circuit breaker switching operations within GIS. The study presented simulation instances that were demonstrated in comparison with test results and showed a reasonable concurrence with the EMTP simulation results.

In (Chung, 2004), a statistical investigation was conducted to analyze the variations in overvoltage associated with the step-up transformer during the switching of vacuum circuit breakers. Certain variables, such as the switching angle, wind turbine power current chopping, high-frequency and current quenching capability were considered as random variables in the analysis. The investigation revealed that relying solely on the amplitude of transient overvoltages was insufficient for forming conclusions regarding the safety of the transformer when subjected to frequent switching surges.

Simulations in (Moreiraa et al., 2020) were performed using EMTP with GIS model for high-frequency analysis and multi-strike electric arc modeling. Field test measurements on 550-kV GIS were compared with simulation results and showed an accurate prediction for VFTO, allowing improved failure analysis.

The work in (Zhao et al., 2022) handled the complex frequency-related parameters. The transfer function of the ultra-high voltage GIS voltage transformer was obtained with the impulse test as exciting signal. Simulation was employed to model the VFTO and their associated conducted disturbances at the Wuhu substation. The waveforms of VFTO, both calculated and measured, exhibited notable consistency in terms of shape, amplitude, and duration. This matching substantiates the accuracy of the employed model. A special online sensor to VFTOs based on the optical sensor technology was introduced in (Chatrefou et al., 2000). A fraction of the high voltage was applied by a geometrical capacitive divider near the base of the high voltage bushing. In (Ma et al., 2009), an innovative measuring system featuring surface-mounted devices was introduced, designed to provide wide-bandwidth capabilities and ensure stability. The measuring technique in (Ma et al., 2011) was based on a transformer bushing sensor. To address the challenge of frequency limitation, a solution was proposed involving the application of both the convolution model and the incremental Wiener filter. Utilizing this methodology, measurements conducted at the 750 kV substation revealed that the disconnector switching off operations generated a VFTO with a peak value of approximately 775 kV. while the predominant oscillating frequencies of the VFTO were identified as 3.5 MHz, 1.6 MHz, and 650 kHz.

A simplified shrinkage ratio criterion was presented in (Yang et al., 2016) to calculate the distribution of lightning impulse voltage within transformer windings based on the relationship between physical quantities. The authors employed finite element (FE) simulation software to model both the reduced-scale and the original electromagnetic field configurations.

In (Florkowski et al., 2016), an extensive analysis of the propagation of overvoltages through distribution transformer windings was presented, focusing on typical medium and low-voltage electrical networks. The authors in (Gongchang et al., 2013) introduced a complete frequency bandwidth measurement system utilizing a porthole capacitive voltage divider. Three measurement circuits were studied and the effect of cable length on the measurements was discussed. The objective of the study presented in (Soloot et al., 2013) was to examine the impact of resonant overvoltage generated in wind turbine transformers across different winding designs: disc, layer, and pancake configurations.

A transient overvoltage monitoring system was introduced in (Filipović-Grči et al., 2017). This system used an on-line overvoltage transient recorder with the ability to sample, analyze and store transients at transformer terminals in real-time.

The results of overvoltages resulted from the switching of a compensation coil to the tertiary winding of a transformer were proposed in (Wouters et al., 2019). The method provided bandwidth, up to 10 MHz, Enabling the observation of fast transient events within the waveforms.

A statistical correlation technique was introduced in (Garg et al., 2020) to determine the optimal correlation between transient signals to assess the insulation's condition, distinguishing between pass and fail states. The effectiveness of the technique was confirmed through the validation of partial discharge detection in windings subjected to impulse voltage application, utilizing an 11 kV single-layer winding.

In (Jurisic et al., 2021), the illustration of 123 measured overvoltages in 220 kV air-insulated substations served the purpose of dimensioning transformer insulation to withstand potential overvoltages in the power network. This precaution aims to prevent potentially hazardous situations arising from resonances. The severity factor in the frequency domain was computed for the observed signals. The authors in (Oliveira et al., 2022) successfully demonstrated the achievement of improved time-domain reproduction by emphasizing the significance of extending frequency-domain measurements into higher frequencies, accomplished through the utilization of S-Parameters. Table 1 gives the contributions and shortcomings of the works which deal with the VFTOs of GIS.

3. The transformer modelling for VFTOs

As mentioned above the transformer modeling is categorized into three categories:

(a) Lumped parameter Model.
(b) MTL Model.
(c) Hybrid Model.

3.1. Lumped parameter model

The model involves dividing the winding into segments, each represented by a ladder network comprising lumped resistive, inductive, and capacitive components, as illustrated in Fig. 3. In this model the voltages and currents are related to each other through the following equation (Van Jaarsveld, 2013):

$$[C_n]\frac{d}{dt}v(t)+\frac{1}{[L_n]}\int_{t2}^{t_1}v(t).dt=I(t) \quad (4)$$

A reduced order lumped parameter model of the transformer windings designed for the analysis of high-frequency transients was presented in (de Leon and Semlyen, 1992). This model underwent validation through both frequency and time domain simulations. A coupled circuit FE model was proposed in (Abed and Mohammed, 2010) with an additional high-frequency branch, operating in parallel with the nominal power frequency model.

The models in (Liang et al., 2008; Wang et al., 2008) used the Krylov subspace technique to reduce the order of the transfer function (TF) derived from the lumped circuit modeling of the transformer under VFTOs. In (Liang et al., 2008) Arnoldi algorithm, one of Krylov subspace methods, was used. In (Wang et al., 2008) a fast algorithm utilizing the Precise Integration Method and Krylov subspace technique was presented. A simulation study using P-Spice program was proposed in (Srinivasamurthy and Dixit, 2016). The study was performed for continuous disc-type winding and interleaved winding.

A methodology for applying black-box transformer models to the lumped-parameter representation of transformer windings was proposed in (Theocharis et al., 2016). The amplification factor $N_{tm,k}$ from an external node t to a specific internal node m concerning the node k where an input is applied is determined by (Theocharis et al., 2016)

$$N_{tm,k}=\frac{e_{t,k}-e_{m,k}}{e_{k,k}} \quad (5)$$

Where e denotes the node-to-reference voltage in the frequency domain. The internal voltage distribution was calculated by utilizing an approximation with a lumped-parameter model. The method was

Table 1. Contributions and shortcomings of the illustrating techniques of the VFTOs of GIS.

REF	Year	Contributions	shortcomings
Ahmad et al. (1992)	1992	Presenting methodology to examine transient overvoltages easily in both easily in simple and complex cases.	Nonlinear characteristics were not be taken into account using this algorithm.
Yu et al. (2009)	2009	Deduction of the analytical formulae of VFTO waveform.	The running time of the analytical methods was larger than the simulation time.
Zhan et al. (2014)	2014	The measurement system for VFTO and VFTC in a 252 kV GIS circuit.	Modification was required in VFTO simulation for extra and ultra-high voltage systems.
Ametani et al. (2018)	2018	Illustrating the oscillating frequencies of very fast transients.	The radiation losses were not included.
Chatrefou et al. (2000)	2000	Introducing a special online sensor to VFTOs based on the optical sensor technology.	The vibrations and temperature rise affected the accuracy.
Ma et al. (2009)	2009	Proposing a measuring system featuring surface-mounted devices designed for wide bandwidth and stability. The measuring system was stable and applicable in the field.	The coaxial cable used in the measuring system would produce overvoltage on the GIS tank.
Yang et al. (2016)	2016	Presenting A simplified shrinkage ratio criterion to quantify nanosecond pulse voltage and assess the distribution of lightning impulse voltage within transformer windings.	The assumption of constant electric field intensity taken in the design of the shrinkage model reduced the accuracy of the model.
Gongchang et al. (2013)	2013	Presenting a measurement methodology with bandwidth range up to 300 MHz.	The circuit has a limitation in its low frequency response band (below 113.7 Hz).
Li et al. (2012)	2012	Illustrating a set of measured overvoltages in 220 kV air-insulated substations.	The correlation between different amplitude and front time or front and tail time was not discussed.

based on the transformation matrix utilization of the voltage distribution factors. The simulation was performed via MATLAB software.

A systematic methodology was proposed in (Zhongyuan et al., 2008) for developing a high-frequency two-port circuit model for transformer windings under VFTO by using its frequency responses. The experiment results showed the practicality and the accuracy of the model. Because of the complexity of the model, the simulation time is relatively large.

A refined lumped RLC model was formulated in (Yang et al., 2011) whose parameters were derived as

$$Y_1 = \frac{1}{2}(G + sC) Y_2 = (R + sL)^{-1} - \frac{1}{8}(G + sC) \tag{6}$$

To counteract the reduction in susceptance with increasing frequency, a negatively valued capacitive branch was introduced in parallel with the inductive branch as shown in Figs. 3−5.

