Transformer Resonance

Reasons, Modeling Approaches, Solutions

Heidary, Amir; Niasar, Mohamad Ghaffarian; Popov, Marjan; Lekić, Aleksandra

DOI
10.1109/ACCESS.2023.3284552

Publication date
2023

Document Version
Final published version

Published in
IEEE Access

Citation (APA)
Heidary, A., Niasar, M. G., Popov, M., & Lekić, A. (2023). Transformer Resonance: Reasons, Modeling Approaches, Solutions. *IEEE Access*, *11*, 58692-58704. https://doi.org/10.1109/ACCESS.2023.3284552

IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 23 May 2023, accepted 6 June 2023, date of publication 9 June 2023, date of current version 16 June 2023.

Digital Object Identifier 10.1109/ACCESS.2023.3284552

TOPICAL REVIEW

Transformer Resonance: Reasons, Modeling Approaches, Solutions

AMIR HEIDARY, (Member, IEEE), MOHAMAD GHAFFARIAN NIASAR, MARJAN POPOV, (Fellow, IEEE), AND ALEKSANDRA LEKIĆ, (Senior Member, IEEE)
Faculty of EEMCS, Delft University of Technology, 2628 CD Delft, The Netherlands

Corresponding author: Amir Heidary (a.heidary@tudelft.nl)

This work was supported by Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO) in collaboration with TSO TenneT, DSO Alliander, and Royal Smit Transformers in the framework of the NWO-TTW Project–Protection of Future Power System Components (PRoteuS) under Grant 18699.

ABSTRACT Due to the extension of the power grid with many complex and compact pieces of power equipment, transformers will be more exposed to fast transient, resulting from various resonance conditions. Transformer resonance can result in severe overvoltage on internal parts of the winding, leading to insulation failure and, consequently, transformer outage. The main reasons for resonance occurrence, the practical method to measure the resonance of transformers, and the solution for preventing transformer resonances have been discussed in the scientific reports over the past few decades; however, a comprehensive review of these studies is not present in the literature. Hence this paper aims to provide a comprehensive review to categorize the main reasons for transformer resonance, modeling methods, and appropriate solutions to suppress this phenomenon and suggest some prospective protection for future works.

INDEX TERMS Fast transient, transformer's resonance, protection, models.

I. INTRODUCTION

As a well-known power system element, the transformer is an electromagnetic device that transforms the voltage level at the same power transfer and frequency in the electrical network [1]. There are two types of transformers: power transformers that supply electric energy and instrument transformers that measure power system signals [2]. The protection of this critical device is essential for the system's operation [3].

Resonance is one of the most significant phenomena affecting transformers' operation [4]. Various types of resonances may influence the operation of transformers [5]. Transformer resonance may occur due to the inductive and capacitive nature of the transformer windings and the connected power system, which can occur at a frequency different than the power frequency [6]. Most of the resonances in the transformer cause a harmful effect that needs to be prevented by protection methods [7]. The Diverse nature of transformers' resonance is classified in [8] based on how they affect the system.

Measurement and modeling of transformers in a wide frequency range not only help to optimize the design of the transformer but also provide insight into the risk of resonance during various transformer operations [9], [10]. Several types of solutions have been investigated to protect transformers against resonance faults [11]. These solutions are categorized as parallel damper circuits [12], series components [13], and solid-state protection devices [14]. Parallel dampers are nonlinear resistors known as surge arresters, or R-C circuits, which are mature solutions for transformer overvoltage protection [15]. They can be series components such as fast frequency suppressing circuits (FTSC) [16] and frequency-dependent devices (FDDs) [17]. In addition, the solid-state device includes controllable switches, a capacitor bank, or a reactor that can help to eliminate the overvoltages due to transformer resonance successfully [18], [19].

This paper aims to provide a clear review of significant concerns of resonance occurrence for the most crucial part of the power system (transformers). The main purpose of this paper is to provide a review of the most important reasons

The associate editor coordinating the review of this manuscript and approving it for publication was Hui Ma.

for transformer resonance occurrence, transformer modeling approaches, and the industrial methods to suppress transformer resonance overvoltage.

This paper is organized in the following way. Section II deals with the reasons for resonance occurrence in transformers, presented based on recently reported scientific research. In section III, different methods to measure the resonance of transformers are expressed. Next, the methods to suppress the resonance of transformers are debated, and their main features are extracted. Section IV deals with the existing protection topologies. Finally, section V summarizes the results and provides insight for future work in this field.

II. REASONS FOR TRANSFORMERS' RESONANCE

Two main reasons for the resonance occurrence are the high voltage multiple restrikes or the power line switching because of either the fault and protection equipment operation or renewable resources management [20]. When the system's topology changes, the predominantly inductive circuit changes to capacitive and the other way around. Consequently, the system is exposed to oscillations with different frequencies and amplitudes [21], and therefore, the components like transformers may experience resonances during the system transient [22]. The reasons for resonance occurrence are presented in the following subsections.

A. TRANSFORMER RESONANCE OCCURRING DUE TO LIGHTNING EFFECT

Lightning overvoltages are the crucial source of transformer resonance when the lightning impulse occurs in the vicinity of a power transformer [23]. Lightning modeling is explained in [24], [25], [26], and [27]. These models include electromagnetic models, distributed-circuit models, and engineering models. In the case of the electrical system studies engineering model comprises of Duality of Engineering models, lightning striking tall objects, and ground-truth testing are employed [24]. As shown in Fig. 1, there are four types of lightning strikes in power systems: lightning strike to a ground wire, phase conductor, ground near towers [24], as well as to a wind generator tower, which causes a surge that proceeds toward the transformer [28]. Generally, it occurs due to their height and installation location. Under these circumstances, several tens of kilo amperes may flow from the tower, which can induce a high overvoltage nearby the power transformers [28]. The lightning current usually includes a current with a high rate of rise, around 10 kA/μs, and a slower rate of fall, such as 0.6 kA/μs [29], demonstrating a variety of harmonic contents.

This signal can induce a voltage with different harmonics and stimulate the transformer's resonance frequency after the lightning strike takes place [30]. The explained phenomenon can easily affect transformers with resonance overvoltage, partially or totally damaging the transformer's isolation [30]. Therefore, the best approach is to examine the transformer using the lightning test before finalizing the manufacturing process [31] and protect transformers against lightning effects [32], which this standard is provided in IEEE Std 998$^{\text{TM}}$-2012. In this standard, firstly, the detail of charge formation in the cloud is expressed to show various charge distributions in lightning, and then the shield wire design is defined in detail to protect the transformer of the substation from lightning strikes [32]. The standard test of the induced voltage of lightning (transformer lightning test) is shown in Fig. 2 [33], considering that this voltage waveform is similar to a lightning impulse [34].

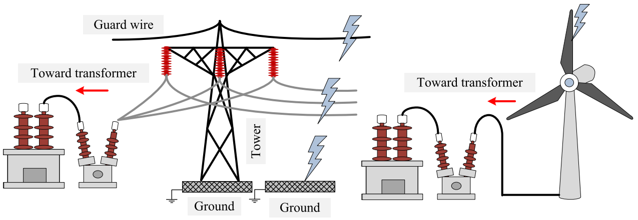

FIGURE 1. Various types of lightning strict to the power line and wind tower.

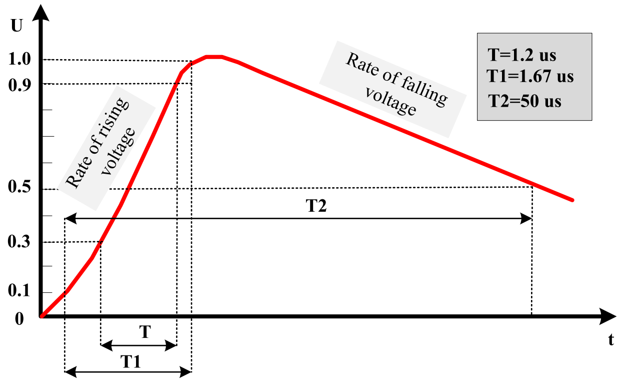

FIGURE 2. Transformer lightning test, described on voltage diagram.

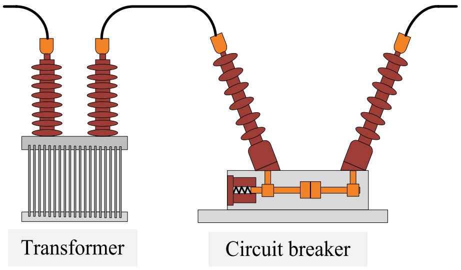

FIGURE 3. Configuration of transformer and circuit breaker.

B. TRANSFORMER RESONANCE OCCURRED DUE TO BREAKER SWITCHING

Circuit breakers are a crucial part of the power system, which generally either operate to protect the power system from fault current damage or disconnect the unloaded transformer [35]. Fig. 3 depicts the configuration of the circuit breaker and the transformer.

