

Frequency-Domain Modeling of Electrical Insulation and Application to High-Voltage Power Electronics: A Review

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Abstract—Modern power applications, such as high-voltage direct current transmission, electrified transportation, and industrial systems, increasingly rely on wide-bandgap semiconductors, driving the need for electrical insulation systems capable of withstanding high electric fields and switching voltage waveforms. The reliable design of insulation systems is critical to ensuring the high-power density and operational stability for high-voltage power electronics. Under multifrequency voltage conditions, frequency-dependent polarization dynamics within insulation materials significantly influence the macroscopic dielectric properties and insulation performance. This article provides a comprehensive review of frequency-domain modeling methodologies for electrical insulation exposed to switching voltage waveforms with varying rising times. It examines advancements in semi-empirical equations and equivalent circuit models for characterizing frequency-dependent polarization dynamics behaviors, analyzing the strengths, limitations, and suitability for various applications. Challenges caused by the fast-rising voltage waveforms to electrical insulation are addressed by integrating frequency-domain models. Practical case studies such as electrothermal field calculations and health assessments are discussed, demonstrating the necessity of the inclusion of polarization dynamics behaviors. The review concludes with insights into emerging trends, including the development of advanced insulating materials and diagnostic techniques. This work offers valuable guidance for insulation design and reliability analysis in high-voltage power electronics applications.

Index Terms—Electrical insulation, frequency-domain modeling, high-voltage power electronics, multifrequency voltage waveforms, polarization dynamics behaviors.

I. INTRODUCTION

WITH the rapid development of the wide-bandgap (WBG) semiconductor devices, the multifrequency

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power applications involving high-voltage power assets and power electronics devices play a key role in renewable energy, electrified transportation, and high-voltage direct current (HVDC) transmissions, as illustrated in Fig. 1 [1], [2], [3]. Different from the electrical insulation usually adopting thicker materials at power frequency, these modern multifrequency power applications put forward more stringent requirements with high power density, miniaturization, and reliability [4], [5]. The electrical insulation challenges exposed to high-frequency voltage waveforms occur in high-frequency power inverters, inverter-fed electrical machines, solid-state transformers, and power module packages and other high-voltage power assets [5], [6], [7], [8]. Electrical insulation as the core of these high-voltage applications is one of the most easily destroyed components, particularly under the power electronics voltage waveforms with fast rising times and high switching frequencies [9]. It is therefore significant to address the critical bottleneck of electrical insulation in high-voltage power electronics applications.

Intrinsic physiochemical performance and extrinsic partial discharge activities are intertwined as two critical factors, which threaten the reliability and durability of electrical insulation materials used in high-voltage power electronics applications. The influence of high-frequency switching waveforms on the aging, degradation, and lifetime of electrical insulation materials in solid-state transformers, power modules, and motor windings have been extensively investigated [10], [11], [12], [13], [14], [15]. In [12], the results exhibit that the insulation lifetime of medium-frequency transformer can be sharply reduced as a function of the switching frequency (from 10 to 50 kHz). The higher slew rate (dv/dt) would shorten the insulation lifetime under the same switching frequency. In [13], research shows that the electro-thermal-frequency coupling stress can cause an obvious synergistic influence on the performance degradation of insulation materials. In contrast, more research focuses have been on the influence analysis of power electronics voltage waveforms on partial discharge activities (e.g., partial discharge inception voltage, PDIV) inside insulation materials used in high-voltage power electronics applications, such as power module packaging [14], [16], [17], solid-state transformers [12], [18], printed circuit boards [7], and inverter-fed motors [15], [19], [20], [21]. Predominant research results exhibit that the switching frequencies, rising time of power electronics voltage waveforms would obviously decrease in the PDIV and

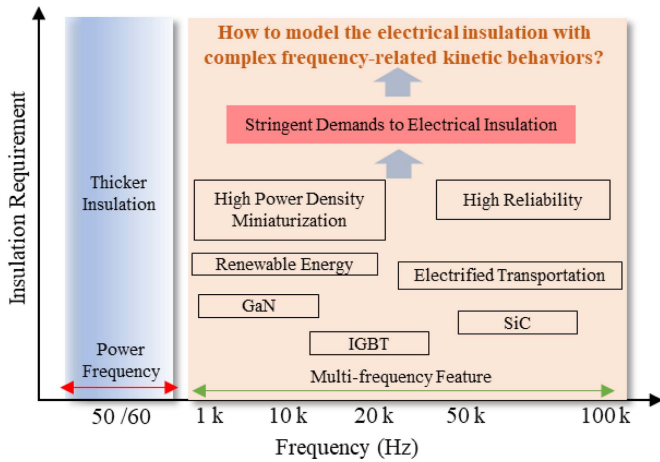


Fig. 1. Illustration of practical requirements for electrical insulation in high-voltage power assets. Compared to the traditional power-frequency voltage, the switching voltage stresses can stimulate the frequency-dependent polarization dynamics behaviors inside insulation materials.

accelerate the partial discharge (PD) activities. Additionally, harsh environmental factors like high temperature, humidity, and low gas pressure can synergistically decline PDIV values [22], [23], [24], [25]. It is worth noting that the aging, degradation, and partial discharge activities are closely associated with the fundamental variations in underlying dielectric properties of electrical insulation materials like polymeric epoxy resin, silicone gel, and polyimide [26], [27], [28], [29], [30]. Therefore, it is crucial to model the frequency-related dielectric properties and understand the physical mechanisms of electrical insulation materials subjected to power electronics voltage waveforms, aiming to address the aforementioned issues.