The work in (Colqui et al., 2019) showed a refined π-circuit cascade with a damping resistor in series with the shunt capacitor as illustrated in Fig. 3, In this topology, the artificial damping resistance R_D is given by (Colqui et al., 2019)

$$R_D = K_P \frac{2L}{\Delta t} \tag{7}$$

where K_P is an adjustable factor that varies between 2 and 10, L is the longitudinal per-unit value inductance and Δt is the time step size simulation.

The authors in (Ding et al., 2020) proposed a modified lumped parameter model with parameters deduced as (Ding et al., 2020)

$$Y_1 = 0.5078(G + sC) \tag{8}$$

$$Y_2 = (R + sL)^{-1} - 0.1703(G + sC) \tag{9}$$

The model minimized the errors impacted by the lumped parameter approach, and the hyperbolic functions of the distributed parameter model.

3.2. MTL model

In the MTL model, each disc or turn is represented by transmission line and these discs are connected to each other in a cascaded manner as shown in Fig. 2 the telegrapher equations can be applied to this circuit as (Van Jaarsveld, 2013)

$$\frac{d}{dx}\widehat{V}(x,s) + \widehat{Z}(s)\widehat{I}(x,s) = 0 \tag{10}$$

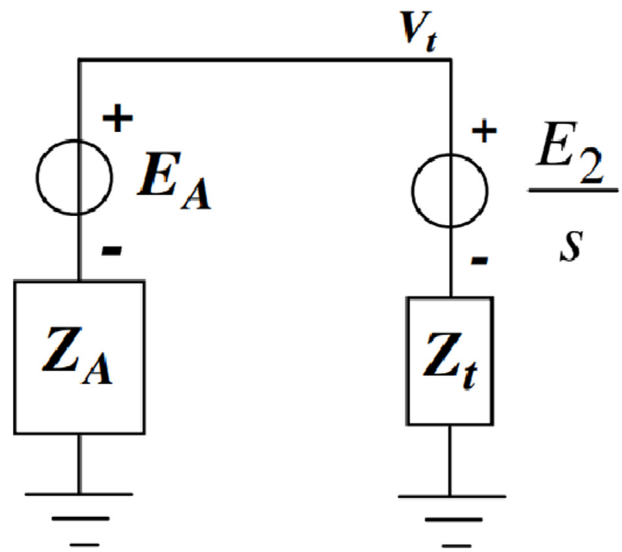

Fig. 2. Thevenin Equivalent of GIS system (Yu et al., 2009).

$$\frac{d}{dx}\widehat{I}(x,s) + \widehat{Y}(s)V(x,s) = 0 \tag{11}$$

Where $\widehat{V}$, $\widehat{I}$ are the voltage and current matrices, and $\widehat{Z}$ and $\widehat{Y}$ are the impedance and admittance matrices which can be calculated as (Van Jaarsveld, 2013)

$$\widehat{Z} = R + sL \tag{12}$$

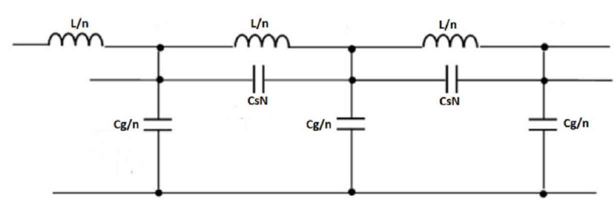

Fig. 3. A segment of lumped parameter model of transformer winding (Fattal, 2017).

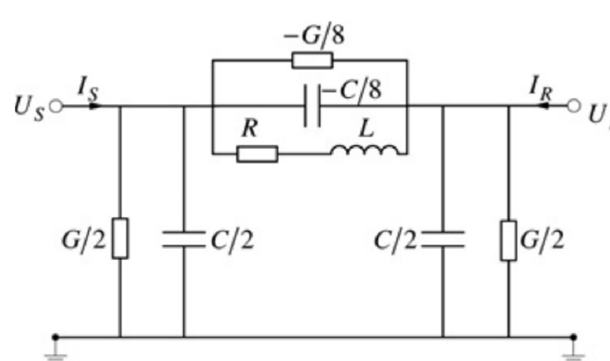

Fig. 4. Equivalent two-port circuit of lumped RLC model (Colqui et al., 2019).

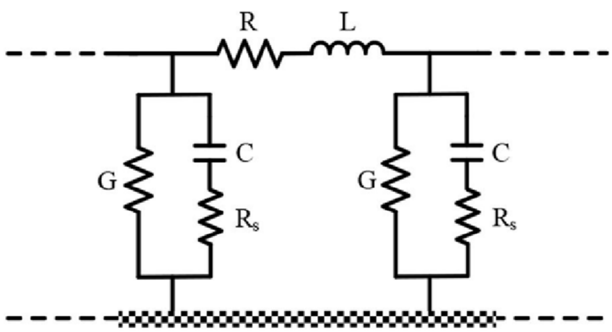

Fig. 5. Modified RLC circuit using damping resistance (Portillo et al., 2020).

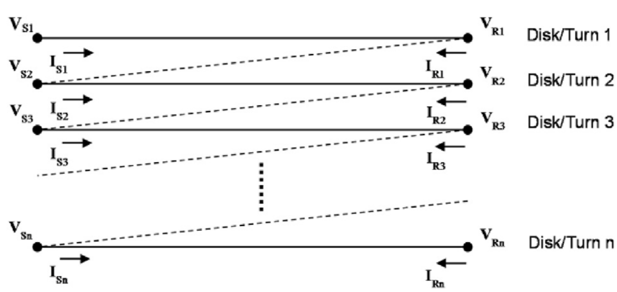

Fig. 6. Multiconductor transmission line model, each turn in a disk is represented as a transmission line and connected to the subsequent turn in a zig-zag configuration (Fattal, 2017).

$$\widehat{Y} = G + sC \tag{13}$$

Fig. 6.

A lumped parameter model based on state-space equations, and a distributed parameter model based on the multi conductor line theory and Bergeron's model were introduced in (Villanueva-Ramí et al., 2014). The models were based on MATLAB SIMULINK. The results indicated that the distributed parameter model was theoretically more accurate where the time required for the lumped parameter model was smaller.

A MTL model was used in (Shibuya et al., 1997), where The entirety of the transformer windings was modeled and simulated as a single transmission line, then the first coil was simulated using the MTL model. The voltage for each turn V_i was solved in form (Shibuya et al., 1997)

$$V_i = KE_0 + A_i \exp(-\Gamma x) + \beta_i \exp(\Gamma x) \tag{14}$$

$$\Gamma = \frac{j\omega}{v_s}$$

$$v_s = \frac{c}{\sqrt{\varepsilon_r}}$$

E_0 is the voltage supplied to the winding, and the values of A_i and β_i are determined through the boundary conditions, c, ε_r are the speed velocity and the relative permittivity of the winding insulation. Further study was necessary to assess the reliability of the applied model to determine the effects of the VFTOs' on transformers in field. The authors in (Shibuya et al., 2001) aimed to reduce the number of unknowns in the MTL methodology by combining multiple turns under common parameters.

A model based on turn-to-turn modelling of the windings using a wavelet filter bank was proposed in (Saleh and Rahman, 2002). The transformer model utilizing the wavelet filter bank can be depicted by stages, which correspond to the number of turns in the transformer. The model considered the active coupling between the windings and the iron core.

The work in (Zhongyuan et al., 2006) adopted a MTL model, where the computing equations of the model were based on FDTD methodology. The voltage recursion relations can be derived by employing second-order central differences (Zhongyuan et al., 2006)

$$V_k^{n+1} = V_k^n - \frac{\Delta t}{\Delta z} C_k^{-1} \left(I_k^{n+\frac{1}{2}} - I_{k-1}^{n+\frac{1}{2}} \right) \tag{15}$$

n stands for the time point, and k stands for the position point.

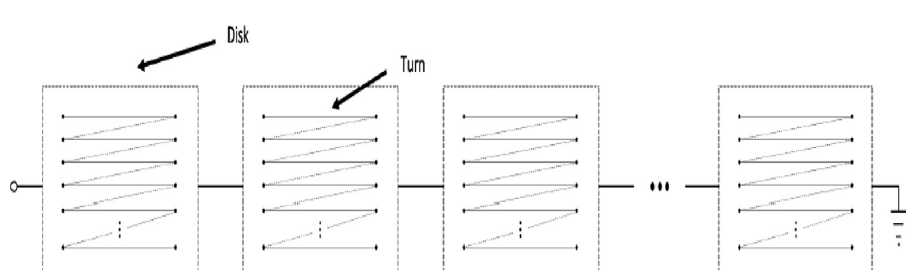

Fig. 7. The hybrid model representation pf the transformer winding (Fattal, 2017).

The authors in (Liang et al., 2006a) integrated the theory of compact finite difference with the precise integration method within the MTL model.