By opening the circuit of the unloaded transformer, overvoltage occurs on both the circuit breaker and the transformer

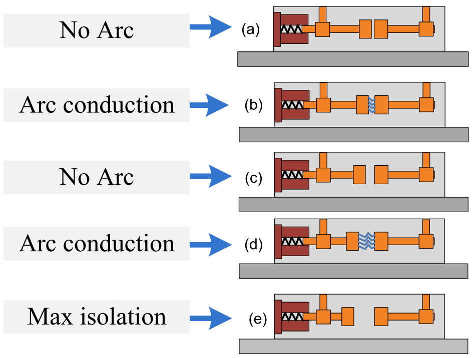

FIGURE 4. Operation procedure of the circuit breaker.

due to the magnetic energy stored in the transformer [36]. Equations (1) and (2) define the transformer and the circuit breaker voltages, respectively, throughout the breaking process by ignoring the damping effect [36].

$$U_t = I_{ch}\sqrt{L_m/C_t} \tag{1}$$

$$U_{cb} = E_{kr}.v.t \tag{2}$$

Here, U_t and U_{cb} are the voltage of the transformer and the circuit breaker, respectively. Ich is the chopping current of the circuit breaker, L_m and C_t are the magnetization inductance and the transformer capacitor, E_{kr} is the electric field between the contacts, v is the speed of contact separation, and t refers to the time.

Fig. 4(a)-(e) depicts the operation sequence of the circuit breaker. It clarifies that during the operation of the circuit breaker, the electric arc will be formed and interrupted several times. Finally, the breaker reaches the end of the cycle, where maximum isolation is applied, and the arc interrupts permanently [37]. The no-load transformer can easily face resonance overvoltage considering harmonically polluted voltage during the breaker's operation [38], [39].

Fig. 5 illustrates an example of the open no-load transformer voltage during the vacuum circuit breaker operation to open no-load transformer. Reference [38] provides analytical and experimental tests of CB prestrike and restrike effects on the winding of the transformer. By performing a test setup of three-phase switching of a CB by applying different cable lengths at different loading conditions, the occurred resonance overvoltage of the transformer was studied. The obtained results clarify the effects of vacuum CB operation on the transformer overvoltage. This operation may cause the transformer resonance.

Another reason that may cause resonance is the no-loaded transformer energization. By closing the breaker to the energized transformer, the fast transient phenomenon may excite resonance in the internal transformer windings, causing high voltage overvoltages [10].

C. TRANSFORMER RESONANCE OCCURRED DUE TO THE OPEN BREAKER EFFECTS

After power line interruption, the no-loaded transformer is always connected in series with the circuit breaker, considering there is no transient phenomenon in the power system. In this state, the circuit breaker behaves as a series capacitor, and the transformer (power or voltage transformer) is a large reactor [40]. This situation is illustrated in Fig. 6.

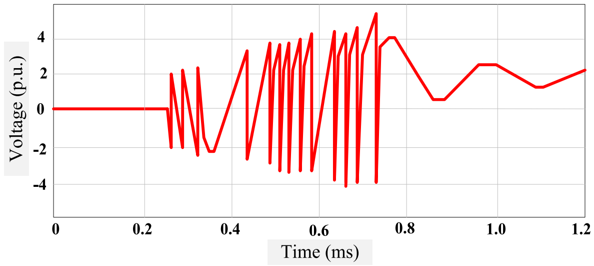

FIGURE 5. The voltage of the transformer during circuit breaker operation.

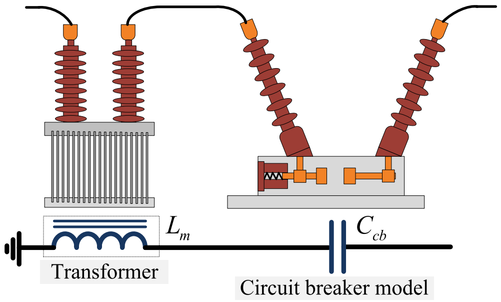

FIGURE 6. Equivalent circuit of the transformer and open circuit breaker.

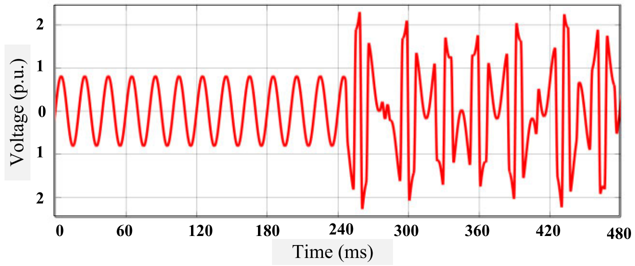

FIGURE 7. Ferroresonance overvoltage of the transformer.

Considering the open circuit breaker capacitive model, a series resonance [41] may occur. However, by increasing the transformer current, the core will reach the saturation region, and the ferroresonance may happen [42].

In addition, the harmonic content of voltage during the ferroresonance can cause many harmonic for nearby transformers [43], [44]. An example of the voltage signal of the transformer in the ferroresonance state is presented in Fig. 7 [19].

Observing Fig. 8, the nonlinear ferroresonance voltage of the transformer causes overvoltages higher than 2 p.u. Additionally, in the case of transformer ferroresonance, equation (3) presents the nonlinear characteristic of the transformer as a generic n-order polynomial. The order n is defined by the character of the transformer's core. Then applying the derivative to (3) transformer voltage can be

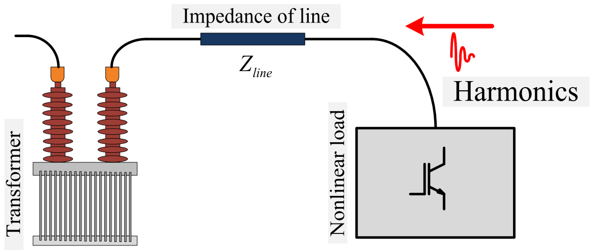

FIGURE 8. Nonlinear loads effects on the transformer.

expressed by (4) [19].

$$\lambda(t) + \lambda^n(t) = L\, i_t(t) \tag{3}$$

$$u_t(t) = N d\left(\varphi(t) + \varphi^n(t)\right)/dt \tag{4}$$

Here φ refers to the transformer core and L, which are the transformer winding inductance and current, respectively.

D. TRANSFORMER RESONANCE DUE TO NONLINEAR LOADS

The introduction of DC systems and DC nonlinear loads contribute to the increase of power system harmonic content [45]. Some harmonics may be close to the resonance frequency of large transformers [46]. Considering the power quality standard IEC 61000 in the power system, the magnitude of these harmonics should not exceed the values defined in the standard. However, the harmonics' magnitude might rise because of a power system malfunction, faults, or heavy nonlinear load switching [47], [48], resulting in transformer resonance and overvoltage. Due to the injection of harmonics in the transformer [49], as depicted in Fig. 8.

According to IEEE Std 1159-1995, the amplitude of the harmonics and the total harmonic distortion should be below the permissible values [50]. However, in system dynamics and power equipment interactions, the harmonic content can be increased and induce transformer resonance [51]. An example of the resonance possibility due to generated harmonics of the HVDC voltage source converter (VSC) in the High Voltage Direct Current (HVDC) power system is given in Fig. 9 [52]. It is shown that the transformer can be exposed to a risk of resonance caused by nonlinear power electronic devices, mainly triggered by the harmonics of the 30th-60th order.

E. TRANSFORMER RESONANCE CAUSED BY CABLE MODEL

In the power system, the high-voltage cable is used for power transmission or distribution between substations around urban areas. Accurate cable modeling is needed to investigate the interaction between the cable and the transformer [53]. The theoretical formulation of the cable, considering bundle-shielded cable as the most common cable, shows the capacitive cable's impedance in various harmonic domains [54], which may interact with the inductive impedance of the transformer.

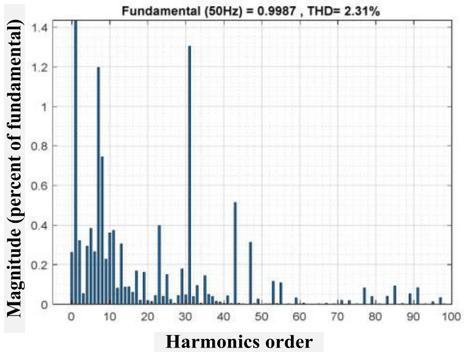

FIGURE 9. Harmonic pollution of the transformer connected to VSC.

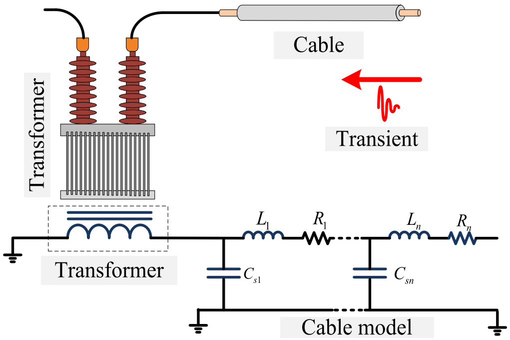

FIGURE 10. Cable-transformer model.

The cable's analysis conducted in the power system transient studies [55] proves its influence on the overvoltage and resonance [56], as it is illustrated in Fig. 10.

Considering the R-L-C models of the transformer and the cable, many resonance points may appear, which can be stimulated by the harmonic content of fast transients and cause transformer overvoltage. The critical length of the connected cables in both the primary and secondary of the transformer is determined by the travel time or the cable's resonance frequency and the transformer's resonance frequency which can be the main reason for transformer damage by overvoltage [57]. Mostly, cables have been modeled using frequency-dependent models designed using the cable's geometry [58] to study their effects. One of the cases in which resonance overvoltage occurs is where the transformer's secondary side is not loaded, and its primary winding is connected to the grid by a cable [59].

III. METHODS OF TRANSFORMER RESONANCE MEASUREMENT AND MODELING

This section presents the method which is currently applied for the transformer's frequency-dependent modeling and measurement. Data is categorized, including theoretical modeling of transformer resonance and measurement methods.