The switching voltage waveforms can be transformed to a series of multifrequency sinusoidal waveforms in frequency domain, which would stimulate the underlying frequency-dependent polarization dynamics behaviors inside electrical insulation materials [31]. Massive analysis results in traditional high-voltage engineering show that the frequency-dependent polarization dynamics phenomena will also be strongly enhanced by the complex coupling stresses of high temperature, high humidity, strong electric field, and frequency [32], [33], [34], [35], [36]. The underlying frequency-dependent polarization dynamics will directly influence the macroscopic dielectric properties like relative permittivity, dielectric loss, and conductivity, further, determining the electrothermal field distribution of insulation systems inside high-voltage power electronics [17], [26], [31]. However, the frequency-dependent polarization dynamics behaviors inside electrical insulation systems have not yet received enough attention in the emerging high-voltage power electronics applications. Therefore, it is imperative for high-voltage power electronics applications to take frequency-dependent polarization dynamics behaviors of electrical insulation materials exposed to multifrequency switching voltages into account. This will provide theoretical and technical support for insulation design, degradation understanding, and insulation diagnostics and health management of high-voltage power electronics assets.

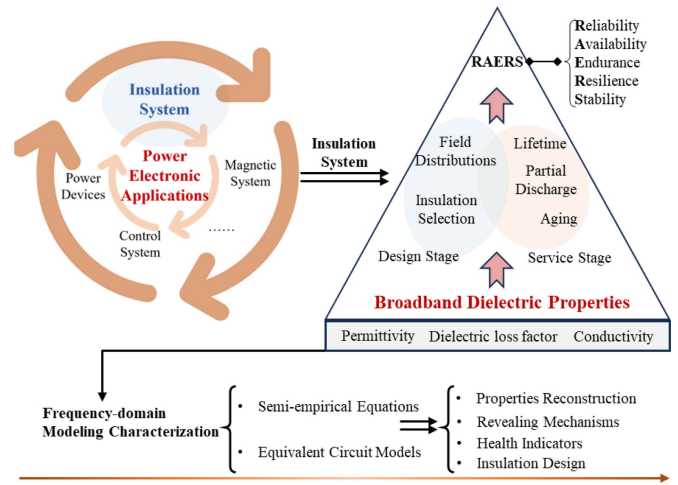


Fig. 2. Schematic diagram of the role of insulation systems in multifrequency power electronics applications involving other parts, including power devices, magnetic systems, and control systems. The schematic diagram consists of the procedure of frequency-dependent dielectric properties of insulation systems under multifrequency voltage waveforms.

To address the current challenges, this article will conduct a systematic review of the modelling approaches of frequency-dependent polarization dynamics behaviors of electrical insulation materials and their applications to high-voltage power electronics applications as presented in Fig. 2. The research backgrounds and relevant challenges of electrical insulation materials exposed to power electronics voltage waveforms are analyzed. Subsequently, two types of frequency-domain models for characterizing frequency-dependent polarization dynamics behaviors are summarized, consisting of semi-empirical equations and equivalent circuit models (ECMs). The effectiveness and accuracy of frequency-domain models are discussed through a range of practical applications under multifrequency voltage waveforms. Additionally, the advantages and shortcomings of the semi-empirical equations and ECMs for electrical insulation materials are concluded. The typical practical cases of frequency-dependent polarization dynamics of electrical insulation materials exposed to the multifrequency voltage waveforms are provided for the high-voltage power electronics applications. These applications can support insulation modeling, design analysis, and condition assessment for high-voltage power electronics applications. Finally, the future development trends of electrical insulation materials exposed to multifrequency voltage waveforms are discussed, which can serve as a reference in the interdisciplinary exploration of electrical insulation and high-voltage power electronics.

The structure of this article is as follows. Section II presents the relationship between frequency-dependent polarization dynamics mechanisms inside insulation systems and multifrequency switching voltage waveforms. Section III provides a detailed summary of the semi-empirical equations for characterizing the frequency-dependent polarization dynamics behaviors for insulation materials. Section IV analyzes the theoretical basis and development processes of equivalent circuit models for insulation systems. Section V presents a series of research cases

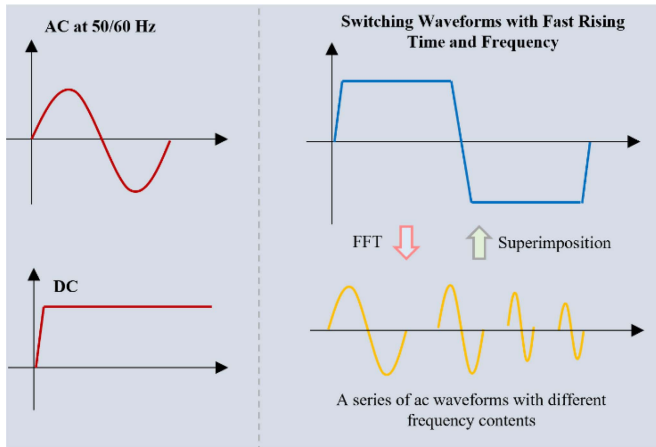


Fig. 3. Comparison figures of traditional power-frequency AC voltage, DC voltage, and switching voltage waveforms.

exploring the applications of frequency-dependent polarization behaviors to the physical mechanism analysis, system design, and health condition assessment of electrical insulation using dual frequency-domain modeling approaches. Section VI outlines future research directions to address existing challenges of electrical insulation in high-voltage power electronics applications. Finally, Section VII delivers a comprehensive conclusion, summarizing the key insights and contributions of this paper to the interdisciplinary field of electrical insulation and high-voltage power electronics.