A high frequency model based on s-parameters was introduced in (Zhang et al., 2008a). The authors derived voltage TF from s-parameters which was measured or calculated from transformer windings. The vector fitting was used to fit the derived voltage TF, and then the voltage TF was order-reduced by the optimal Pade-approximation algorithm. Frequency-dependent parameters were computed using vector fitting and recursive convolution techniques. The work in (Popov et al., 2007) dealt with layer type transformer windings. A step pulse with 50 ns rise time was used as exciting signal of transformer to measure the response. The MTL model was used to calculate the voltage distribution across the transformer layers and turns. The computations were performed by using the inductance matrix which was calculated by inverse capacitance matrix and by making use of Maxwell formulas. The complete iron core losses and the proximity effect between the layers were considered. More work was needed for the analysis of the voltage distribution along the windings in a three-phase transformer.

The high order Radau method was presented in (Wang and Yangm, 2016). The integration scheme of the high-order Radau method and its features were presented, with particular emphasis on the coefficient matrix satisfying V-transformation. The EMT simulations for overvoltages of transmission line were carried out.

In (Venegas et al., 2011), the electric parameters of the transformer were calculated via conventional formulation. Then these parameters were utilized in MTL model.

A single-input and multiple-output model relied on MTL was presented in (Liang et al., 2006b). Vector fitting and recursive convolution (Grivet-Talocia, 2004) were used to represent the response in the time domain, the voltage and current at the beginning and the end of the coil were related as (Liang et al., 2006b)

$$\begin{pmatrix} I_s \\ I_s \end{pmatrix} = \begin{pmatrix} Y_0 cothPl & -Y_0 cschPl \\ -Y_0 cschPl & Y_0 cothPl \end{pmatrix} \begin{pmatrix} U_s \\ U_r \end{pmatrix} \tag{16}$$

$$P^2 = ZY\, Y_0 = Z^{-1}P \tag{17}$$

The results showed that the model was adequate to calculate the resonances in transformer winding under very fast transients.

The work in (Shibuya and Fujita, 2002) introduced the anisotropic complex permeability of the lamination core in computing inductances and resistances required for the MTL model.

Modifications were made in (Zhang et al., 2013) to the MTL to consider the inserted capacitance and the duplex winding to illustrate the electromagnetic induction between the transformer windings. The terminal conditions of the MTL models considering screen tapes were predicted. Another model employing alternative modal decoupling technique was introduced in (de Carvalho et al., 2016). The decoupling was performed using the real and constant Clarke matrix and a reduced frequency dependent matrix for decoupling the remaining mutual terms in the admittance and impedance matrices.

The fundamental principle of rotating transformation was combined with the traditional EMT modeling method in (Yao et al., 2018). The low-frequency line models incorporating single-phase lossless, single-phase lossy, and three-phase decoupling models were deduced. A hybrid simulation involving distinct steps and its sequential coordination method was discussed.

In (Mombelloa and Diaz Florez, 2020) a process for determining the model parameters was introduced that enhanced the model stability. The FEM was used to obtain the basic impedance data. Subsequently, the approach for processing these data to derive parameters for a stable and robust model was illustrated, utilizing Vector Fitting in conjunction with Particle Swarm Optimization. The model was verified by the results of a 50 MVA unit.

3.3. Hybrid model

To address the complexities of the MTL model, a hybrid model has been developed to efficiently reduce computation time and hardware requirements. This hybrid model computes overvoltage in two steps. First, the winding is modeled using a single transmission line per disk to determine the voltage of each disk. Second, the disks of interest are represented by an MTL model to compute the voltages for each turn. The Lyout of this model is illustrated in Figs. 3 and 7.

A hybrid model was introduced in (Gharehpetian et al., 1998), consisting of a detailed, coil-by-coil model and an inter-coil black box model. The detailed model's parameter determination and the synthesis of the black box model relied on frequency domain measurements. The model was simulated using EMTP. The measurements verified the accuracy of the model in the frequency range from 10 kHz to few MHz.

In (Babaei et al., 2012) the transformer models used for electromagnetic transient studies were described and compared together. The comparison showed that the lumped parameter models have better characteristics in transient phenomena which have a very high frequency such as the overvoltages introduced by lightning. The number of calculations required for single transmission line model (STLM) was less than other models. The MTL model was more accurate than STLM but the amount of calculation required for this model was more.

The applied algorithm in (Popov et al., 2003) used a hybrid model which was a combination of the MTL model and STLM. By means of STLM, the voltages at the end of each coil were computed, and these values were subsequently employed in the MTL model to calculate the voltage distribution within the coils.

In (Shintemirov et al., 2009b) the voltage and the current at the beginning and the end of the disc is calculated as (Shintemirov et al., 2009b)

$$\begin{bmatrix} I(s,0) \\ I(s,l) \end{bmatrix} = \begin{bmatrix} Y_{11}(l) & Y_{12}(l) \\ Y_{21}(l) & Y_{22}(l) \end{bmatrix} = \begin{bmatrix} U(s,0) \\ U(s,l) \end{bmatrix} \quad (18)$$

$$Y_{11}(l) = -\phi_{12}(l)^{-1}\phi_{11}(l) \quad (19)$$

$$Y_{12}(l) = -\phi_{12}(l)^{-1}$$

$$Y_{21}(l) = \phi_{21}(l) - \phi_{22}(l)\phi_{12}(l)^{-1}\phi_{11}(l)$$

$$Y_{22}(l) = -\phi_{22}(l)\phi_{12}(l)^{-1}$$

Where $I(s,0)$, $I(s,l)$, $U(s,0)$ and $U(s,l)$ are the currents and the voltages in the beginning and end of the disc, $\varnothing(l)$ was calculated in iterative manner as

$$\varnothing(l) = e^{A\alpha_p} \times \cdots \times e^{A\alpha_2} \times e^{A\alpha_1} \quad (20)$$

Where α_i denotes the length of the i th turn and p is the number of turns in the disc.

In (Zhang et al., 2008b), a lumped parameter circuit model is utilized to derive the MTL model of the transformer under VFTO. Each winding was modeled as one unit, others were modeled as another unit, transient over-voltage distribution of practical transformer is calculated using FDTD methodology.

Table 2 gives the contributions and shortcomings of the transformer modelling techniques.

4. The transformer parameter determination

An early trial to compute the mutual inductance of coaxial cable was by Grover in 1933 (Grover, 1933) where tables and formulae were introduced to obtain the mutual inductance. To calculate the leakage reluctance of the transformer, equations were presented in (Rabins, 1956). An impedance formula based on the frequency was introduced in (Wilcox et al., 1989). The authors in (De Leon and Semlyen, 1992; Heinemann and Helfrich, 2000) aimed to calculate the capacitance and the inductance for the high frequency transient models. In (De Leon and Semlyen, 1992) the capacitance was computed by the charge simulation method, while the inductance was computed by the method of image.

A method was introduced in (Cornick, 1992) to obtain the proximity losses of the transformer winding based on the reluctance network of the magnetic paths in the insulation of the winding, and the magnetic flux which penetrates the turn's sides facing each other.

A novel method to calculate the inductance of the transformer was introduced in (Yan et al., 2005). This method was on the basis of the magnetic circuit. The calculation of the leakage and mutual inductances were assured by the dynamic analog tests.

A precise equivalent circuit model designed for three winding transformers was proposed in (Hosimin Thilagar and Sridhara Rao, 2002). The genetic algorithm based parameter estimation method was introduced. One measurement under loaded conditions was performed to determine the parameters which excluded all empirical elements inherent in conventional measurement methods. The mutual coupling between secondary windings and the series-branch leakage reactance was detected by this method.

The work in (Alfuhaid, 2001) deduced the frequency characteristics of the input impedance, considering both open and short-circuited conditions, through graphical representations of the resistance, the reactance, and its phase versus frequency. The natural frequencies derived from the proposed s-domain model exhibited a strong correspondence with outcomes obtained through the SPICE circuit simulation program for both open-circuited and short-circuited secondary configurations, but when the winding was divided into more sections.

In (Martinez et al., 2005), a summary of the implementable models for parameter estimation in transient analysis software like EMTP was introduced. These approaches were valid in the low and medium-frequency domains. The nameplate data were used to deduce the value of the circuit parameters.

A methodology to compute the self capacitance of a high-voltage transformer was presented in (Dalessandro et al., 2007). Measurements were

Table 2. Contributions and shortcomings of the transformer modeling techniques.