A. FREQUENCY-DEPENDENT MODELING OF THE TRANSFORMER

The possibility of resonance between the transformer and the rest of the power system equipment concerns designers

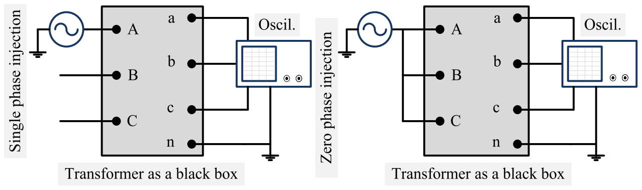

FIGURE 11. Example configuration of transformer black box model.

and system providers. Thus, the transient analysis of the transformer and its accurate modeling is vital for protecting transformers against resonance overvoltage [60]. The mostly used transformer modeling approaches are:

- Black box model [61], [62], [63], [64],
- White box model (physical model) [65], [66], [67], [68],
- Gray box model (hybrid model) [65], [69], [70], [71], [72].

1) BLACK BOX MODEL

In this model, the transformer is considered a black box, and then the electrical behavior of internal circuits is studied based on measurements [61]. The back box model is the standard and traditional method proposed in 1988, which helps to understand power transformers' behavior within the high-frequency range [61].

As a black box, the three-phase transformer is connected to the source and the measurement device, and its behavior is examined [62]. In this model, the source can be considered as a sinusoidal variable frequency [62] or an impulse generator [63], while the oscilloscope records measured signals from a terminal of the black-boxed transformer [62], [63].

Applying different configurations to this black box (short circuit or open circuit connection), connecting specific terminals with the source, and measuring currents and/or voltages is used to approximate admittance matrix elements [64]. An example of a black box model setup for the single phase and zero phase injection test for the black box model of the transformer is illustrated in Fig. 11 [62].

2) WHITE BOX MODEL

White box models, also known as physical models, are based on either FEM (Finite Element Method) or analytical analysis of R-L-C elements that define the transformer's characteristic (also called a detailed model). The white box is a model considering the geometry of all layers in the transformer, such as conductors, isolators, and core, as well as their interaction. The simulation of the transformer used to extract the results requires a long computational processing time due to the large matrices, with elements that should be computed for each frequency of the selected bandwidth [65].

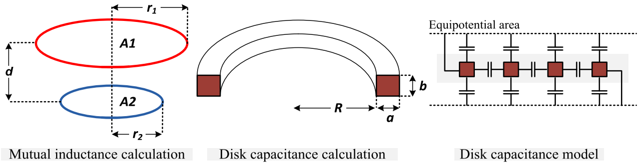

FIGURE 12. Example configuration for transformer's white box model.

The geometrical position of winding turns, the cross-section of the core, and the cross-section of the windings' wire are considered in a FEM transformer model [66]. Moreover, the capacitor calculation method between winding disks can be implemented using series-parallel capacitors, which improves the accuracy of the transformer white box model [67]. A 3D design and a 2D scheme can focus on a simplified simulated model of a section of the transformer to increase the accuracy of the transformer FEM model. According to the procedure of the white box model, the self-inductance of each turn or disk can be calculated, and then the mutual inductance of windings (between the disk of windings or between HV-LV) is studied. In addition, the capacitance of each disk to the transformer tank and capacitance between disks and between HV to LV winding is needed to create a comprehensive model [68]. An example of an accurate calculation of the inductance and capacitance of a transformer coil is illustrated based on geometrical features in Fig. 12.

3) GRAY BOX MODEL

The gray box model (so-called hybrid model) comprises a combination of black box and white box models, which is the method to provide faster and more accurate analysis [69].

In this method, firstly, a signal is applied as input of the transformer, and the output as a system response is measured. Then, the transfer function is calculated using the transformer input and output. This model is improved by considering the winding geometry and FEM to calculate self- and mutual inductance [70]. In [71], the R-L-C model of the transformer is described, and it shows that the most critical issue of the gray box model is its ability to identify the model parameters when no information about the geometry of the transformer is available. Therefore, it is a practical method to model transformers with unidentified geometry or an old transformer (referred to as dielectric aging) and to diagnose the problem of the power system-connected transformer [72]. In addition, by simplifying the gray box model, it will be possible to improve the analysis and parameter estimation of the model faster and more accurately [65]. By developing STM (Simplified Transient Model) in [65], the advantages of the method are presented as follows:

- The time simulation is adequately low.
- Using STM along with the other models of power network elements for power system studies and analysis is possible.
- The parameter identification of STM does not need any costly and time-consuming measurements.
- Considering the effects of faults on STM is possible.

B. TRANSFORMER RESONANCE STUDY BASED ON TRANSFORMER MODEL

One of the vital goals of studying transformer models in the wideband frequency domain is the detection of the resonance

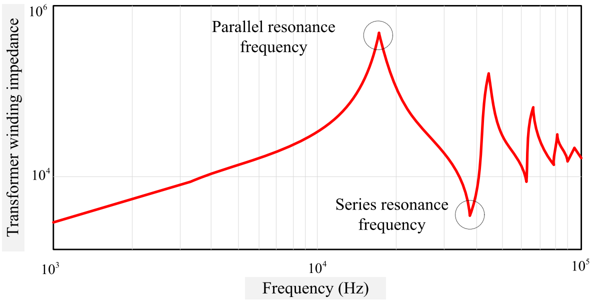

FIGURE 13. **Example of transformer resonance diagnosed by frequency sweep.**

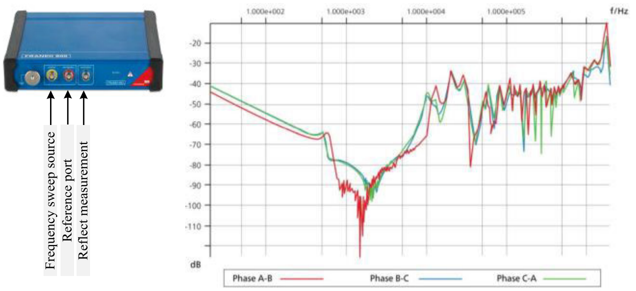

FIGURE 14. **Example of transformer measurement using omicron SFRA.**

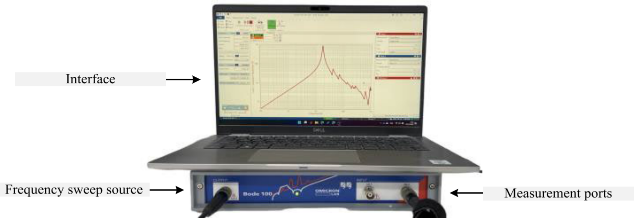

FIGURE 15. **Example of transformer measurement using bode 100 VNA.**

frequencies of the transformer [73]. The resonance frequencies closely depend on the type of transformer and its design conditions, which can be estimated by the nodal admittance measurement [73]. The frequency-dependent impedance of the transformer is a crucial issue that has to be studied to find extreme impedance points that show the resonance frequency points and transformer phase changes [9]. By studying the resonance frequency of the transformer, it is observed that it may cause disk overvoltage. This overvoltage can occur for several resonance frequencies, and the overvoltage magnitude might reach more than 5 p.u [74].

For monitoring power transformer resonance, electromagnetic simulation by EMTP software and using algorithms to diagnose resonance class is suggested in [75]:

For the transformer resonance determination and voltage distribution in each coil, it is investigated that a sinusoidal impulse with a 250 ns period is applied to the transformer winding. Then in [76], it is recommended that before applying the single-transmission line model (STLM) method to calculate transformer overvoltage against the transient, actual measurement of the frequency characteristic of the inter-turn voltage distribution, the resonant frequencies and the amplitude of the inter-turn overvoltage should be considered. Fig. 13 depicts an example of the magnitude of the transformer's impedance as a function of frequency and points out the resonance frequencies.

C. *TRANSFORMER RESONANCE MEASUREMENT METHODS*

In this subsection, the methods of transformer measurement are introduced. These methods are widely used to extract the resonance frequency of transformers in practice. These methods provide appropriate protection of the transformer around the resonance frequency points [10].

The frequency response analysis (FRA) test is based on measuring the transformer response in a wide frequency bandwidth, which is known as a vital method to diagnose resonance frequencies of transformer [6]. This method is presented in IEC 60076-18. The FRA device consists of three channels. The first channel comprises a source connected in series with a resistor. The second channel provides a reference value using a voltage drop on a 50 Ω resistor, and the third channel is the measurement port [77]. There are two types of FRA, depending on their internal source. The first type is designed based on an impulse source frequency response analyzer (IFRA), and the second one is designed using a sinusoidal sweep frequency response analyzer (SFRA) [77]. SFRA is the most commonly used device.

FRA test is a method to test the terminal or internal resonance of various types of transformers as complex electrical circuits [78]. In addition, it is an appropriate test method to study wideband analysis of transformer admittance and modeling of transformer [79], [80], [81]. Omicron SFRA is a commonly utilized device to test power transformers to diagnose their internal faults or resonance overvoltage [82]. Fig. 14 depicts the interface of the Omicron device in frequency sweep [83].

The second wideband measurement method uses a vector network analyzer (VNA) device [84]. The most crucial difference between VNA and SFRA is the different types of connection to the transformer, and only SFRA passes the requirement of the standard for transformer measurement [84], [85]. In [85], transformer measurements were compared for black-box modeling by employing two different methods and measurement equipment (sFRA and VNA). These two methods had a close agreement in the different ranges of frequencies (up to several MHz). For the frequencies higher than the MHz range, the results obtained by the VNA device were shifted to higher frequencies compared with the results measured with the SFRA. Fig. 15 shows VNA (Bode 100) and its measurement interface.