II. RELATIONSHIP BETWEEN POLARIZATION DYNAMICS OF ELECTRICAL INSULATION AND MULTIFREQUENCY APPLICATIONS

A. Switching Voltage Waveforms With Fast Rising Time

The most prominent challenge to electrical insulation systems used in high-voltage power electronics applications is the switching voltage waveforms with fast rising time and high switching frequency, as presented in Fig. 3. Compared to power-frequency ac stress, the high-frequency switching voltage stresses applied to electrical insulation are becoming more complex. Deeply understanding the underlying physics mechanisms inside electrical insulation materials subjected to switching voltage waveforms with faster rising time is very concerned. This fundamentally determines the reliability and endurance of electrical insulation in high-voltage power electronics applications.

It should be an effective solution for the above issue from the perspective of frequency domain. The switching voltage waveforms with different rising times can be mathematically decomposed into a series of sinusoidal waveforms with different frequency components, as displayed in Fig. 3 [31], [37]. Inversely, the superimposition of a range of frequency-related sinusoidal waveforms forms the switching voltage waveforms. Thus, the dielectric properties for electrical insulation exposed to switching voltage waveforms with fast rising time present frequency-related. The frequency-dependent polarization dynamics behaviors inside insulation materials would be

stimulated. Additionally, dc voltage in the time domain is special because dc voltage forms also involve an energization stage or superimpose with ac ripples. The long-term dc steady states also stimulate underlying multi-timescale polarization dynamics properties inside insulation systems [38], [39], [40]. Notably, this article mainly addresses the impact of switching voltage waveforms, which could also provide the indirect reference for addressing dc voltage effects like MVDC power electronics applications.

The electrical insulation material is stimulated by a range of frequency-related sinusoidal excitation waveforms. The ionic, charge carriers, dipoles, and electrons inside insulation materials will migrate, move, and transfer under the sinusoidal electric field with different frequency components, causing charge storage and energy loss [41], [42]. Furthermore, the complex permittivity, dielectric loss tangent, and impedance properties due to intrinsic frequency-dependent polarization dynamics mechanisms would work as a function of the applied voltage frequency [41]. If only considering power-frequency relative permittivity or dc conductivity, the design and modelling of insulation systems exposed switching voltage waveforms and dc voltage superimposed by ac ripples could lead to large deviations from the realistic phenomena occurring frequency-dependent polarization dynamics behaviors.

Additionally, the frequency-dependent polarization dynamics behaviors could be highly dependent on the rising time of switching voltage waveforms, particularly when superimposed by harsh environmental factors like high temperature and high humidity [32], [33], [34], [35], [36]. According to the Fourier transformation theory, if the switching voltage waveforms have fast rising time, the decomposed sinusoidal voltage waveforms exhibit higher frequency ranges and higher magnitude. This would result in two main effects on frequency-dependent polarization dynamics mechanisms: high frequency and dielectric heating caused by power loss. Therefore, the switching voltage waveforms with different rising times would generate noticeable effects on frequency-domain modelling of electrical insulation.

B. Frequency-Dependent Polarization Dynamics Mechanisms

The frequency-dependent polarization dynamics types inside electrical insulation materials subjected to multifrequency voltage waveforms generally consist of interfacial polarization, dipole/orientation polarization, ionic polarization, atomic polarization, and electronic polarization from low-frequency to high-frequency regions, as exhibited in Fig. 4 [41]. These frequency-dependent polarization dynamics phenomena are closely associated with applied electric field, magnetic field, and environmental factors.

The polarization dynamics behaviors are composed of the relaxation and resonance regime in Fig. 4 [41], [43], [44]. The relaxation regime mainly includes interfacial polarization and dipolar polarization. The resonance regime consists of atomic and electron polarizations, between 10^{12} and 10^{16} Hz. Particularly, ionic polarization refers to the small movement of ions from the original steady state under an ac electric field, usually seen in the infrared frequency region [44]. It is noteworthy that

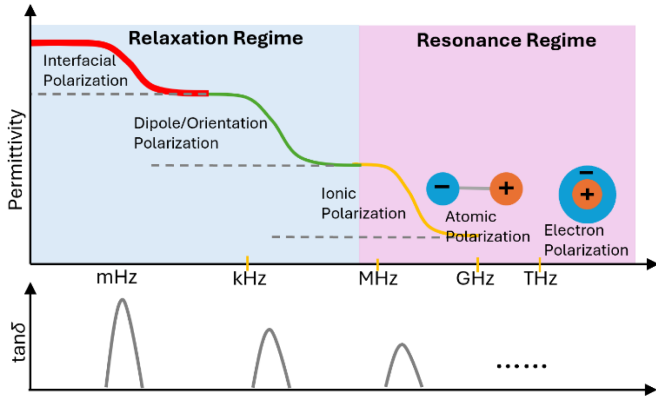


Fig. 4. Schematic diagram of different polarization mechanisms and types for insulation systems as a function of voltage frequency [41], [44].

the occurrence frequency ranges of various polarization mechanisms would vary with external factors, such as temperature, electric field, humidity, aging states, chemical structures, which highly depend on application cases.

Notably, the research group from ETH Zurich has considered the effects of the frequency-dependency and temperature-dependency of complex permittivity of electrical insulation materials on power electronics transformers design [45]. The frequency- and temperature-dependent polarization dynamics mechanisms of electrical insulation materials have been described as shown in Fig. 5 [45]. Particularly, the dielectric properties like complex permittivity of insulation materials would sharply change when the temperature exceeds the glass transition temperature (T_g). [33] also discusses the influence of T_g on frequency-dependent dielectric properties of epoxy resin in multifrequency power electronics applications.