REF	Year	Model Type	Contributions	shortcomings
de Leon and Semlyen (1992)	1992	Lumped parameter	Introducing a methodology to reduce the order of high order models.	The iron core was assumed to have infinite permeability which reduced the accuracy of the model.
Abed and Mohammed (2010)	2010	Lumped parameter	Proposing high frequency variable model of the transformer with good accuracy.	The simulation time of the model was large because of the complex equations
Liang et al. (2008)	1997	Lumped parameter	The results matched with the experiments on an actual 525 kV transformer.	VFTOs of Transformers in field were not considered.
Gharehpetian et al. (1998)	1998	hybrid	Proposing a hybrid model using frequency domain measurements to determine the transformer parameters.	The accuracy was limited to few MHz range
Wang et al. (2008)	2001	Lumped parameter	The high frequency response of the transformer was calculated directly from the transformer geometry.	Dissipation was not represented.
Shibuya et al. (1997)	2002	MTL	Introducing a model based on Turn-to-turn modelling of the windings which covers a wide range of frequencies from 15 Hz to 108 MHz.	Large computing time due to the several stages.
Zhongyuan et al. (2006)	2006	MTL	Using FDTD methodology to compute the equation of MTL model	Lower accuracy of the results.
Liang et al. (2006a)	2006	MTL	The results of the model were better than traditional MTL model. The approach results in a reduction of 30% in CPU utilization time.	Lower accuracy in frequency range higher than 2 MHz.
Popov et al. (2007)	2007	MTL	Simulating VFTOs in layer type transformer winding. Accuracy verified by measurements. Considering iron core losses and the proximity effect observed between adjacent layers.	The mutual capacitance and inductance was not considered
Zhang et al. (2008a)	2008	MTL	Reducing the order of the TF of S-parameters model. The results were consistent with the simulation results of EMTP.	The stability and the accuracy were not guaranteed.Restriction to continual transformers.
(Liang et al., 2008; Wang et al., 2008)	2008	Lumped parameter	Overcoming the problems of stability and accuracy of the Pade-approximation model (Wang et al., 2018).	Restriction to continual transformers.
Zhang et al. (2008b)	2008	Hybrid	Utilizing a lumped parameter model to derive the MTL model with the results validated via the results of EMTP.	Restriction to inner-shielding continual transformers.
Popov et al. (2003)	2003	hybrid	Presenting a Hybrid model combining STLM with an MTL model with a reduced number of equations.	Slight deviations from the actual characteristics were noticed as this method didn't consider the mutual inductance between the coils.
Srinivasamurthy and Dixit (2016)	2016	Lumped parameter	Simulating voltage surge distribution in a transformer winding utilizing P-Spice program.	The skin effect was not considered.
Wang and Yangm (2016)	2016	MTL	Implementing model for EMT simulations using the high order Radau method.	Software with high capabilities is required
Zhongyuan et al. (2008)	2008	MTL	Establishing a high frequency two-port circuit model high accuracy.	The simulation time was relatively large
Venegas et al. (2011)	2011	MTL	Introducing conventional formulation to specify the electric parameters of the transformer.	That model was validated using a scaled down prototype of a power transformer not an actual transformer.
Liang et al. (2006b)	2006	MTL	Proposing a single input multiple output MTL model and calculating the resonances in transformer winding.	Deviation between the calculated and measured data was noticed.
Shibuya and Fujita (2002)	2002	MTL	Considering the anisotropic complex permeability within the laminated core in the computation of inductances and resistances for the MTL. The accuracy was confirmed by a comparative analysis between the measured and simulated FRA within the frequency range of 10 Hz to 10 MHz.	The simulation outcomes, when comparing scenarios with and without accounting for the frequency-dependent property of the lamination core didn't exhibit considerable differences.

(*continued on next page*)

Table 2. (continued)

REF	Year	Model Type	Contributions	shortcomings
Zhang et al. (2013)	2013	MTL	Considering the electromagnetic induction between the transformer windings in the MTL model. Provided a detailed voltage distribution with high precision.	The simulation time of the model is lager compared with MTL model.
de Carvalho et al. (2016)	2016	MTL	Presenting a multi-conductor transmission line model utilizing alternative modal decoupling technique. The computational cost was reduced.	The conductance is neglected.
Yao et al. (2018)	2018	MTL	Combining the basic principle of rotating transformation with traditional EMT modelling. The analytic signal was more accurate and easier.	Reduced computational efficiency
Mombelloa and Diaz Florez (2020)	2020	MTL	Proposing a white-box transformer model with identifying its parameters to improve the stability of the model. The model enabled successful practical implementation.	The proximity and skin effect were ignored.
Yang et al. (2011)	2011	Lumped parameter	Presenting a lumped RLC model. Lower computational complexity than MTL model.	The frequency range was limited to 4 MHz to ensure the accuracy.
Colqui et al. (2019)	2019	Lumped parameter	Modifying π-circuit to reduce numerical oscillations on electromagnetic transient responses.	The accuracy of the model was limited to low frequency range.
Ding et al. (2020)	2020	Lumped parameter	Modifying the lumped parameter model to minimize the errors impacted by the lumped parameter approximation in conjunction with the hyperbolic functions of the distributed parameter model.	Minimizing the global error was not guaranteed.

performed on three transformers with different construction, and the results of the methodology matched well with these measurements.

A two-dimensional FE model of transformer winding was used in (Du et al., 2008) to obtain the distribution parameters. C matrix is obtained by solving static electric field considering hollow winding and iron core. To evaluate the L and R parameters of a transformer with iron core within the frequency range of MHz, by considering the skin effect of conductors and the associated iron area. The authors in (Ouaddi et al., 2010) calculated the impedance of the transformer utilizing measurements performed on different configurations.

A procedure to calculate the series capacitance and inductance was presented in (Li et al., 2011). The two dimensional FEM was used to analyze the electrostatic fields to obtain the capacitance, and the magnetic fields were analyzed to obtain the inductance using the three dimensional FEM.

An algorithm for the incorporating of hysteresis effect in three phase transformer models for electromagnetic transient investigations was proposed in (Prousalidis et al., 1996a). It relied on a simplification of the Preisach model requiring only a limited amount of easily available data. An agreement was noted between measured excitation currents and their harmonics, with the corresponding calculated values.

To model VFTOs, the multi-layer method of the image was used in (Gomez et al., 2011) to obtain the inductance matrix. The results matched well with the results of the FEM. This work was extended in (Gomez et al., 2013) to consider multi-layer transformers. A novel approach was introduced in (Eslamian and Vahidi, 2012) to consider the core effects in calculating the inductance matrix. The results matched well with the results of the FEM.

A modal experiment was implemented in (Geng et al., 2013) on a real 10 kV power transformer to determine the modal parameters of transformer winding. A refined Empirical Mode Decomposition (EMD) algorithm was introduced for the identification of modal parameters associated with transformer windings.

A recursive least square algorithm utilizing the measured voltage and current for the terminal of single phase transformer, to obtain the resistance and the inductance, was introduced in (Araú et al., 2013). A formula to compute the core inductance component was proposed in (Gomez et al., 2014). The formula relied on the complex flux penetration. This method showed good accuracy in the high frequency range.

A methodology providing online monitoring for the equivalent circuit parameters of the transformer was introduced in (Dirik et al., 2014). The determination of series winding parameters was achieved through the application of differential equations algorithm to fundamental frequency components of the transformer data that are obtained utilizing the discrete cosine transform. The nonlinear inductance was derived through polynomial curve fitting utilizing the least squares error method.

The work in (Drandić et al., 2017) proposed employing a solver based on boundary element methods (BEM) for computing the electric field within a transformer. Linear functions served as base functions, and the point-matching technique, along with both analytical and numerical integration, was employed. The problem was solved for real transformer geometry by both BEM and FEM. The results of both models were in good agreement.

An application of artificial intelligence (AI) techniques was introduced in (Abu-Siada et al., 2020) to determine the electrical parameters of a high-frequency model based on the transformer FRA signature. This approach depended on change of the electrical model parameters results instead of a graphical comparison that may result in inconsistent interpretation for the same FRA signature. The genetic algorithm and PSO were employed for the estimation of equivalent circuit parameters. Table 3 gives the contributions and shortcomings of the transformer parameter determination Methods.

5. The frequency response analysis of the transformer

The work in (Dick and Erven, 1978) introduced a FRA methodology to identify winding deformation. This method is an alternative to the time domain method like the low voltage impulse method (Lech and Tyminiski, 1966). The work in (Satish and Sahoo, 2005) provided quantitative evidence about how the resultant TF of two winding transformer originates. The work in (Zhongdong and Sofian, 2009) addressed the impact of the winding structure on the FRA responses. The winding was classified into windings of either a high or low series capacitance relative to shunt capacitance. In (Abeywickrama et al., 2006), a model was presented to characterize the quality of the insulation using FRA. The model in (Rahimpor and Bigdeli, 2009) calculated several TFs for several winding configurations to detect the type of fault based on which TF was changed. There was a

Table 3. The contributions and shortcomings of the transformer parameter determination Methods.