IV. SOLUTIONS FOR TRANSFORMER RESONANCE

By taking into account the state-of-the-art about transformer protection against resonance overvoltage, several solutions

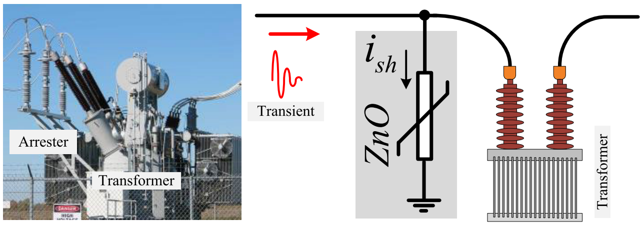

FIGURE 16. Configuration of surge arrester to protect transformer resonance.

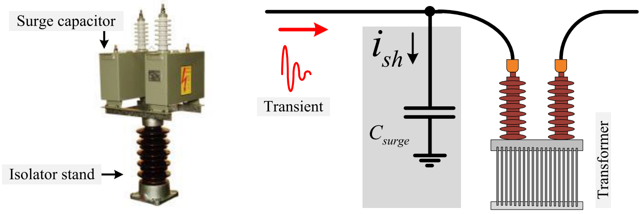

FIGURE 17. Configuration of surge capacitor to prevent transformer resonance.

have been introduced to suppress transient effects in power transformers. These structures are series or parallel protection devices that can act as filters to reduce and suppress transient resonance overvoltage [11]. Due to the operation, the content of harmonics that stimulate the transformer's resonance frequency will decrease to the acceptable value. The parallel protection equipment imposes mainly the capacitive-resistive model in parallel with the transformer, and series protection components impose the inductive-resistive model in series with the transformer; their operation is based on magnetic effects [12], [86], [87], [88], [89], [90], [91], [92], [93], [94], [95], [96], [97], [98].

A. THE PARALLEL-CIRCUIT SOLUTION AGAINST TRANSFORMER RESONANCE

1) SURGE ARRESTER PROTECTION

The most practical protection device against resonance (PDAR), which only limits the occurred overvoltage of a transformer, is the use of surge arresters connected in parallel to the transformer terminals. Surge arresters are known as overvoltage protection, developed mainly from Zinc oxide material [86]. Nevertheless, it can just chop overvoltage occurred by each reason. Moreover, it cannot behave as a harmonic filter [12], [87]. Surge arresters are categorized based on the voltage level, particularly between 24-800 kV (RMS) [87]. The configuration of the surge arrester is illustrated in Fig. 16 [88].

2) SURGE CAPACITOR PROTECTION

The solution of transformer resonance through a surge capacitor is very similar to the surge arrester protection. In this method, a surge capacitor is able to tolerate high dU/dt values in parallel with the transformer to suppress the transient voltage of the system as a low-pass filter. In contrast with the surge arrester, the surge capacitor damps the magnitude of high-frequency overvoltage and decreases the transient's harmonic content, which may stimulate transformer inter-disk or terminal resonance [89]. Fig. 17 [90] shows an in-market surge capacitor and its configuration to protect the transformer. The conventional surge capacitors are designed for a 7.2-36 kV (medium voltage) range, and their capacity is between 0.05-0.8 μF [90].

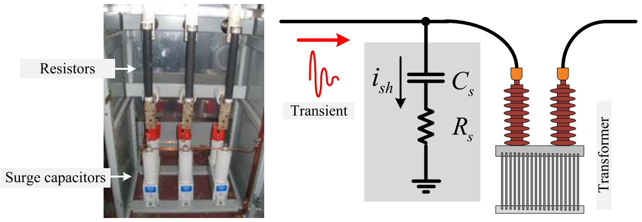

FIGURE 18. Configuration of RC snubber to protect the transformer.

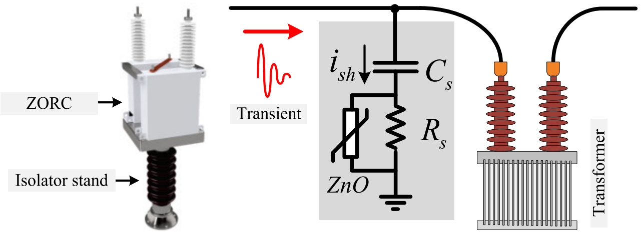

FIGURE 19. Configuration of ZORC to protect the transformer.

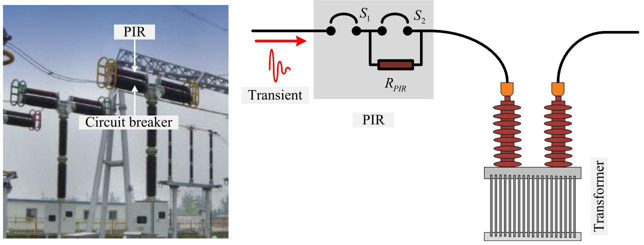

FIGURE 20. Configuration of the pre-inserted resistor to protect the transformer.

3) R-C SNUBBER

Using a shunt R-C circuit as a snubber is a standard method to protect transformers from transient and resonance. This method connects a high-impedance R-C in parallel to the transformer [91]. The operation of R-C acts as a low-pass filter and absorbs the energy of the transient signal in the resistor. The voltage range of the conventional R-C snubber of the power system is between 7-34.5 kV, and the range of the resistor is 20-500 Ω (300-750 W). Also, the range of the capacitance is 0.08-0.75 μF [92]. Fig. 18 shows a configuration of RC snubber with a transformer [92].

4) ZNO-RC PROTECTION

A modified structure of the R-C snubber has been developed as a solution to prevent transformer resonance, known as

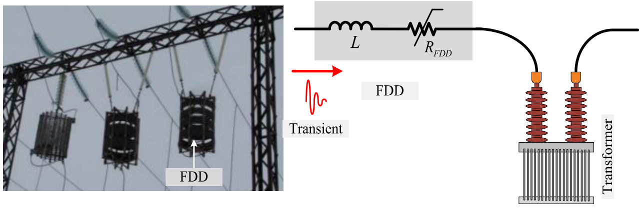

FIGURE 21. Configuration of FDD to protect the transformer.

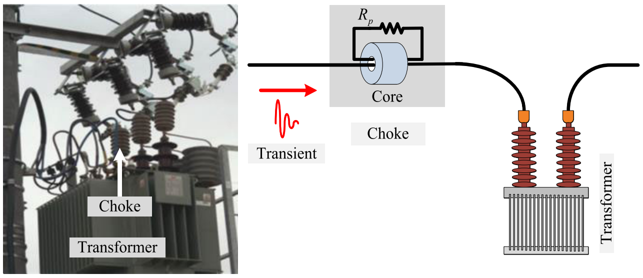

FIGURE 22. Configuration of choke to protect the transformer.

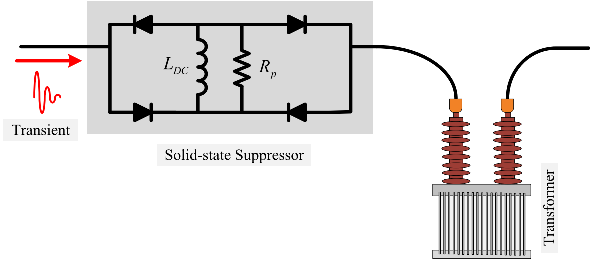

FIGURE 23. Configuration of solid-state suppressor to protect the transformer.

ZORC. This structure comprises Zinc Oxide (ZnO) surge arresters, resistors, and capacitors, which are very effective devices for suppressing the transient oscillations and protecting the transformer against resonance. Its operation is very similar to RC snubber; however, it includes a nonlinear resistor which can improve the operation of RC snubber [93], [94]. A conventional ZORC is designed for a 3-40 kV voltage level. Fig. 19 illustrates a ZORC to protect the transformer [94].

B. SERIES-CIRCUIT SOLUTION AGAINST TRANSFORMER RESONANCE

1) PRE-INSERTION RESISTOR PROTECTION

A practical way to mitigate the high rate of transient variations in the power system is by using pre-inserted resistors (PIR) before switching [95]. Two types of PIRs exist: series switches PIR or parallel switches connection PIR. Both can protect the transformer against resonance. This method's advantage is that it applies to high voltage transformers up to 400 kV, and its challenge is very high power loss during power switching. Also, this method suppresses only the transients occurred by switching [96]. Fig. 20 shows the configuration of PIR with a transformer [97].

TABLE 1. Summary of the transformer resonance review.