C. Frequency-Dependent Polarization Dynamics Modeling

Over the past few decades, several research works have provided a deep understanding on frequency-dependent polarization dynamics inside insulation materials based on experimental characterizations and modelling analysis [32], [33], [34], [35], [36], [46]. The general measurement method is broadband dielectric spectroscopy (BDS), also called frequency-domain dielectric spectroscopy (FDS), frequency domain spectroscopy, dielectric spectroscopy. The modelling approaches of frequency-dependent polarization mechanisms of electrical insulation materials have been developed for capturing these physical phenomena. The grey-box methodology for modelling frequency-dependent polarization dynamics have been extensively adopted, as it integrates both advantages of white-box as a pure physics method and black-box as a pure data method in Fig. 6. The grey-box approach not only involves prior physical knowledge but also requires the input of experimental FDS data [47].

The grey-box methodologies for electrical insulation materials include semi-empirical equations and equivalent circuit models (ECMs). The semi-empirical equations are primarily employed to represent the complex permittivity, assuming that the geometric dimensions of the measured insulation

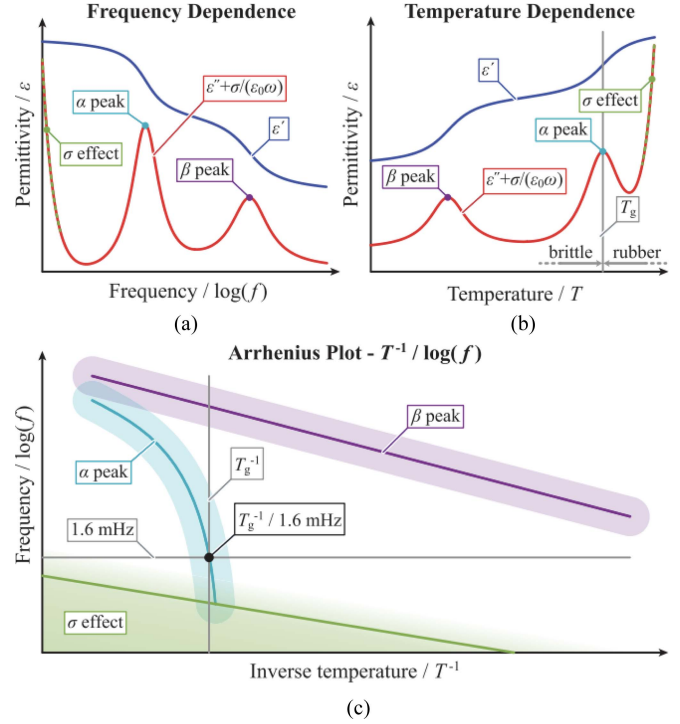


Fig. 5. Schematic diagram of the frequency-dependency and temperature-dependency of complex permittivity dominated by polarization mechanisms for an exemplary insulation material. (a) Frequency dependency. (b) Temperature dependency. (c) Effects of frequency and temperature on loss properties, including conductance loss and polarization loss. T_g is the glass transition temperature. Note: the temperature dependency of polarization mechanisms follows the Arrhenius equation [45].



Fig. 6. Schematic diagram of basic principles of white box, grey box, and black box for insulation systems.

system are known [48], [49], [50], [51], [52]. The ECMs established by basic circuit elements represents the complex impedance/capacitance and does not necessarily require prior knowledge of the geometric information of the measured insulation system [53], [54], [55]. These semi-empirical equations and ECMs are applied to fit and reconstruct the measured broadband dielectric/impedance spectroscopy curves of insulation systems under different external factors [48], [49], [50], [51], [52], [53], [54], [55]. The most fundamental purpose is to understand the underlying polarization dynamics processes and physics mechanisms of electrical insulation materials. This will provide the basic support for insulation design, health management, material selection in high-voltage power electronics applications. The frequency-dependent dynamics modeling of electrical insulation materials exposed to multifrequency switching waveforms has

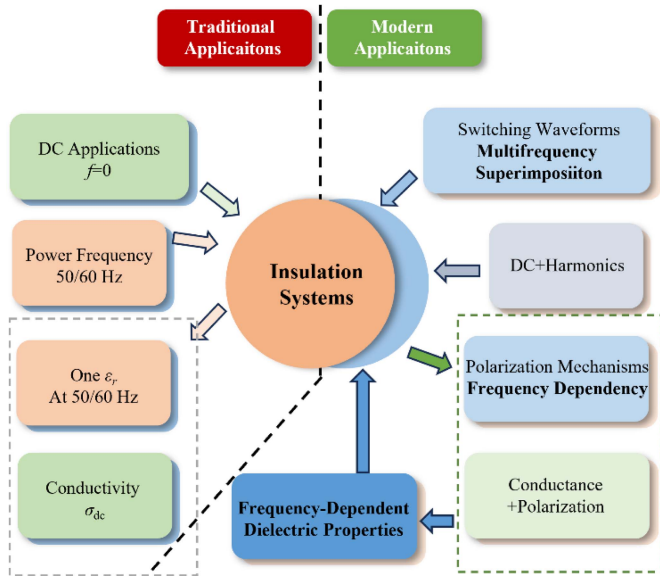


Fig. 7. Schematic diagram of insulation system properties under different voltage forms. Note: Based on the existing works, the electric field calculation of insulation systems under DC voltage usually considers the DC conductivity. Hence, the multi-timescale polarization mechanisms occurring under DC voltage have not been added. In Section VI, the authors introduce one research case of the electric field calculation of insulation systems under DC voltage, but the polarization mechanisms are included.

become extremely important, different from traditional power-frequency voltage.