REF	Year	Contributions	shortcomings
Wilcox et al. (1989)	1956	Presenting equations To calculate the leakage reluctance of the transformer.	The equations neglected the adjacent windings and the tank, The yoke was considered to extend to infinity so the accuracy was reduced.
De Leon and Semlyen (1992)	1989	Introducing an impedance formula based on the frequency.	The accuracy was lower in the case of a transformer with inhomogeneous core.
Heinemann and Helfrich (2000)	1992	Calculating the capacitance and the inductance for the high frequency transient models. The results were efficient and matched well with the results of the FEM and mathematical design formulae.	The frequency response deviated from the field tests above the resonance frequency due to the neglected losses in the simulation.
Alfuhaid (2001)	2002	Estimating all impedance parameters of three winding transformers utilizing the genetic algorithm. Detecting the mutual coupling between secondary windings and the series-branch leakage reactance	This methodology was more complex than traditional optimization techniques.
Li et al. (2011)	2010	Calculating the impedance of the transformer utilizing measurements performed on different configurations.	Discrepancy was observed in the results when comparing with the wide frequency range.
Gomez et al. (2013)	2011	Utilizing the multi-layer method of image to obtain the inductance matrix.	The multi-layer transformer was not considered.
Araú et al. (2013)	2013	Determining the modal parameters associated with transformer winding.	The model needs to be extended to incorporate the high voltage power transformers.
Drandić et al. (2017)	2014	Providing online monitoring for the transformer equivalent circuit parameters including core losses and saturation effects.	The accuracy of the model was reduced due to measurement errors of current and voltage transformers.
Lech and Tyminiski (1966)	2020	Estimating the electrical parameters of a high-frequency model from the transformer based on FRA signature based on AI techniques with easy implementation	The model was not verified by investigations on real transformer. The percentage change in the parameters was not correlated to the fault level.

deviation between the results of this model and the measured data.

The work in (Tang and Wu, 2010) used the simplified hybrid model (Shintemirov et al., 2009a) to detect minor axial winding faults and minor radial winding faults. A quantitative analysis was introduced by statistical indicators to analyze the FRA data. The hybrid model (Shintemirov et al., 2009a) was also employed in (Ji and Wu, 2012) to carry out a comprehensive investigation on frequency response characteristics of winding deformation and measurement connection variation.

The contribution in (Kraetge et al., 2009) summarized various aspects of the practical application of sweep FRA. The different sources of reference data and their significance were discussed. The methods used to assess the measured data were classified into time-based, type-based, and phase comparison. The choice of the proper method was discussed. A summary of guidelines to achieve repeatability was given.

The work in (Mitchell and Welsh, 2011) proposed a modeling methodology utilized to simulate FRA tests on three-phase power transformers. To ensure the validity of the FRA models, several of the parameters, whose values were accurately determined through internal inspection, were compared against their estimated counterparts.

The work in (Gomez-Luna et al., 2013) discussed the status and future trends for online FRA. The online FRA was categorized into impulse FRA (IFRA) and sweep FRA (SFRA). The IFRA seemed to provide increased potential for obtaining satisfactory results. A technique was introduced in (Behjat et al., 2011) for online monitoring of the power transformer winding based on the FRA. The signal was injected into the transformer through a simple and economical capacitive sensor implemented within the surface of the transformer bushing. Another online monitoring technique was presented in (Rahinpour et al., 2016). The model employed a wide-frequency voltage excitation signal and high-frequency current transformers, using the bushing test taps.

In (Hashemnia et al., 2015), the three dimensional FE) analysis was employed to simulate the actual operational behavior of a single-phase transformer by incorporating the physical and geometrical dimensions. An investigation into the influence of each fault level on the electrical parameters of the equivalent circuit of the transformer was conducted. A double-ladder circuit model of transformer winding which considered the frequency-dependent effects and core loss was proposed in (Zhang et al., 2013). The FEM-based software COMSOL Multiphysics was employed to obtain the frequency-dependent parameters. The frequency-dependent characteristics of inductance proved that the effect of the transformer core was greater at frequencies less than tens of kilohertz. The results indicated that accurately representing the frequency-dependent parameters of the core and insulation materials resulted in an improved circuit model for the transformer winding.

The model in (Zhao et al., 2019) considered the detailed winding structure, mutual inductance, and interturn capacitance. These parameters were calculated and simulation results were validated through experimental measurements. The study outlined in (Zhou1 et al., 2019) introduced a lumped parameter circuit model that took into account intersection capacitances and mutual inductance between windings. The model was implemented for a 220 kV traction transformer, and the analysis included the examination of parameter variations and characteristics in response to axial displacement across various windings. The spectral clustering of transformer FRA signatures was proposed in (Zhao et al., 2021). A total of 360 sets of FRA signatures were acquired, each corresponding to different types, degrees, and locations of faults. These were obtained using a validated transformer model based on FEM simulations.

The authors in (Duvvury and Pramanik, 2021) proposed an advanced FRA measurement technique designed for the identification of the faulty phase in actual three-phase delta-connected HV windings. The method was illustrated using an appropriate terminal configuration to ensure the symmetry in the physical inter-connection between the middle phase and the other two phase windings.

The effort in (Arumugam, 2021) aimed to bridge the gap between the theoretical concepts and the practical application of white noise as an alternative test for identifying FRA. Pertinent magnitude transfer function revealed the natural frequencies with good accuracy.

The work in (Prousalidis et al., 1996b) analyzed the frequency response and voltage ratio response. Transformer frequency response was compared with transient response to understand the impact of the applied voltage amplitude, rise time, and duty cycle, on transient distribution along the transformer winding. The research helped in the design of transformer insulation subjected to varying transient parameters. Table 4 illustrates the contributions and shortcomings of the FRA analysis techniques used to monitor the transformer condition.

Table 4. Contributions and shortcomings of the FRA analysis techniques used to monitor the transformer condition.

REF	Year	Contributions	shortcomings
Dick and Erven (1978)	1978	Introducing FRA to detect winding deformation	The model was not accurate. The large exposure to Electromagnetic Interference (EMI)
Zhongdong and Sofian (2009)	2005	Interpreting TF of a two winding transformer knowledge of the TF function of each winding with close agreement and practical viability	Restriction to the two winding transformer
Abeywickrama et al. (2006)	2009	Addressing the impact of winding structure on the FRA responses.	Interaction between tested windings and untested ones in the same phase, and interaction between different phases affected the measured responses.
Rahimpor and Bigdeli (2009)	2006	Applying FRA technique to distinguish between winding deformation and the change of the dielectric permittivity considering moisture content and ageing of insulation	More work is needed to establish reliable frequency dependence of the complex dielectric permittivity of materials used in transformer insulation system. Measuring system need to be improved to give more precise results.
Tang and Wu (2010)	2009	Detecting the type of fault based on TFs of several winding with simple technique and proper simulation time.	Reduced accuracy due to the use of lumped elements for representation of distributed magnetic and electric behavior.
Shintemirov et al. (2009a)	2009	Introducing a simplified hybrid model with an extended frequency range to analyze resonance under VFTOs.	Considering only single-phase transformers without
Ji and Wu (2012)	2010	Utilizing a simplified hybrid model (Zhang et al., 2013) to detect minor axial winding faults and minor radial winding faults	Only applicable to single-phase transformers.
Gomez-Luna et al. (2013)	2011	Presenting model utilized to FRA tests on three-phase power transformers	Transformer was of core-type construction with concentric windings. The consideration of leakage inductance was confined to the axial path between the high and low-voltage windings.
Rahinpour et al. (2016)	2011	Online monitoring of the power transformer winding on the basis the FRA providing sufficient information concerning the occurrence of faults with sensitivity to a few shorted turns.	The apparatus of online monitoring changed some features of the transfer function then reduced the sensitivity of approach to detect winding inter-turn fault.
Christian and Xie (2006)	2006	Utilizing a simplified hybrid model (Zhang et al., 2013) to include new scenarios like the impact of the number of deformed discs, the impact of the degree of deformation, the effect of high contact resistance failure, the impact of the high voltage bushing and the influence of lead deformation.	Restricted to single phase transformers
Hashemnia et al. (2015)	2016	Online monitoring of the power transformer winding deformation on the basis of the FRA. Detecting slight changes in the FRA when the load was varied. The changes in transformer parameters affected the FRA response	Further research is needed to guarantee its robustness in the presence of lightning and switching surges.
Zhao et al. (2019)	2015	Incorporating charts to establish correlations between different axial displacement levels and the percentage change of the parameters of transformer equivalent circuits.	Restricted to single phase transformers
Zhao et al. (2021)	2019	Numerical indices showed a good agreement between the simulation and the practical FRA signatures' trends.	Further research was required to develop a reliable expert system based on the detailed transformer equivalent electric circuit model to assess the transformer mechanical integrity automatically.
Zhao et al. (2021)	2019	Proposing a lumped parameter circuit model incorporating intersection capacitances and mutual inductance between windings. The viability of the model was substantiated through testing on a 10 kV test transformer.	The model ignored the effect of the insulating paper on the calculation of the inductance.

(*continued on next page*)

Table 4. (continued)

REF	Year	Contributions	shortcomings
Duvvury and Pramanik (2021)	2021	Proposing the spectral clustering of transformer FRA signatures. The robustness, accuracy and optimization capability of the clustering algorithms was confirmed.	The data obtained in this model was not valid for a dry type transformer.
Arumugam (2021)	2021	Proposing an advanced FRA measurement technique to detect the faulty phase in actual three-phase delta-connected HV windings. The simulation results and the measurements assured the feasibility of the method.	The work did not consider any fault severity and assumed that the fault occurred in one winding at a time.
Prousalidis et al. (1996b)	2021	The practical application of the white noise as an alternative test to determine frequency response analysis.	Future work was expected to validate the quality of the obtained results through correlation analysis, and to extend the model to an actual high-power transformer.