<table>
<tr><th colspan="6">Transformer resonance reasons</th></tr>
<tr><td colspan="2">Lightning strike</td><td>Switching arc</td><td>Open circuit breakers</td><td>Nonlinear loads</td><td>Cable effects</td></tr>
<tr><th colspan="3">Modeling of Transformer</th><th colspan="3">employed method</th></tr>
<tr><td colspan="3">Black box model</td><td colspan="3">Input a source and output measurement</td></tr>
<tr><td colspan="3">White box model</td><td colspan="3">Finite element method by physical detail</td></tr>
<tr><td colspan="3">Gray box model</td><td colspan="3">Using both measurement and FEM</td></tr>
<tr><th colspan="6">Transformer resonance measurement methods</th></tr>
<tr><td colspan="2">IFRA</td><td colspan="2">SFRA</td><td colspan="2">VNA</td></tr>
<tr><th colspan="2">Transformer protection</th><th colspan="4">Protection features</th></tr>
<tr><td rowspan="2">Resistive</td><td>Arrester</td><td colspan="4">LV to HV protection, resonance overvoltage protection of transformer terminal</td></tr>
<tr><td>PIR</td><td colspan="4">MV to HV protection, resonance protection of transformer in the switching case</td></tr>
<tr><td rowspan="3">Capacitive</td><td>Surge capacitor</td><td colspan="4">MV protection, harmonic content filter, resonance protection of transformer terminal, and inter disk</td></tr>
<tr><td>R-C snubber</td><td colspan="4">MV protection, harmonic content filter, resonance protection of transformer terminal, and inter disk</td></tr>
<tr><td>ZORC</td><td colspan="4">MV protection, harmonic content filter, resonance protection of transformer terminal, and inter disk</td></tr>
<tr><td rowspan="3">Inductive</td><td>FDD</td><td colspan="4">MV to HV protection, harmonic content filter, resonance protection of transformer terminal, and inter disk</td></tr>
<tr><td>Choke</td><td colspan="4">MV protection, harmonic content filter, resonance protection of transformer terminal, and inter disk</td></tr>
<tr><td>DCRS</td><td colspan="4">MV protection, resonance protection of transformer terminal, and inter disk</td></tr>
</table>

2) FREQUENCY-DEPENDENT PROTECTION DEVICE

The series R-L circuit is a recently presented solution for protecting the transformer against transient phenomenon and resonance. This circuit can be realized by using ferromagnetic shielded wire as a frequency-dependent device (FDD) [98]. This device comprises a multilayer wire using both aluminum and ferromagnetic material, which are wounded as a reactor and connected to input cables of a power substation. FDD provides meager resistance for grid frequency (50 or 60 Hz) and imposes high resistance of nearly 200 Ω for frequencies around 200 kHz [99]. In [99], it is obtained that FDD protects well from short pulses and has little effect on long pulses. The designed device parameters must be developed or integrated with devices like the arrester to protect the transformer properly. The variable resistor of FDD is created based on the skin effect of composite ferromagnetic material [100]. Fig. 21 depicts the equivalent circuit of FDD and in-practice configuration [99].

3) CHOKE PROTECTION

Choke is a series device that protects the medium voltage power transformer against transients and resonance.

The R-L choke model can appropriately mitigate transient harmonic content and drastically reduce the transformer's resonance overvoltage [16]. In normal operation, the impedance of this component (power network 50/60Hz frequency) is nearly zero. During high-frequency transient, these applications behave as a parallel R-L and suppress the high-frequency oscillation by using the effect of ferromagnetic core [101], [102]. Fig. 22 shows the choke configuration [11].

4) POWER ELECTRONIC-BASED PROTECTION

The solid-state DC reactor suppressor (DCRS) component is normally used to protect transformers against transient and transformer resonance. This practical method protects the transformer against nonlinear resonance comprised of a solid-state bridge (including four diodes) and parallel R-L. It can appropriately protect the transformer by suppressing nonlinear oscillations of voltage transformer ferroresonance, and mitigating harmonic overvoltage on the transformer terminal [103]. The topology of this power electronic-based transient suppressor device is presented in Fig. 23.

TABLE 1 summarizes the essential data concerning reasons, measurement, and associated protection methods. Considering the transformer resonance issue, it is crucial to determine the reason for transformer resonance and then provide an accurate model for the studied transformer. In the final stage, providing the appropriate compound solution for the resonance occurrence of the studied transformer should be considered.

By observing in the summary TABLE 1, it is clear that there is no comprehensive solution to protect transmission level transformers against grid transients and resonance overvoltage.

Considering the circumstance, the applicability of the available solution in the next section is briefly studied to obtain the next step of the research in this field.

V. STUDY OF APPLICABLE PROTECTION AGAINST TRANSMISSION TRANSFORMER RESONANCE

This section provides a brief overview of the limitations of the already used protection methods for the protection of high-voltage transmission transformers. The evaluation of the available protection solutions at a 200 kV voltage level has been considered.

A. PARALLEL PROTECTION METHODS EVALUATION

1) SURGE ARRESTER

This component is connected in parallel with the transformer to protect it from overvoltage. There are two operating concerns: The transformer model is inductive and dependent on the voltage magnitude. An equivalent model of the surge arrester is illustrated in Fig. 24 [12].

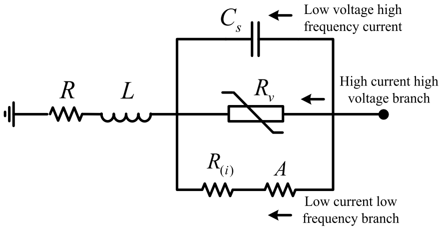

FIGURE 24. Equivalent circuit of the surge arrester.

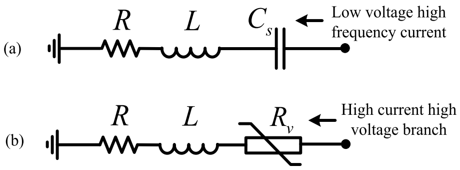

FIGURE 25. Split equivalence circuit of the surge arrester against transient.

When the transients do not exceed the arrester's continuous operation voltage, the equivalent arrester circuit is a series RLC. The circuit depicted in Fig. 25 (a) is a middle-passed filter around its resonance frequency. However, the remaining frequency content can cause the transformer's inter-disk resonance while the transformer's terminal voltage never experiences an overvoltage due to the surge arrester suppressing the voltage.

The next concern about surge arrester protection is caused by high voltage and high-frequency transients. In this case, the surge arrester behaves as an R-L circuit, as shown in Fig. 25 (b). This circuit can cause an operational delay against a very fast transient, resulting in transformer resonance before the arrester operates. These two reasons show that surge arresters cannot provide comprehensive protection for transformer resonance:

1) Surge arrester cannot protect transformer against low voltage high-frequency transients.
2) Operational delay considering its inductive circuit against high voltage high-frequency transients.

2) PARALLEL CAPACITIVE PROTECTION

The capacitive transformer protection consists of three types [89], [92], and [93]: surge capacitor, R-C snubber, and ZORC. Considering the industrial datasheets, to protect a 200 kV transformer, using 0.1 µF, 200 Ω (for R-C snubber and ZORC), and at least 360 kV capacitor (considering that transient impulse adds 50-100 kV to the standard voltage of system) is needed. Condition from equation (5) proves that the steady-state impedance of the capacitor is much higher than the resistance. Therefore, its effect can be ignored in calculating the reactive power consumption of the protection branch.

$$R \ll 1/\omega C_s \tag{5}$$

In addition, the nominal voltage of each industrial capacitor module (existing in the market) is 36 kV, 0.1 µF. Hence, to create a 360 kV, a 0.1 µF series-parallel connection of 100 capacitors is needed. This number is estimated under the

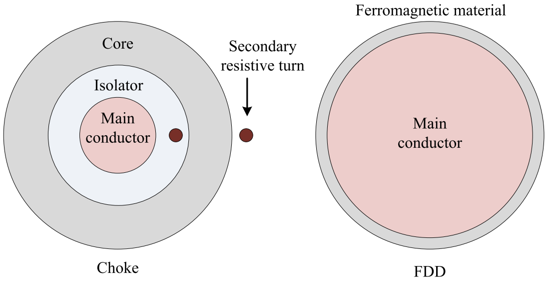

FIGURE 26. **2D illustration of choke and FDD.**

assumption of linear voltage distribution. The leakage capacitor affects the high-frequency content if it is not distributed linearly. Thus, the number of capacitors should be higher than 100.

In the steady state, the protection capacitor bank will consume reactive power Q as calculated by:

$$Q = \omega C_s V_s^2 \tag{6}$$

Where ω is the angular frequency of the grid, C_s is the capacity of the surge capacitor, and V_s is grid voltage. For the described example, the value of consumed reactive power will be 1.25 MVAR.

Furthermore, a higher capacitor number can decline the device's reliability. Moreover, the reliability of the capacitor bank will decrease considering the grid's harmonic pollution, which might increase the consumed reactive power in the steady state even more. Therefore, the surge capacitor for high-voltage transformer protection is not applicable.

3) SERIES INDUCTIVE PROTECTION METHOD EVALUATION

The FDD and the choke [99], [102] are the two main methods for protecting the transformer from resonance overvoltage. The design relies on the ferromagnetic power conductor. However, there are some differences between these two schemes. Fig. 26 depicts a 2D illustration of FDD and the choke structure cross-section.

Namely, the choke contains the core isolated from the main conductor, whereas, in the FDD, the ferromagnetic shield is connected electrically to the main conductor. Furthermore, choke has a resistive secondary turn, while FDD does not. Also, FDD is built by wounding the extensive length of the illustrated cross-section, but choke lengths are very shorter. FDD's ferromagnetic thickness is much smaller than the choke.

Both structures modeled as series R-L can protect transformers against resonance because they do not meet power grid voltage during a steady state. They can filter the harmonic content of transients and protect transformers.

However, the concerns are the deep saturation of the choke core, high power losses, and thermal desaturation of FDD during steady state. This concern can also affect the correct transient operation of these devices. Besides, the wideband operation of these series filters needs to increase the inductance, which causes reactive power loss in the steady state.

Equations (7) and (8) show that core saturation depends on core cross-section and component inductance. The consumed reactive power depends on the inductance value, as seen in equation (9). Finally, equation (10) shows that the protection component's imposed impedance should be comparable to the transformer impedance.

$$B \ll B(\max) \tag{7}$$

$$\frac{L.I_t}{A_{core}} \ll B(\max) \tag{8}$$

$$I_T^2 \omega L \ll 10kVAR \tag{9}$$

$$Z_{T(\min)}(f) < \omega_T L < Z_{T(\max)}(f) \tag{10}$$

Here, B, L, and A_{core} are the protection component's magnetic flux density, inductance, and core cross-section. Z_T, and I_T are the transformer's impedance and current, and ω_T is the angular frequency of the transformer's resonance.