D. Insulation Design Considering Polarization Dynamics Under Multifrequency Switching Voltage Waveforms

The basic properties of electrical insulation systems under traditional dc and power-frequency ac stresses can be characterized by the conductivity (σ_{dc}) and power-frequency permittivity (ϵ_r), respectively, as presented in Fig. 7. Nevertheless, the frequency-dependent polarization dynamics inside insulation materials make a prominent contribution under the multifrequency electric stresses in the modern high-voltage power applications driven by the WBG devices. The dielectric properties of insulation materials cannot be directly reflected by the conventionally simple conductivity (σ_{dc}) and power-frequency permittivity (ϵ_r). Instead, the frequency-dependent polarization mechanisms must be integrated into the modeling, design, and optimization of electrical insulation systems used in high-voltage power electronics applications. For instance, the constitutive equations of electrical field calculation for insulation materials need to be improved by integrating frequency-dependent polarization mechanisms.

E. Insulation Reliability Analysis Considering Polarization Dynamics Under Multifrequency Switching Voltage Waveforms

The relationship between complex coupling stresses and dielectric dynamics mechanisms for electrical insulation materials is shown in Fig. 8.

Behind the variations in macroscopic dielectric properties and accelerated aging of electrical insulation materials, the transport,

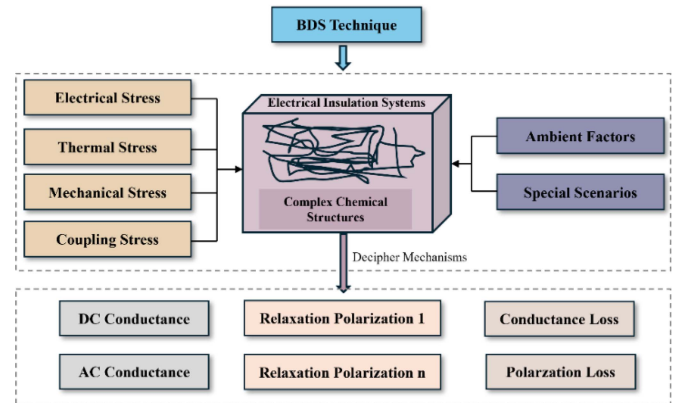


Fig. 8. Schematic diagram of the representation of frequency-dependent polarization mechanism for the reliability analysis of insulation systems in power equipment.

transfer, hopping, and movement of electrons and charge carriers inside insulation materials will occur as a function of the applied electric fields [41]. These microscopic mechanisms will lead to variations of macroscopic dielectric properties of insulation materials, such as conductivity, permittivity, and loss tangent [41], [42]. Under the sinusoidal electric fields with varied frequencies, the microscopic behaviors present the frequency-dependent polarization mechanisms, making a direct relation to the macroscopic permittivity and dielectric loss tangent. In essence, the macroscopic dielectric properties of insulation materials are a precise reflection of microscopic dynamics behaviors. In basic, modelling macroscopic dielectric properties under multifrequency electric stresses is the physical twin of microscopic polarization dynamic mechanisms of charge carriers. Therefore, the modelling and characterization of frequency-dependent polarization dynamics mechanisms will provide effective methodologies for reliability analysis and health condition management of electrical insulation materials used in high-voltage power electronics applications [32].

III. GREY-BOX SEMI-EMPIRICAL EQUATIONS

Since 1912, semi-empirical equations and ECMs have been developed to characterize the frequency dependence of dielectric dynamics behaviors and impedance properties in electrical insulation materials. Semi-empirical equations are primarily used to elucidate frequency-dependent polarization dynamics behaviors of insulation materials, with a focus on complex permittivity (or susceptibility). In contrast, equivalent circuit models serve to characterize frequency-dependent impedance properties of insulation materials.

The foundational semi-empirical equation, the Debye model, was first introduced in 1912 [56]. Building upon this initial Debye equation, other semi-empirical models have been developed to characterize frequency-dependent polarization dynamics behaviors inside insulation materials [56], [57], [58], [59]. Three categories of semi-empirical equations/models are summarized in Fig. 9, including Debye-derived models (1941–1966) [56], [57], [58], [59], the Williams–Watts (WW) model (1970) [60],

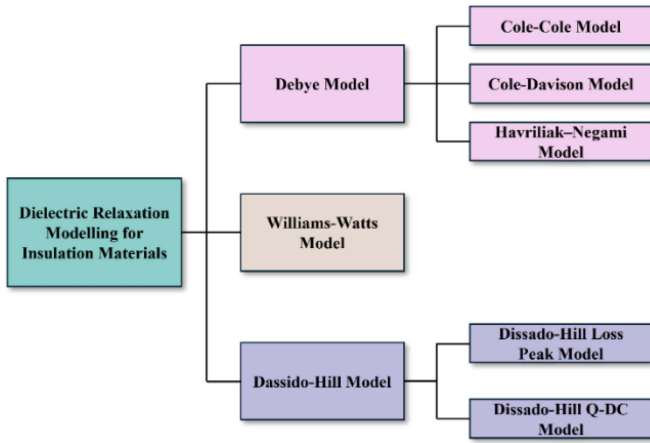


Fig. 9. Summarization of different semi-empirical models, including Debye models, WW model, and DH models.