6. Research gap issues and recommendations

There are many contributions used to model the VFTOs. However, there are several challenges and recommended trends that need to be considered and carried out. Some of these are summarized as follows:

(a) The accurate simulation of VFTOs with high-frequency content (above 2 MHz) is still a challenging issue. So it is recommended that more investigations are carried out to present VFTO models with high frequency simulation capability and small simulation time.
(b) Including the saturation effects and the inrush current in the modeling of three phase transformer with faster calculations.
(c) Providing models to obtain the voltage distribution along the transformer winding with shorted turns under very fast transients.
(d) Accurate online monitoring of the transformer equivalent circuit parameters including core losses and saturation effects.
(e) Estimating the impedance parameters of three phase transformer based on AI techniques with less complexity.
(f) Developing a reliable expert system based on FRA signatures to assess the transformer's mechanical integrity
(g) Online monitoring of transformer utilizing FRA in case of lightning and switching surges.
(h) identifying effective mitigation strategies becomes crucial for reducing their impact on transformer insulation and associated equipment. This may involve optimizing transformer design, implementing surge protection devices, or modifying switching procedures to minimize VFTO generation
(i) Developing accurate measurement techniques and validation procedures is crucial for verifying VFTO models and ensuring their reliability in practical applications.

7. Conclusions

This work summarized the transformer modeling techniques published in the literature showing the pros and cons of each technique. The methodologies used to determine the parameters required for the modeling are also reviewed. The contributions of utilizing the FRA as a diagnostic tool of the transformer condition are summarized. Also, research gap topics and the recommended research issues of the discussed topics are illustrated and discussed.

Author credit statement

The corresponding author is responsible for Visualization, Data collection and tools, Data analysis and interpretation, Methodology and Software.

The second author is responsible for Design of the work, Supervision and Critical revision of the article.

The third author is responsible for and final approval of the version to be published.

Each author has reviewed and approved the final version of the manuscript and agrees to be accountable for all aspects of the work.

Conflicts of interest

There are no conflicts of interest.

References

Abbasi, A.R., 2022. Fault detection and diagnosis in power transformers: a comprehensive review and classification of publications and methods. Elec. Power Syst. Res. 209, 107990.
Abed, N.Y., Mohammed, O.A., 2010. Physics-based high-frequency transformer modeling by finite elements. IEEE Trans. Magn. 46, 3249–3252.

Abeywickrama, K.G.N.B., Serdyuk, Y.V., Gubanski, S.M., 2006. Exploring possibilities for characterization of power transformer insulation by frequency response analysis (FRA). IEEE Trans. Power Deliv. 21, 1375–1382.
Abu-Siada, A., Mosaad, M.I., Kim, D., El-Naggar, M.F., 2020. Estimating power transformer high frequency model parameters using frequency response analysis. IEEE Trans. Power Deliv. 35, 1267–1277.
Ahmad, A., Johannet, P., Auriol, P.H., 1992. Efficient inverse Laplace transform algorithm for transient overvoltage calculation. IEE Proc. 139, 117–121.
Alfuhaid, A.S., 2001. Frequency characteristics of single-phase two-winding transformers using distributed-parameter modeling. IEEE Trans. Power Deliv. 16, 637–642.
Almenweer, R.A., Yixin, S., Xixiu, W., 2018. Research on the fitting method to describe the mathematical expression of VFTO in GIS. J Eng 2019 Iss 16, 2053–2057.
Ametani, A., Xue, H., Natsui, M., Mahseredjian, J., 2018. Electromagnetic disturbances in gas-insulated substations and VFT calculations. Elec. Power Syst. Res. 160, 191–198.
Araújo, J., Florentino, M., Ferreira, T., Luciano, B., Costa, E., 2013. The use of recursive least square to determine the model parameters of a transformer in different frequencies. In: 22nd International Conference and Exhibition on Electricity Distribution (CIRED 2013), Stockholm, pp. 1–4.
Arumugam, S., 2021. Investigation on using white signal as a test signal for performing frequency response measurements on transformers. Elec. Power Syst. Res. 202 (2022), 107586.
Babaei, E., Ebadpour, M., Feyzi, M., Kangarlu, M., 2012. A detailed analysis and comparison of different models of distribution transformers for electromagnetic transient studies. Praiseworthy Prize 2, 324–341.
Behjat, V., Vahedi, A., Setayeshmehr, A., Borsi, H., Gockenbach, E., 2011. Diagnosing shorted turns on the windings of power transformers based upon online fra using capacitive and inductive couplings. IEEE Trans. Power Deliv. 26, 2123–2133.
Chatrefou, D., Pristchepa, M., Uhde, D., 2000. Application of optical sensors for measurement of high frequency overvoltages in power transformers. 2000 IEEE Power Engineering Society Winter Meeting. Conference Proceedings, pp. 2257–2268.
Christian, J., Xie, J., 2006. Very fast transient oscillation measurement at three Gorges left bank hydro power plant. In: Proc. Int Conf Power System Technology, pp. 1–7.
Chung, S.K., 2004. Transient characteristics of high-voltage flyback transformer operating in discontinuous conduction mode. IEE Proc. Elec. Power Appl. 151, 628–634.
CIGRE, 2014. Brochure, 577A Electrical transient interaction between transformers and the power system-part 1: expertise, joint working group a2/c4. 39. CIGRE 176. April.
Colqui, J.S.L., de Araújo, A.R.J., Kurokawa, S., 2019. Improving the performance of a lumped transmission line model used in electromagnetic transient analysis. IET Gener. Transm. Distrib. 13, 4942–4951.
Cornick, K., 1992. Distribution of Very Fast Transient Overvoltages in Transformer Windings. CIGRE report.
Dalessandro, L., da Silveira Cavalcante, F., Kolar, J.W., 2007. Self-capacitance of high-voltage transformers. IEEE Trans. Power Electron. 22, 2081–2092.
de Carvalho, C.G., Marques Costa, E.C., Kurokawa, S., Pissolato, J., 2016. Alternative phase-domain model for multiconductor transmission lines using two modal transformation matrices. Elec. Power Compon. Syst. 44, 1–11.
de Leon, F., Semlyen, A., 1992a. Reduced order model for transformer transients. IEEE Trans. Power Deliv. 7, 361–369.
De Leon, F., Semlyen, A., 1992b. Efficient calculation of elementary parameters of transformers. IEEE Trans. Power Deliv. 7, 376–383.
de leon, F., Gomez, P., Martinez-Velasco, J.A., Rioual, M., 2009. Chapter 4, transformers. In: Mrtinez-Velasco, J.A. (Ed.), Power System Transients: Parameter Determination. CRC Press, Boca Raton FL, pp. 177–250.
Dick, E., Erven, C., 1978. Transformer diagnostic testing by frequency response analysis. IEEE Trans. Power Apparatus Syst. PAS-97, 2144–2153.
Ding, Q., Yao, Y., Wang, B., Fu, J., Zhang, W., Zeng, C., Li, X., Valtchev, S., 2020. A modified lumped parameter model of distribution transformer winding. Global Energy Interconnection 3, 158–165.
Dirik, H., Gezegin, C., Özdemir, M., 2014. A novel parameter identification method for single-phase transformers by using real-time data. IEEE Trans. Power Deliv. 29, 1074–1082.
Drandića, A., Trkuljaa, B., 2017. Transformer electric field calculation using BEM and FEM. In: 4th International Colloquium, Transformer Research and Asset Management, pp. 312–318.
Du, Z., Ruan, L., Zhao, C., Ruan, J., Wu, Y., Wang, T., 2008. Calculation of electrical parameters for studies on propagation characteristic of pd along transformer winding. In: International Conference on Computer and Electrical Engineering, pp. 926–931.
Duan, a S., Zhan, H., Li, C., Zhao, L., Yao, L., 2015. Measurement and modeling of very fast transient current in 220 kV GIS. Vacuum 120, 32–36.
Duvvury, V.S.B.C., Pramanik, S., 2021. An attempt to identify the faulty phase in three-phase transformer windings using an advanced FRA measurement technique. IEEE Trans. Power Deliv. 36, 3162–3171.
Eslamian, M., Vahidi, B., 2012. New methods for computation of the inductance matrix of transformer windings for very fast transients studies. IEEE Trans. Power Deliv. 27, 2326–2333.
Fattal, F.A., Mar. 2017. High Frequency Model for Transient Analysis of Transformer Windings Using Multiconductor Transmission Line Theory. A thesis submitted to the Faculty of Graduate Studies of The University of Manitoba.
Filipović-Grčić, B., Franc, B., Uglešić, I., Pavića, I., Keitoue, S., Murat, I., Ivanković, I., 2017. Monitoring of transient overvoltages on the power transformers and shunt reactors – field experience in the Croatian power transmission system', 4th International Colloquium 'Transformer Research and Asset Management. Procedia Eng. 202, 29–42.
Florkowski, M., Furgał, J., Kuniewski, M., 2016. Propagation of overvoltages transferred through distribution transformers in electric networks. IET Gener. Transm. Distrib. 10, 2531–2537.
Garg, A., Sharma, T., Jain, A., Velandy, J., 2020. Statistical correlation technique for transient signal analysis during impulse testing of transformers. IET Sci. Meas. Technol. 14, 857–863.
Geng, C., Wang, F., Zhang, J., Jin, Z., 2013. Modal parameters identification of power transformer winding based on improved Empirical Mode Decomposition method. Elec. Power Syst. Res. 108, 331–339.
Gharehpetian, G.B., Mohseni, H., Moller, K., 1998. Hybrid modeling of homogenous transformer windings for very fast transient overvoltage studies. IEEE Trans. Power Deliv. 13, 157–163.
Gomez, P., De León, F., 2011. Accurate and efficient computation of the inductance matrix of transformer windings for the simulation of very fast transients. IEEE Trans. Power Deliv. 26, 1423–1431.
Gomez, P., De Leon, F., Espino-Cortes, F.P., 2013. Improvement of a method to compute the inductance matrix of multilayer transformer windings for very fast transients. IEEE Trans. Power Deliv. 28, 1245–1246.
Gomez, P., De Leon, F., Espino-Cortes, F.P., 2014. Improved computation of core inductance for fast transient analysis of transformers. IEEE Trans. Power Deliv. 29, 2034–2036.