It should be mentioned that the consumed active and reactive power can be reduced using the solid-state DC reactor method.

However, the positive aspects of the presented inductive protection methods are as follows:

1) The component is not too bulky,
2) It does not add any electric elements to the power conductor,
3) It is a reliable component.

VI. CONCLUSION

This paper reviews the crucial issue of power transformers' resonance, addressing the reasons of transformer resonance occurrence, transformer wideband frequency model, and protection solution. Eight series and parallel protection strategies are reviewed concerning transformer resonance protection. However, there are limited transformer protection solutions for different inter-disk and terminal resonance frequencies in high-voltage (transmission voltage level) applications. The main shortcoming is expressed by comparing the most significant limitations of the presently used protection devices. The next step of this research field will be the development of a protection device for transmission transformers against transient for both inter-disk and terminal resonance overvoltage.

REFERENCES

[1] E. I. Amoiralis, M. A. Tsili, and A. G. Kladas, "Transformer design and optimization: A literature survey," *IEEE Trans. Power Del.*, vol. 24, no. 4, pp. 1999–2024, Oct. 2009.

[2] F. de Leon, "Transformer modeling for low- and mid-frequency transients—A review," *IEEE Trans. Power Del.*, vol. 23, no. 3, pp. 1696–1697, Jul. 2008.

[3] W. Yuanfang and C. Zhou, "Experimental studies on the use of MOV in transformer windings inner protection," *IEEE Trans. Power Del.*, vol. 20, no. 2, pp. 1441–1446, Apr. 2005.

[4] R. J. Musil, G. Preininger, E. Schopper, and S. Wenger, "The resonance effect of oscillating system overvoltages on transformer windings," *IEEE Trans. Power App. Syst.*, vol. PAS-101, no. 10, pp. 3703–3711, Oct. 1982.

[5] A. M. Miri and C. Sihler, "Damping of resonances at energization of transformers serving large pulse-type loads," *IEEE Trans. Ind. Appl.*, vol. 40, no. 6, pp. 1694–1699, Nov. 2004.

[6] Sriyono, U. Khayam, and Suwarno, "Evaluating the inter-resonance characteristics of various power transformer winding designs," *IEEE Access*, vol. 9, pp. 54649–54656, 2021.

[7] A. H. Soloot, H. K. Høidalen, and B. Gustavsen, "Influence of the winding design of wind turbine transformers for resonant overvoltage vulnerability," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 22, no. 2, pp. 1250–1257, Apr. 2015.

[8] P. Mitra, A. De, and A. Chakrabarti, "Response of EHV grid transformers to system-originated oscillatory switching transients," *IEEE Trans. Power Del.*, vol. 27, no. 1, pp. 224–235, Jan. 2012.

[9] Y. Liu, S. A. Sebo, R. Caldecott, D. G. Kasten, and S. E. Wright, "Power transformer resonance-measurements and prediction," *IEEE Trans. Power Del.*, vol. 7, no. 1, pp. 245–253, Jan. 1992.

[10] T. Abdulahović and T. Thiringer, "Voltage stress in a transformer winding during very fast transients caused by breaker closing event," *IEEE Trans. Power Del.*, vol. 29, no. 4, pp. 1946–1954, Aug. 2014.

[11] D. Smugała, W. Piasecki, M. Ostrogorska, M. Florkowski, M. Fulczyk, and P. Klys, "Distribution transformers protection against high frequency switching transients," *Przegląd Elektrotechniczny, Elect. Rev.*, 2012.

[12] Y. Zhang, Q. Yang, S. Xie, and C. Zhang, "Mechanism and application of arrester block voltage division to lightning transient voltage monitoring in substation transformers," *IEEE Trans. Electromagn. Compat.*, vol. 61, no. 3, pp. 689–696, Jun. 2019.

[13] W. Piasecki et al., "dU/dt protection for distribution transformers," in *Proc. Int. Conf. Power Syst. Transients (IPST)*, Kyoto, Japan, Jun. 2009, pp. 1–5.

[14] A. Heidary, H. Radmanesh, A. Bakhshi, S. Samandarpour, K. Rouzbehi, and N. Shariati, "Compound ferroresonance overvoltage and fault current limiter for power system protection," *IET Energy Syst. Integr.*, vol. 2, no. 4, pp. 325–330, Dec. 2020.

[15] H. Wei, T. Peng, W. Yongkang, and X. Liangle, "Experimental study on consistency of surge test between using gas arrestors and capacitors," in *Proc. China Int. Conf. Electr. Distribution (CICED)*, Sep. 2018, pp. 897–900.

[16] D. Smugała, W. Piasecki, M. Ostrogórska, M. Florkowski, M. Fulczyk, and O. Granhaug, "New approach to protecting transformers against high frequency transients—Wind turbine case study," *Przegląd Elektrotechniczny*, vol. 89, pp. 186–190, Oct. 2013.

[17] S. M. Korobeynikov and N. Ya. Ilyushov, "High-current testing of frequency dependent device," in *Proc. 11th Int. Forum Strategic Technol. (IFOST)*, Jun. 2016, pp. 326–328.

[18] H. Radmanesh, A. Heidary, S. H. Fathi, and G. B. Gharehpetian, "Dual function ferroresonance and fault current limiter based on DC reactor," *IET Gener., Transmiss. Distrib.*, vol. 10, no. 9, pp. 2058–2065, Jun. 2016.

[19] A. Heidary and H. Radmanesh, "Smart solid-state ferroresonance limiter for voltage transformers application: Principle and test results," *IET Power Electron.*, vol. 11, no. 15, pp. 2545–2552, Dec. 2018.

[20] P. Akiki, A. Xémard, C. Trouilloud, and J.-L. Chanelière, "Study of high frequency transient overvoltage caused by cable-transformer quarter-wave resonance," *Electr. Power Syst. Res.*, vol. 197, Aug. 2021, Art. no. 107295.

[21] A. H. Soloot, H. K. Høidalen, and B. Gustavsen, "Resonant overvoltage assessment in offshore wind farms via a parametric black-box wind turbine transformer model," *Wind Energy*, vol. 18, no. 6, pp. 1061–1074, Jun. 2015.

[22] B. Liu, Y. Tong, X. Deng, and X. Feng, "Measuring of very fast transient overvoltage and very fast transient current generated by disconnector operating," in *Proc. Int. Conf. Power Syst. Technol.*, Oct. 2014, pp. 1349–1354.

[23] E. O. Hassan, E. A. Badran, and F. M. H. Youssef, "Effect of lightning impulses on the resonance stresses in the high voltage power transformers," in *Proc. 19th Int. Middle East Power Syst. Conf. (MEPCON)*, Dec. 2017, pp. 496–502.

[24] V. A. Rakov and F. Rachidi, "Overview of recent progress in lightning research and lightning protection," *IEEE Trans. Electromagn. Compat.*, vol. 51, no. 3, pp. 428–442, Aug. 2009.

[25] H. K. Høidalen, "Calculation of lightning-induced voltages in MODELS including lossy ground effects," in *Proc. Int. Conf. Power Syst. Transients (IPST)*, New Orleans, LA, USA, 2003, pp. 1–6.

[26] X. Liu and T. Ge, "An efficient method for calculating the lightning electromagnetic field over perfectly conducting ground," *Appl. Sci.*, vol. 10, no. 12, p. 4263, Jun. 2020.

[27] A. Andreotti, A. Pierno, and V. A. Rakov, "A new tool for calculation of lightning-induced voltages in power systems—Part I: Development of circuit model," *IEEE Trans. Power Del.*, vol. 30, no. 1, pp. 326–333, Feb. 2015.

[28] W. L. M. de Azevedo, W. C. da Silva, A. R. J. de Araújo, and J. P. Filho, "Computation of transient voltages on wind turbines on frequency-dependent soil caused by lightning strikes," in *Proc. Workshop Commun. Netw. Power Syst. (WCNPS)*, Nov. 2021, pp. 1–6.

[29] S. Visacro, "Recent advances in lightning research and their impact on the protection of electric systems," in *Proc. 34th Int. Conf. Lightning Protection (ICLP)*, Sep. 2018, pp. 1–4.

[30] M. Hori, M. Nishioka, Y. Ikeda, K. Noguchi, K. Kajimura, H. Motoyama, and T. Kawamura, "Internal winding failure due to resonance overvoltage in distribution transformer caused by winter lightning," *IEEE Trans. Power Del.*, vol. 21, no. 3, pp. 1600–1606, Jul. 2006.

[31] X. Zhang, M. Shi, C. He, and J. Li, "On site oscillating lightning impulse test and insulation diagnose for power transformers," *IEEE Trans. Power Del.*, vol. 35, no. 5, pp. 2548–2550, Oct. 2020.

[32] *IEEE Guide for Direct Lightning Stroke Shielding of Substations*, IEEE Standard 998-2012 (Revision IEEE Standard 998-1996), Apr. 2013, pp. 1–227.

[33] J. Chang, A. J. Kelly and J. M. Crowley, *Handbook on Electrostatic Processes*. New York, NY, USA: Marcel Dekker, 1995.