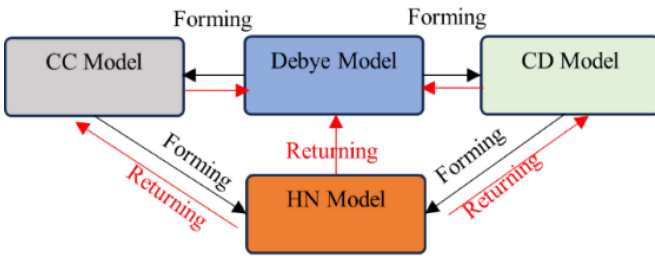


Fig. 10. Logic correlation representation of Debye and its derived models.

and the Dissado–Hill (DH) model (1983) [61], [62]. The Debye-derived models comprise the Cole– (CC), the Cole–Davison (CD), and the Havriliak–Negami (HN) models. The DH model includes the DH loss peak and QDC models [61], [62].

In comparison to Debye-derived models, WWM and DHMs have complex mathematical expressions, involving Gaussian functions. Concluded from existing literature, Debye-derived models with relatively easy-to-understand advantages have extensive practical applications in characterizing conductance and polarization dynamics mechanisms of insulation materials. This work will introduce more details about Debye-derived models, aiming to support the multifrequency power electronics applications. The basic theory and physical mechanisms of DH model have been comprehensively introduced by [63].

Beginning with the basic Debye model, an evolutionary diagram and correlation of the Debye-derived semi-empirical models are presented in Fig. 10.

The correlation relationship among different Debye-derived models is intertwined, where the Debye model is the starting point. The CC and CD models play a crucial role in characterizing frequency-dependent polarization dynamics behaviors of insulation materials until now. The HN model is a unification model that integrates Debye, CC, and CD models.

The mathematical relationships and physical meanings of exponents (shape parameters, α or β) within these Debye-derived models are further summarized in Fig. 11. When the exponents α and β of the unification HN model are equal to 1, the unification

HN model returns to Debye model, which corresponds to an ideal semicircle shape [59]. When α is equal to 1, the unification HN model becomes the CD model, which is a compressed asymmetric semicircle shape. When β is equal to 1, the unification HN model becomes the CC model, which forms a compressed semicircle shape. More specific analytical expressions of these Debye-derived semi-empirical models will be discussed in the following subsections.

A. Basic Debye Model

The Debye relaxation model proposed by physicist Prof. Peter Debye in 1912 is the most fundamental equation to characterize the ideal relaxation response behavior of dielectric materials as shown in the following [56]:

$$\varepsilon_r^*(\omega) = \varepsilon_\infty + \frac{\Delta\varepsilon}{1 + j\omega\tau} = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + j\omega\tau} \quad (1)$$

where τ is the relaxation time constant (s), ε_∞ is the optical-frequency permittivity, ε_s is the static-state permittivity, and ω is the angular frequency (rad/s).

Remarkably, one important assumption of Debye model is that the polarization dynamics behavior of insulation materials under the applied alternating electric field is ideal, which is closely correlated with the independent dipole movement. The intrinsic polarization behavior follows the exponential decay law. The Nyquist plot exhibits a perfect semi-circle shape as shown in Fig. 11. However, most insulation materials like nanocomposites with complex structures are nonideal, particularly under harsh operating conditions. As a result, the ideal Debye model has its intrinsic limitations for characterizing the frequency-dependent dielectric dynamics.

Therefore, a series of derived semi-empirical equations were proposed to characterize nonideal polarization dynamics inside insulation materials. The frequency dependence behaviors of complex permittivity based on different semi-empirical equations are illustrated in Fig. 12 [64]. The exponents in semi-empirical equations determine the curve shapes of complex permittivity for insulation materials.

B. Cole–Cole Model

Kenneth S. Cole and Robert H. Cole proposed the derived Debye model, named the Cole–Cole (CC) semi-empirical equation/model. In comparison to the typical Debye model, the CC model introduces a shape parameter α , as shown in (2) [57]. The function of the shape parameter α (belonging to 0–1) is to characterize the semi-circle with the change of magnitude. The frequency dependence of complex permittivity based on the CC model is in Fig. 12

$$\varepsilon_r^*(\omega) = \varepsilon_\infty + \frac{\Delta\varepsilon}{1 + (j\omega\tau)^\alpha} \quad (2)$$

C. Cole–Davidson Model

The CD semi-empirical equation as an asymmetric generalization form derived from the basic Debye model was developed in (3). A shape parameter β (belonging to 0–1)