Gomez-Luna, E., Mayor, G., Gonzalez-Garcia, C., Guerra, J., 2013. Current status and future trends in frequency-response analysis with a transformer in service. IEEE Trans. Power Deliv. 28, 1024–1031.

Gongchang, Y., Weidong, L., Weijiang, C., Yonggang, G., Zhibing, L., 2013. Development of full frequency bandwidth measurement of VFTO in UHV GIS. IEEE Trans. Power Deliv. 28, 2550–2557.

Grivet-Talocia, S., 2004. The time-domain vector fitting algorithm for linear macromodeling. AEU-International Journal of Electronics and Communications 58, 293–295.

Grover, F.W., 1933. Tables for the calculation of the mutual inductance of any two coaxial single-layer coils. Proc. Inst. Radio Eng. 21, 1039–1049.

Haseeb, M.A., Joy Thomas, M., 2018. Disconnector switching induced transient voltage and radiated fields in a 1100 kV gas insulated substation. Elec. Power Syst. Res. 161, 86–94.

Hashemnia, N., Abu-Saida, A., Salem, S., 2015. Improved power transformer winding fault detection using fra diagnostics – part 1: axial displacement simulation. IEEE Trans. Dielectr. Electr. Insul. 22, 556–563.

Heinemann, L., Helfrich, J., 2000. Modeling and accurate determination of winding losses of high frequency transformers in various power electronics applications. In: Applied Power Electronics Conference and Exposition, 2000, APEC 2000, Fifteenth Annual IEEE, vol. 2, pp. 647–653.

Hosimin Thilagar, S., Sridhara Rao, G., 2002. Parameter estimation of three-winding transformers using genetic algorithm. Eng. Appl. Artif. Intell. 15, 429–437.

Ji, T., Wu, 2012. Detection of power transformer winding deformation and variation of measurement connections using a hybrid model. Elec. Power Syst. Res. 87, 39–46.

Jurisic, B., Filipovic-Grcic, B., Zupan, T., Levacic, G., 2021. Statistical analysis of non-standard overvoltage waveforms measured at 220 kV terminals of a power transformer. Elec. Power Syst. Res. 197, 107318.

Kraetge, A., Kruger, M., Velasquez, J., Heindel, M., Tenbohlen, S., 2009. Experiences with practical application of sweep frequency response analysis (SFRA) on power transformers. In: Proceedings of the 16th International Symposium on High Voltage Engineering.

Lech, W., Tyminiski, L., 1966. Detecting Transformer winding damage-the low voltage method. Electr. Rev. 179, 768–772.

Li, Y., Du, J., Li, X., Li, D., 2011. Calculation of capacitance and inductance parameters based on FEM in high-voltage transformer winding. In: Electrical Machines and Systems (ICEMS), International Conference on IEEE, pp. 1–4.

Li, Y., Shang, Y., Zhang, L., Shi, R., Shi, W., 2012. Analysis of very fast transient overvoltages (VFTO) from onsite measurements on 800 kV GIS. IEEE Trans. Dielectr. Electr. Insul. 19, 2102–2110.

Liang, G., Ma, Y., Dong, H., Sun, H., 2006a. Time-domain overvoltage calculation of frequency-dependent transformer winding under VFTO. In: 2006 China International Conference on Electricity Distribution, pp. 28–33.

Liang, G., Son, H., Zhang, X., Sui, X., 2006b. Modeling of transformer windings under very fast transient overvoltages. IEEE Trans. Electromagn C. 48, 621–627.

Liang, G., Yao, M., Dong, H., Ji, C., 2008. Modeling of transformer windings under VFTO using the lumped element equivalent circuit approach. In: 2008 Third International Conference on Electric Utility Deregulation and Restructuring and Power Technologies, pp. 1109–1114.

Lovass-Nagy, V., Szendy, C., 1964. Calculation of transient voltages in a transformer connected to a transmission line. IEE Proc. 111, 1133–1136.

Lu, T., Zhang, B., 2005. Calculation of very fast transient overvoltages in GIS. In: 2005 IEEE/PES Transmission and Distribution Conference & Exhibition: Asia and Pacific, pp. 1–5.

Ma, G.M., Li, C.R., Chen, W.J., Sun, Z.L., Guo, P.H., Chen, M., et al., 2009. A Reliable Wide-Bandwidth VFTO sensor based on surface-mounted devices. IEEE Trans. Power Deliv. 28, 1839–1846.

Ma, G.M., Li, C.R., Quan, J.T., Jiang, J., 2011. Measurement of VFTO based on the transformer bushing sensor. IEEE Trans. Power Deliv. 26, 684–692.

Martinez, J.A., Walling, R., Mork, B.A., Martin-Arnedo, J., Durbak, D., 2005. Parameter determination for modeling system transients-Part III: transformers. IEEE Trans. Power Deliv. 20, 2051–2062.

Miki, A., Hosoya, T., Okuyama, K., 1978. A calculation method for impulse voltage distribution and transferred voltage in transformer windings'. Power Apparatus Syst. IEEE Trans. PAS-97, 930–939.

Mitchell, S.D., Welsh, J.S., 2011. Modeling power transformers to support the interpretation of frequency-response analysis. IEEE Trans. Power Deliv. 26, 2705–2717.

Mombelloa, E.E., Diaz Florez, G.A., 2020. An improved high frequency white-box lossy transformer model for the calculation of power systems electromagnetic transients. Elec. Power Syst. Res. 190.

Moreiraa, D.C., Nunes, M.V.A., Moreira, D.D.C., Costa, D.K.D., 2020. Analysis of VFTO during the failure of a 550-kV gas-insulated substation. Elec. Power Syst. Res. 189.

Oliveira, J.G.H.C., Ihlenfeld, L.P.R.K., Rodrigues, L.F.M., Rocha, A.C.O., Santo, D.J.D.E., Feb. 2022. Expanding the measuring range via S-parameters in a EHV voltage transformer modelling for reliable GIS VFT simulations. Elec. Power Syst. Res. 203, 107672.

Ouaddi, H., Nottet, G., Baranowski, S., Kone, L., Idir, N., 2010. Determination of the high frequency parameters of the power transformer used in the railway substation. In: Vehicle Power and Propulsion Conference (VPPC). IEEE, pp. 1–5.

Popov, M., Sluis, L., Geradus, Herdt, H., 2003. Computation of very fast transient overvoltages in transformer windings. IEEE Trans. Power Deliv. 18, 1268–1274.

Popov, M., Sluis, L.V.D., Smeets, R.P.P., Roldan, J.L., 2007. Analysis of very fast transients in layer-type transformer windings. IEEE Trans. Power Deliv. 22, 238–247.

Portillo, Á., de Oliveira, L.F., Portillo, F., 2020. Calculation of circuit parameters of high frequency models for power transformers using FEM. In: 5th International Colloquium on Transformer Research and Asset Management. Springer Singapore, Singapore, pp. 163–182.

Prousalidis, J.M., Hatziargyriou, N.D., Papadias, B.C., 1996a. Representation of hysteresis in three-phase transformer models for electromagnetic transients. IEE Proc. Elec. Power Appl. 143, 331–338.

Prousalidis, J.M., Hatziargyriou, N.D., Papadias, B.C., 1996b. Representation of hysteresis in three-phase transformer models for electromagnetic transients. IEE Proc. Elec. Power Appl. 143, 331–338.

Rabins, L., 1956. Transformer reactance calculations with digital computers. Transactions of the American Institute of Electrical Engineers, Part I: Communication and Electronics 75, 261–267.

Rahimpor, E., Bigdeli, M., 2009. Simplified Transient Model of Transformer Based on Geometrical Dimensions Used in Power Network Analysis and Fault Detection Studies. Iran transformer research institute.