[34] A. F. Nematollahi and B. Vahidi, "Investigating the effect of lightning channel inclination on the induced voltage in overhead lines in the presence of horizontally stratified ground," *Electr. Power Syst. Res.*, vol. 208, Jul. 2022, Art. no. 107919.

[35] M. Popov, R. P. P. Smeets, L. van der Sluis, H. de Herdt, and J. Declercq, "Experimental and theoretical analysis of vacuum circuit breaker prestrike effect on a transformer," *IEEE Trans. Power Del.*, vol. 24, no. 3, pp. 1266–1274, Jul. 2009.

[36] M. Popov and E. Acha, "Overvoltages due to switching off an unloaded transformer with a vacuum circuit breaker," *IEEE Trans. Power Del.*, vol. 14, no. 4, pp. 1317–1326, Oct. 1999.

[37] M. Popov, L. van der Sluis, and G. C. Paap, "Investigation of the circuit breaker reignition overvoltages caused by no-load transformer switching surges," *Eur. Trans. Electr. Power*, vol. 11, no. 6, pp. 413–422, Nov. 2001.

[38] A. Theocharis, M. Popov, R. Seibold, S. Voss, and M. Eiselt, "Analysis of switching effects of vacuum circuit breaker on dry-type foil-winding transformers validated by experiments," *IEEE Trans. Power Del.*, vol. 30, no. 1, pp. 351–359, Feb. 2015.

[39] L. Liljestrand, C. Roy, E. Lindell, E. Dullni, and D. Bormann, "Vacuum circuit breaker and transformer interaction in a cable system," in *Proc. 22nd Int. Conf. Exhib. Electr. Distrib. (CIRED)*, Jun. 2013, pp. 1–4.

[40] H. Radmanesh, G. B. Gharehpetian, and H. Fathi, "Ferroresonance of power transformers considering non-linear core losses and metal oxide surge arrester effects," *Electr. Power Compon. Syst.*, vol. 40, no. 5, pp. 463–479, Mar. 2012.

[41] Y. Li, W. Shi, R. Qin, and J. Yang, "A systematical method for suppressing ferroresonance at neutral-grounded substations," *IEEE Trans. Power Del.*, vol. 18, no. 3, pp. 1009–1014, Jul. 2003.

[42] S. J. Kruger and J. A. de Kock, "Ferroresonance: A review of the phenomenon and its effects," in *Proc. Southern Afr. Universities Power Eng. Conf./Robot. Mechatronics/Pattern Recognit. Assoc. South Afr. (SAUPEC/RobMech/PRASA)*, Jan. 2021, pp. 1–6.

[43] Q. S. Charles, *Electromagnetic Transients in Transformer and Rotating Machine Windings*. 2012, doi: 10.4018/978-1-4666-1921-0.

[44] R. P. Pineda, R. Rodrigues, and A. Aguila Tellez, "Analysis and simulation of ferroresonance in power transformers using simulink," *IEEE Latin Amer. Trans.*, vol. 16, no. 2, pp. 460–466, Feb. 2018.

[45] A. Heidary, K. Ghorbanyan, H. Radmanesh, and H. R. R. Khamse, "Voltage sag and harmonic analysis in distribution network," in *Proc. 21st Conf. Electr. Power Distrib. Netw. Conf. (EPDC)*, Apr. 2016, pp. 102–105.

[46] C. Boonseng, R. Boonseng, and K. Kularbphettong, "Diagnosis of oscillation and vibration of dry-type transformers caused by harmonic resonance," in *Proc. Int. Conf. Diag. Electr. Eng. (Diagnostika)*, Sep. 2020, pp. 1–4.

[47] *IEEE Recommended Practice for Monitoring Electric Power Quality*, IEEE Standard 1159-2019 (Revision of IEEE Standard 1159-2009), Aug. 2019, pp. 1–98.

[48] *IEEE Guide for Identifying and Improving Voltage Quality in Power Systems*, IEEE Standard 1250-2018 (Revision of IEEE Standard 1250-2011), Nov. 2018, pp. 1–63.

[49] E. F. Ewald and M. A. S. Masoum, "Harmonic models of transformers," in *Power Quality in Power Systems and Electrical Machines*. New York, NY, USA: Academic, 2008, pp. 55–108.

[50] *IEEE Recommended Practice for Monitoring Electric Power Quality*, IEEE Standard 1159-1995, Nov. 1995, pp. 1–80.

[51] *IEEE Standard Conformance Test Procedures for Instrument Transformers*, IEEE Standard C57.13.2-1991, Jul. 1992, pp. 1–12.

[52] Y. Zhang, C. Klabunde, and M. Wolter, "Harmonic resonance analysis for DFIG-based offshore wind farm with VSC-HVDC connection," in *Proc. IEEE Milan PowerTech*, Jun. 2019, pp. 1–6.

[53] A. Ametani, T. Ohno, and N. Nagaoka, "Cable modeling for transient simulations," in *Cable System Transients: Theory, Modeling and Simulation*. Piscataway, NJ, USA: IEEE, 2015, pp. 163–184.

[54] T. Ohno, A. Ametani, and C. L. Bak, "Derivation of theoretical formulas of sequence currents on underground cable system," in *Proc. Int. Conf. Power Syst. Transients (IPST)*, Delft, The Netherlands Jun. 2011, pp. 1–6.

[55] N. Nagaoka and A. Ametani, "Transient calculations on crossbonded cables," *IEEE Trans. Power App. Syst.*, vol. PAS-102, no. 4, pp. 779–787, Apr. 1983.

[56] L. Colla, S. Lauria, and F. M. Gatta, "Temporary overvoltages due to harmonic resonance in long EHV cables," in *Proc. IPST*, 2007, pp. 1–6.

[57] G. C. Paap, A. A. Alkema, and L. Van der Sluis, "Overvoltages in power transformers caused by no-load switching," *IEEE Trans. Power Del.*, vol. 10, no. 1, pp. 301–307, Jan. 1995.

[58] A. Morched, B. Gustavsen, and M. Tartibi, "A universal model for accurate calculation of electromagnetic transients on overhead lines and underground cables," *IEEE Trans. Power Del.*, vol. 14, no. 3, pp. 1032–1038, Jul. 1999.

[59] B. Gustavsen, "Study of transformer resonant overvoltages caused by cable-transformer high-frequency interaction," in *Proc. IEEE Power Energy Soc. Gen. Meeting*, Jul. 2011, pp. 1.

[60] S. M. H. Hosseini, M. Vakilian, and G. B. Gharehpetian, "Comparison of transformer detailed models for fast and very fast transient studies," *IEEE Trans. Power Del.*, vol. 23, no. 2, pp. 733–741, Apr. 2008.

[61] P. T. M. Vaessen, "Transformer model for high frequencies," *IEEE Trans. Power Del.*, vol. 3, no. 4, pp. 1761–1768, Oct. 1988.

[62] T. A. Papadopoulos, A. I. Chrysochos, A. I. Nousdilis, and G. K. Papagiannis, "Simplified measurement-based black-box modeling of distribution transformers using transfer functions," *Electr. Power Syst. Res.*, vol. 121, pp. 77–88, Apr. 2015.

[63] M. F. Horvat, Z. Jurković, B. Jurišić, T. Župan, and B. Ćućić, "Black-box power transformer winding model," in *Proc. 7th Int. Adv. Res. Workshop Transformers (ARWtr)*, Oct. 2022, pp. 18–23.

[64] A. Morched, L. Marti, and J. Ottevangers, "A high frequency transformer model for the EMTP," *IEEE Trans. Power Del.*, vol. 8, no. 3, pp. 1615–1626, Jul. 1993.

[65] E. Rahimpour and M. Bigdeli, "Simplified transient model of transformer based on geometrical dimensions used in power network analysis and fault detection studies," in *Proc. Int. Conf. Power Eng., Energy Electr. Drives*, Mar. 2009, pp. 375–380.

[66] P. Gomez, F. de Leon, and F. P. Espino-Cortes, "Improvement of a method to compute the inductance matrix of multilayer transformer windings for very fast transients," *IEEE Trans. Power Del.*, vol. 28, no. 2, pp. 1245–1246, Apr. 2013.

[67] M. G. Niasar and W. Zhao, "Impulse voltage distribution on disk winding: Calculation of disk series capacitance using analytical method," in *Proc. IEEE Int. Conf. High Voltage Eng. Appl. (ICHVE)*, Sep. 2020, pp. 1–4.

[68] M. García-Gracia, M. Villén, M. A. Cova, and N. El Halabi, "Detailed three-phase circuit model for power transformers over wide frequency range based on design parameters," *Electr. Power Syst. Res.*, vol. 92, pp. 115–122, Nov. 2012.

[69] E. Rahimpour, V. Rashtchi, and R. Aghmasheh, "Parameters estimation of transformers gray box model," in *Proc. Int. Conf. Modern Electr. Energy Syst. (MEES)*, Nov. 2017, pp. 372–375.

[70] E. Rahimpour, J. Christian, K. Feser, and H. Mohseni, "Transfer function method to diagnose axial displacement and radial deformation of transformer windings," *IEEE Trans. Power Del.*, vol. 18, no. 2, pp. 493–505, Apr. 2003.

[71] R. Aghmasheh, V. Rashtchi, and E. Rahimpour, "Gray box modeling of power transformer windings for transient studies," *IEEE Trans. Power Del.*, vol. 32, no. 5, pp. 2350–2359, Oct. 2017.

[72] S. D. Mitchell and J. S. Welsh, "Initial parameter estimates and constraints to support gray box modeling of power transformers," *IEEE Trans. Power Del.*, vol. 28, no. 4, pp. 2411–2418, Oct. 2013.