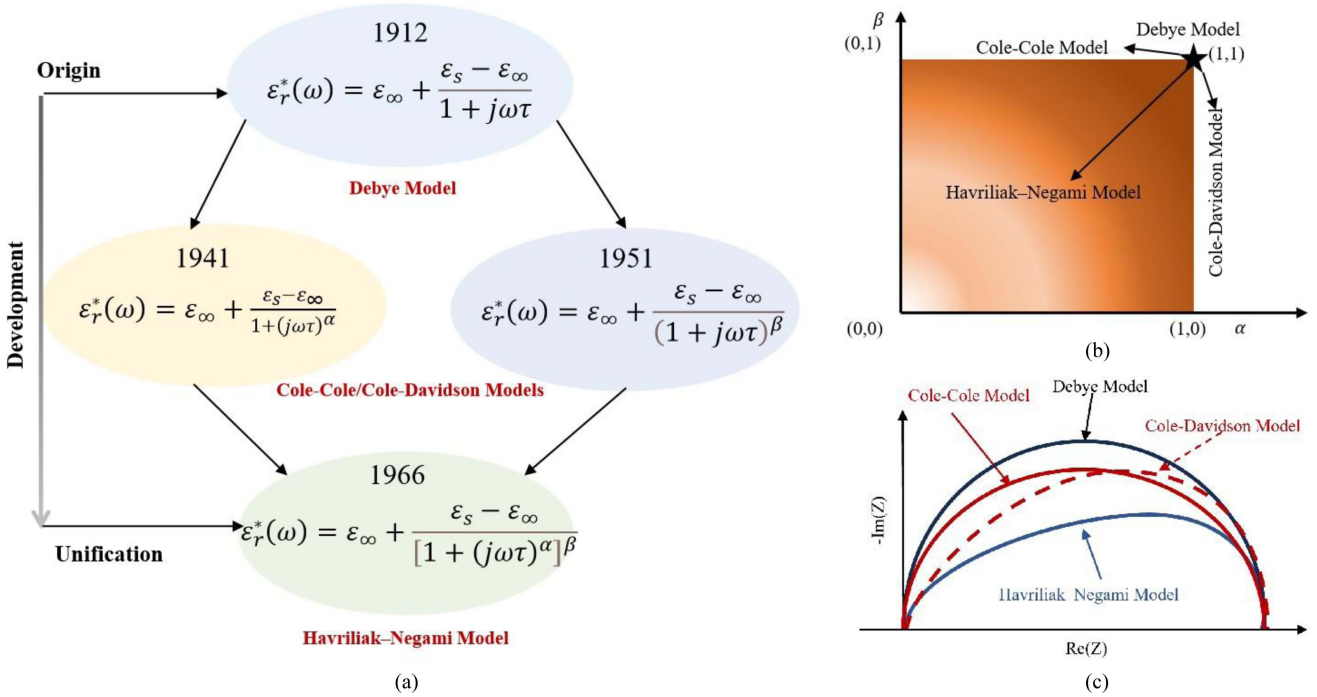


Fig. 11. (a) Evolution history of Debye and its derived models. (b) Range of exponent parameters of different Debye models. (c) Semi-circle graphical representation of four Debye models.

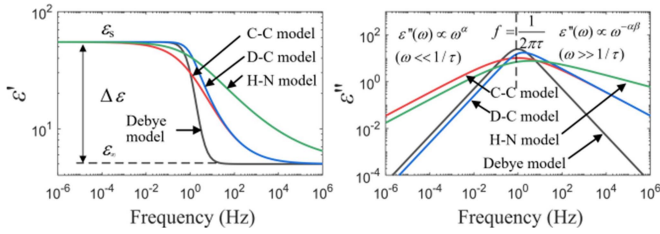


Fig. 12. Frequency-dependent complex permittivity is characterized by four semi-empirical equations within broadband frequency ranges. (a) Real permittivity. (b) Imaginary permittivity [64].

is added to describe the nonlinear and nonideal polarization dynamics mechanisms of insulation materials subjected to variable-frequency ac voltage waveforms. It can be shown in Fig. 12 that the CD model presents a deviation of real permittivity from the ideal Debye model and a noticeable variation in the high-frequency imaginary permittivity [58]

$$\epsilon_r^*(\omega) = \epsilon_\infty + \frac{\Delta\epsilon}{(1 + j\omega\tau)^\beta}. \quad (3)$$

D. Havriliak–Negami Model

Based on CC and CD models, the Havriliak–Negami (HN) semi-empirical equation/model as a unification was proposed to comprehensively characterize both asymmetry and broadness of frequency-dependent complex permittivity of insulation materials in (4) [59]. Both two shape parameters α and β belonging to between 0 and 1 are employed. The influence of the α and β on

the frequency dependency of complex permittivity is illustrated in Fig. 12

$$\epsilon_r^*(\omega) = \epsilon_\infty + \frac{\Delta\epsilon}{[1 + (j\omega\tau)^\alpha]^\beta}. \quad (4)$$

In contrast with CC and CD models, the integrated HN model, as a final solution for complex permittivity reconstruction, provides a comprehensive semi-empirical equation to replicate intricate polarization dynamics processes of insulation materials. Nevertheless, the integrated HN semi-empirical equation has some drawbacks about the solution of model parameters. In particular, the shape parameters calculations of α and β are difficult to obtain and remains some debates currently. Different combinations of α and β values may lead to the same reconstructed complex permittivity curves, which needs researchers to have rich experiences and theoretical expertise in understanding underlying polarization mechanisms of insulation materials.

E. Extended Semi-Empirical Equations With Multiple Polarization Processes

The Debye and its derived models have certain limitations, only characterizing a single polarization process inside insulation materials. It is noteworthy that polarization dynamics phenomena inside (polymeric) insulation materials are extremely complex under a range of internal (e.g., material components) and external conditions (e.g., frequency ranges, temperature). Two detailed aspects are as follows: 1) Internal conditions: Insulation material or system itself usually as a composite material has complex chemical structures and physical properties. 2)

External conditions: The measurement conditions (e.g., voltage frequency range, voltage magnitude) and ambient factors (e.g., temperature, humidity) influence the underlying polarization dynamics processes. Therefore, the traditional semi-empirical equations present certain difficulties in capturing the underlying multiple superimposed polarization dynamics processes inside insulation materials.