Rahinpour, H., Mitchel, S., Tusek, J., 2016. The application of sweep frequency response analysis for the online monitoring of power transformers. In: 2016 Australasian Universities Power Engineering Conference (AUPEC).

Saleh, S.A., Rahman, M.A., 2002. Transient model of power transformer using wavelet filter bank. In: 2002 Large

Engineering Systems Conference on Power Engineering. Conference Proceedings. LESCOPE'02, pp. 47−54.
Satish, L., Sahoo, S.K., 2005. An effort to understand what factors affect the transfer function of a two-winding transformer. IEEE Trans. Power Deliv. 20, 1430−1440.
Shibuya, Y., Fujita, S., 2002. High frequency model and transient response of transformer windings. IEEE/PES Transmission and Distribution Conference and Exhibition 3, 1839−11844.
Shibuya, Y., Fujita, S., Hosokawa, N., 1997. Analysis of very fast transient overvoltage in transformer winding. IEE Proc. Generat. Transm. Distrib. 144, 461−467.
Shibuya, Y., Fujita, S., Tamaki, E., 2001. Analysis of very fast transients in transformer. IEE Proc. Generat. Transm. Distrib. 148, 377−383.
Shintemirov, A., Tang, W.H., Wu, Q.H., 2009a. A hybrid model of disc-type power transformers for frequency response analysis. IEEE Trans. Power Deliv. 24, 730−739.
Shintemirov, A., Tang, W.H., Wu, Q.H., 2009b. A hybrid winding model of disc-typepower transformers for frequency response analysis. IEEE Trans. Power Deliv. 24, 730−739.
Soloot, A., Hoidalen, H., Gustavsen, B., 2013. Modeling of wind turbine transformers for analysis of resonant overvoltages. International Conference on Power Systems Transients (IPST2013) in Vancouver, Canada 115, 26−43.
Srinivasamurthy, R.V., Dixit, P., 2016. Simulation study of voltage distribution in a transformer winding. Int. J. Eng. Res. Technol. 5, 307−311.
Taikina-aho, M., 2010. Survey of transformer failure causes and consequences. Finland: Bachelor of Science and Technology Thesis, University of Vaasa.
Tang, S., Wu, 2010. Detection of Minor Winding Deformation Fault in High Frequency Range for Power Transformer.
Theocharis, A., Popov, M., Terzija, V., 2016. Computation of internal voltage distribution in transformer windings by utilizing a voltage distribution factor. Elec. Power Syst. Res. 138, 11−17.
Van Jaarsveld, B.J., 2013. Wide-band Modelling of an Air-Core Power Transformer Winding. Ph.D. dissertation. Stellenbosch University, Stellenbosch.
Venegas, V., Guardado, J.L., Melgoza, E., Maximov, S., Hernandez, M., 2011. A computer model for transient voltage distribution studies in transformer windings. In: Proceedings of the 9th WSEAS/IASME International Confernce on Electrical Power Systems, High Voltages, Electrical Machines, pp. 121−126.
Villanueva-Ramírez, J.M., Gómez, P., Espino-Cortés, F.P., Nájera, G., 2014. Implementation of time domain transformer winding models for fast transient analysis using Simulink. Int. J. Electr. Power Energy Syst. 61, 118−126.
Vinod Kumar, V., Joy Thomas, M., Naidu, M.S., 1999. VFTO computation in a 420 kV GIS. High Voltage Engineering Symposium, Conference publication No 467, 1319−1322.
Wang, F., Yangm, M., 2016. Fast electromagnetic transient simulation for over-voltages of transmission line by high order Radau method and V-transformation. IET Gener., Transm. Distrib. 10, 3639−3645.
Wang, T., Dong, H., Liang, G., 2008. Overvoltage distribution calculation of transformer windings under VFTO considering frequency-dependent parameters via Krylov subspace technique. In: 2008 Third International Conference on Electric Utility Deregulation and Restructuring and Power Technologies, pp. 887−891.
Wang, S., Guo, Z., Zhu, T., Feng, H., Wang, S., 2018. A new multiconductor transmission line model of transformer winding for frequency response analysis considering the frequency-dependent property of the lamination core. Energies 4, 826−838.
Wilcox, D., Hurley, W., Conlon, M., 1989. Calculation of self and mutual impedances between sections of transformer windings. IEE Proc. Commun. 136, 308−314.
Wong, H.K., Chen, S., 2009. Very Fast Transient Overvoltage Analysis for 400KV GIS', 8th International Conference on Advances in Power System Control. Operation and Management, pp. 1−5.
Wouters, P., van Deursen, A., Vermeer, M., 2019. Methodology and accuracy for non-invasive detection of switching transient overvoltages from compensation coils connected to power transformers. IET Sci. Meas. Technol. 14, 173−181.
Xixiu, W., Fan, Z., Shipu, W., et al., 2017. Study on the transient characteristics of 1100 kV VFTO. In: Xian, China: 4th Int. Conf. On Electric Power Equipment-Switching Technology, pp. 66−75.
Yan, X., Zengping, W., Qing, L., 2005. A novel inductance calculation method in power transformer model based on magnetic circuit. TENCON 2005, 1−4.
Yang, Y., Wang, Z.-J., Cai1, X., Wang, Z.D., 2011. Improved lumped parameter model for transformer fast transient simulations. IET Electr. Power Appl. 5, 479−485.
Yang, Q., Chen, Y., Sima, W., Zhao, H., 2016. Measurement and analysis of transient overvoltage distribution in transformer windings based on reduced-scale model. Elec. Power Syst. Res. 140, 70−77.
Yao, S., Zhang, S., Zhan, P., Huang, W., 2018. Modified electromagnetic transient model of transmission line based on rotation transformation. J. Eng. 2019, 1045−1050.
Yu, Y., Wang, Z., Shao, C., 2009. Determination of VFTO waveform in GIS according to simplified structure of GIS bus and circuit parameters. In: 2009 IEEE/PES Power Systems Conference and Exposition, pp. 1−9.
Zhan, H., Duan, S., Li, C., Yao, L., Zhao, L., 2014. A novel arc model for very fast transient overvoltage simulation in a 252-kv gas-insulated switchgear. IEEE Trans. Plasma Sci. 42, 3423−3429.
Zhang, P., Wang, Y.H., Nie, X.P., Yan, W.L., Zhang, H.J., 2008a. Modeling for transformer windings under VFTO based on s-parameters. In: 2008 International Conference on Machine Learning and Cybernetics, vol. 4, pp. 2314−2319.
Zhang, P., Wang, Y., Nie, X., Yan, W., Zhang, H., 2008b. Transient modeling and analysis of transformer windings under VFTO. In: Proceedings of the 7th World Congress on Intelligent Control and Automation June 25 - 27, 2008, Chongqing, China, pp. 2442−2445.
Zhang, Q., Wang, S., Qui, J., Jing, X., Gao, C., Zhu, J.G., Gue, Y., 2013. Application of multi-conductor transmission line model in power transformer. IEEE Trans Machines 49, 2029−2032.
Zhang, H., Wang, S., Yuan, D., Tao, X., 2015. Double-ladder circuit model of transformer winding for frequency response analysis considering frequency-dependent losses. IEEE Trans. Magn. 51, 11.
Zhao, X., Yao, C., Abu-Siada, A., Liao, R., 2019. High frequency electric circuit modeling for transformer frequency response analysis studies. Int. J. Electr. Power Energy Syst. 111, 351−368.
Zhao, Z., Tang, C., Chen, Y., Zhou, Q., Yao, C., Islam, S., 2021. Interpretation of transformer winding deformation fault by the spectral clustering of FRA signature. Int. J. Electr. Power Energy Syst. 130.
Zhao, J., Chen, W., Li, K., Wan, B., Zhang, J., Wen, T., Zhang, X., 2022. Frequency domain algorithm in the whole process simulation from VFTO to its conducted disturbance via voltage transformer in GIS substations. Elec. Power Syst. Res. 209, 11−17.
Zhongdong, J.L., Sofian, D., 2009. Interpretation of transformer FRA responses_Part I: influence of winding structure. IEEE Trans. Power Deliv. 24, 703−710.
Zhongyuan, Z., Lu, G.S., Yunpeng, F.L., 2006. The calculation of the voltage distribution in transformer windings under

VFTO based on FDTD method. In: APCCAS 2006 - 2006 IEEE Asia Pacific Conference on Circuits and Systems, pp. 856−859.

Zhongyuan, Z., Yutong, C., Yupeng, L., Fangcheng, L., 2008. High frequency circuit model of transformer windings based on frequency responses for VFTO studies. In: 2008 Third International Conference on Electric Utility Deregulation and Restructuring and Power Technologies, pp. 1528−1532.

Zhou1, L., Jiang, J., Li, W., Wu, Z., Gao, S., Guo1, L., Liu, H., 2019. FRA modelling for diagnosing axial displacement of windings in traction transformers. IET Electr. Power Appl. 13, 2121−2127.