[73] M. Popov, "General approach for accurate resonance analysis in transformer windings," *Electr. Power Syst. Res.*, vol. 161, pp. 45–51, Aug. 2018.

[74] E. Mombello and K. Möller, "Impedances for the calculation of electromagnetic transient phenomena and resonance in transformer windings," *Electr. Power Syst. Res.*, vol. 54, no. 2, pp. 131–138, May 2000.

[75] S. Wei, L. Zhendong, Z. Jinxiang, C. Junfa, B. Feng, L. Qimeng, and Z. Wei, "Analysis and study of resonance monitoring and suppression strategies of EHV main transformer," in *Proc. 3rd Int. Conf. Inf. Sci. Control Eng. (ICISCE)*, Jul. 2016, pp. 848–852.

[76] M. Popov, L. van der Sluis, G. C. Paap, and H. De Herdt, "Computation of very fast transient overvoltages in transformer windings," *IEEE Trans. Power Del.*, vol. 18, no. 4, pp. 1268–1274, Oct. 2003.

[77] R. K. Senobari, J. Sadeh, and H. Borsi, "Frequency response analysis (FRA) of transformers as a tool for fault detection and location: A review," *Electr. Power Syst. Res.*, vol. 155, pp. 172–183, Feb. 2018.

[78] Sriyono, Suwarno, and U. Khayam, "Investigating the internal winding resonance characteristics of various power transformer winding designs," in *Proc. Int. Symp. Elect. Insulating Mater. (ISEIM)*, Tokyo, Japan, 2020, pp. 541–544.

[79] B. Gustavsen, "Wide band modeling of power transformers," *IEEE Trans. Power Del.*, vol. 19, no. 1, pp. 414–422, Jan. 2004.

[80] D. Filipovic-Grcić, B. Filipovic-Grčić, and I. Uglešić, "High-frequency model of the power transformer based on frequency-response measurements," *IEEE Trans. Power Del.*, vol. 30, no. 1, pp. 34–42, Feb. 2015.

[81] E. Al Murawwi, R. Mardiana, and C. Q. Su, "Effects of terminal connections on sweep frequency response analysis of transformers," *IEEE Elect. Insul. Mag.*, vol. 28, no. 3, pp. 8–13, May 2012.

[82] V. Nurmanova, M. Bagheri, A. Zollanvari, K. Aliakhmet, Y. Akhmetov, and G. B. Gharehpetian, "A new transformer FRA measurement technique to reach smart interpretation for inter-disk faults," *IEEE Trans. Power Del.*, vol. 34, no. 4, pp. 1508–1519, Aug. 2019.

[83] M. Rädler et al. *Electrical Interferences in SFRA Measurements—How to Overcome Undesirable Effects*. [Online]. Available: https://www.omicronenergy.com

[84] B. Gustavsen, "Removing insertion impedance effects from transformer admittance measurements," *IEEE Trans. Power Del.*, vol. 27, no. 2, pp. 1027–1029, Apr. 2012.

[85] F. Grecki and B. Wunsch, "Validation of power transformer wideband modeling using standard sFRA method with VNA equipment," in *Proc. IEEE PES Asia–Pacific Power Energy Eng. Conf. (APPEEC)*, Dec. 2019, pp. 1–5.

[86] M. A. Atefi, M. Sanaye-Pasand, and S. Bahari, "Preventing transformer energizing resonant overvoltages using surge arrester temperature rise index and controlled closing method," *IEEE Trans. Power Del.*, vol. 28, no. 2, pp. 998–1006, Apr. 2013.

[87] *High Voltage Surge Arresters*. [Online]. Available: https://library.e.abb.com

[88] *Insulation Coordination Study for Lightning Overvoltages in 420 kV Power Substation*. [Online]. Available: https://electrical-engineering-portal.com/download-center/books-and-guides/power-substations/insulation-coordination-study

[89] Qual-Tech Engineers. *Surge Protection of Arc Furnace Transformers*. [Online]. Available: https://www.Qualtecheng.com

[90] VISHAY ESTA. *Surge Suppressor Capacitors*. [Online]. Available: https://www.vishay.com

[91] T. Dionise and S. Johnston, "Surge protection for ladle melt furnaces: LMF transformer terminals were equipped with primary surge protection consisting of surge arresters and RC snubbers," *IEEE Ind. Appl. Mag.*, vol. 21, no. 5, pp. 43–52, Sep. 2015.

[92] P. E. Sutherland and M. E. Valdes, "Snubber design for transformer protection," in *Proc. IEEE Petroleum Chem. Ind. Tech. Conf. (PCIC)*, Sep. 2014, pp. 343–351.

[93] Trike Technologies. *High Frequency Transient Surge Suppressors Zorc*. [Online]. Available: https://strike.co.za/surge-suppressors

[94] *Zinc Oxide RC-Surge Suppressor (ZORC) Capacitors, for HV-Motor and Transformers*. [Online]. Available: https://www.vishay.com

[95] K. Munji, J. Horne, and J. Ribecca, "Design and validation of pre-insertion resistor rating for mitigation of zero missing phenomenon," in *Proc. Int. Conf. Power Syst. Transients (IPST)*, 2017, pp. 26–29.
[96] H. Heiermeier and R. B. Raysaha, "Power testing of preinsertion resistors: Limitations and solution," *IEEE Trans. Power Del.*, vol. 32, no. 4, pp. 1688–1695, Aug. 2017.
[97] GE Grid Solutions. *Live Tank Circuit Breakers 72.5–550 kV*. [Online]. Available: https://www.gegridsolutions.com
[98] S. M. Korobeynikov, N. Y. Ilyushov, Y. A. Lavrov, S. S. Shevchenko, and V. A. Loman, "High-frequency transients suppression at substation," in *Proc. IEEE Int. Conf. High Voltage Eng. Appl. (ICHVE)*, Sep. 2018, pp. 1–4.
[99] S. M. Korobeynikov, S. I. Krivosheev, S. G. Magazinov, V. A. Loman, and N. Ya, "Suppression of incoming high-frequency overvoltage in transformer coils," *IEEE Trans. Power Del.*, vol. 36, no. 5, pp. 2988–2994, Oct. 2021.
[100] G. G. Sutton, "Skin effect in composite and ferromagnetic wires," *Nature*, vol. 147, Jun. 1941, Art. no. 719, doi: 10.1038/147719a0.
[101] W. Piasecki, G. Bywalec, M. Florkowski, M. Fulczyk, and J. Furgal, "New approach towards very fast transients suppression," in *Proc. IPST*, 2007, pp. 1–6.
[102] D. Smugala, W. Piasecki, G. Bywalec, M. Ostrogorska, O. Granhaug, and P. Skryten, "Very fast transient suppressing device," U.S. Patent 8 929 048 B2, Jan. 6, 2015.
[103] A. Heidary, K. Rouzbehi, H. Radmanesh, and J. Pou, "Voltage transformer ferroresonance: An inhibitor device," *IEEE Trans. Power Del.*, vol. 35, no. 6, pp. 2731–2733, Dec. 2020.

AMIR HEIDARY (Member, IEEE) was born in Tabriz, Iran, in 1987. He received the B.Sc. and M.Sc. degrees from the Electrical Engineering Department, IAU, Iran, in 2009 and 2020, respectively. He is currently pursuing the Ph.D. degree with the Delft University of Technology (TU Delft). He was with Eleprotect Company, as a Researcher of electrical applications, from 2012 to 2017. His research has published in books, journal articles, and several patents. His main research interests include power system protection, power electronics, magnetic-based power applications, smart grids, and fast transients. His invention was awarded to the Iranian Elite Committee, in 2014.

MOHAMAD GHAFFARIAN NIASAR was born in Tehran, Iran, in 1984. He received the M.Sc. degree from the Sharif University of Technology, Tehran, in 2008, and the Ph.D. degree in electrical engineering from the Royal Institute of Technology (KTH), Stockholm, Sweden, in 2015. He is currently an Assistant Professor with the High Voltage Technology Group, Delft University of Technology, The Netherlands. His main research interests include aging of electrical insulation, HVDC insulation systems, partial discharges, high voltage power electronics, high-frequency power transformers, power cables, and FEM modeling.

MARJAN POPOV (Fellow, IEEE) received the Ph.D. degree in electrical power engineering from the Delft University of Technology, Delft, in 2002. He is a Chevening Alumnus. 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 research interests include 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 received the IEEE PES Prize Paper Award and the IEEE Switchgear Committee Award, in 2011. In 2017, together with the Dutch utilities TenneT, Alliander, and Stedin, he has founded the Dutch Power System Protection Centre to promote research and education in power system protection. He is an Associate Editor of *International Journal of Electrical Power and Energy Systems* (Elsevier).

ALEKSANDRA LEKIĆ (Senior Member, IEEE) received the B.S., M.S., and Ph.D. degrees in electrical engineering from the School of Electrical Engineering, University of Belgrade, Serbia, in 2012, 2013, and 2017, respectively. From 2012 to 2018, she was a Teaching Assistant with the School of Electrical Engineering, University of Belgrade, where she was an Assistant Professor, from 2018 to 2019. In 2019, she was a Postdoctoral Researcher with the Department of Electrical Engineering (ESAT), KU Leuven, and the Institute EnergyVille, Genk, Belgium. Since January 2020, she has been an Assistant Professor with the Intelligent Electrical Power Grids Group, Faculty of Electrical Engineering, Mathematics, and Computer Science, TU Delft.

• • •