To address the above gaps, the extended Debye models involving diverse physics processes are developed from basic Debye and its derived models, aiming to accurately capture polarization dynamics processes and then characterize the frequency dependence of insulation materials subjected to switching voltage waveforms with fast rising time. The complex dielectric physics behaviors involve conductance mechanisms with different origins and polarization processes with different time constants. Extended semi-empirical equations are proposed as shown in (5) to (8). The essence of extended equations is to add various polarization terms and conductivity terms such as quasi-DC conductivity term (σ_{DC}) and hopping conductivity term (σ_h). The hopping conductivity term follows the power law behavior. For example, (5) consists of n Debye relaxation processes, quasi-DC conductance behavior, and hopping conductance process. Compared to (5), (6) to (8) represents n CC, CD, and HN relaxation processes, respectively. Notably, the use (n value, σ_{DC} or σ_h term) of extended semi-empirical equations strictly depends on real physical processes observed from the measured BDS of insulation materials in high-voltage power electronics

$$\varepsilon_r^*(\omega) = \varepsilon_\infty + \sum_{i=1}^n \frac{\Delta\varepsilon_i}{1 + j\omega\tau_i} + \frac{\sigma_{DC}}{j\omega\varepsilon_0} + \frac{\sigma_h}{(j\omega)^\gamma\varepsilon_0} \quad (5)$$

$$\varepsilon_r^*(\omega) = \varepsilon_\infty + \sum_{i=1}^n \frac{\Delta\varepsilon_i}{1 + (j\omega\tau_i)^{\alpha_i}} + \frac{\sigma_{DC}}{j\omega\varepsilon_0} + \frac{\sigma_h}{(j\omega)^\gamma\varepsilon_0} \quad (6)$$

$$\varepsilon_r^*(\omega) = \varepsilon_\infty + \sum_{i=1}^n \frac{\Delta\varepsilon_i}{(1 + j\omega\tau_i)^{\beta_i}} + \frac{\sigma_{DC}}{j\omega\varepsilon_0} + \frac{\sigma_h}{(j\omega)^\gamma\varepsilon_0} \quad (7)$$

$$\varepsilon_r^*(\omega) = \varepsilon_\infty + \sum_{i=1}^n \frac{\Delta\varepsilon_i}{[1 + (j\omega\tau_i)^{\alpha_i}]^{\beta_i}} + \frac{\sigma_{DC}}{j\omega\varepsilon_0} + \frac{\sigma_h}{(j\omega)^\gamma\varepsilon_0} \quad (8)$$

where n presents the types of polarization dynamics processes; $n = 1$, the equation represents the classical Debye model with one relaxation process; For example, if two types of polarization processes occur in BDS, the value of the parameter n should be 2; γ is a constant belonging to $[0, 1]$.

IV. GREY-BOX EQUIVALENT CIRCUIT MODELS

The equivalent circuit modeling approaches have been developed for characterizing the frequency dependency of dielectric dynamics behaviors inside insulation materials, which are complementary to semi-empirical equations. The prominent advantages of ECMs involve the translation of underlying polarization dynamics mechanisms into impedance forms, which is easy to understand, friendly for engineers from various fields, system-level simulation, and so on. The ECM approaches mainly consist of RC-based impedance circuits, fractional-order impedance circuits, and DH relaxation circuits as summarized

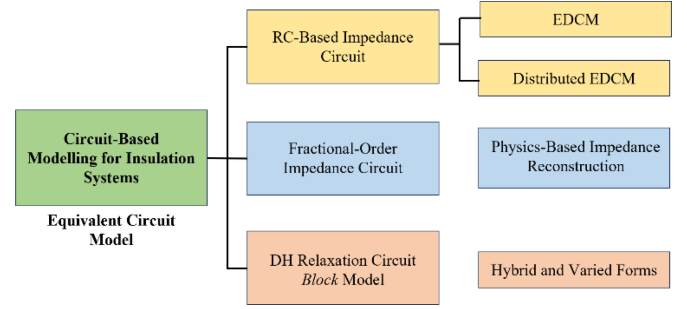


Fig. 13. Summarization of different ECMs, including RC-based ECM, fractional-order ECMs, and DH circuit model.

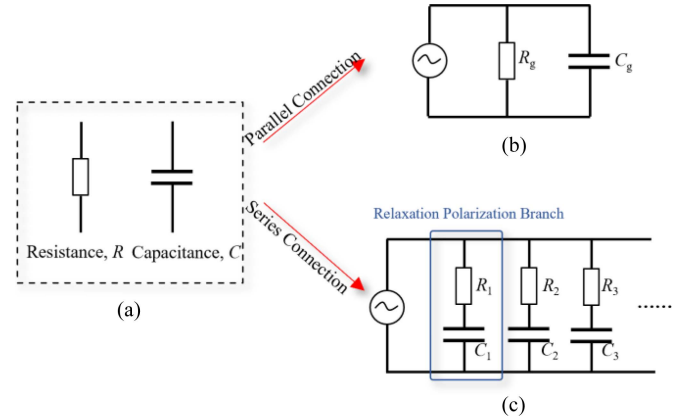


Fig. 14. Schematic diagram of the equivalent Debye circuit model involving frequency-independent geometry module and frequency-dependent polarization module [65]. (a) Basic circuit elements of resistance and capacitance. (b) Geometry circuit module. (c) Frequency-dependent polarization circuit module.

in Fig. 13. First, the RC-based ECM, also named equivalent Debye circuit model, is constructed by different combination forms of linear circuit elements, resistance (R) and capacitance (C). Subsequently, the fractional-order ECM is composed of nonlinear circuit elements derived from fractional-order calculus theory. Strictly, the time constant calculated by capacitance and resistance does not follow the exponential decay, instead, is determined by power-law behaviors. Additionally, another ECM is the DH circuit model. In essence, the DH circuit model is a structured block diagram, where each block is from DH theory [63].

A. Equivalent Debye Circuit Model

The equivalent Debye circuit model (EDCM) as an integer-order form was developed by constructing the combination forms of linear circuit elements, like resistance (R) and capacitance (C) in Fig. 14 [65]. The physical mechanism of the RC branch exhibits the interpretation of the ideal Debye polarization process that follows the exponential decay behavior. Specifically, one independent RC branch marks an ideal relaxation polarization process with one time constant.

The integer-order EDCM is the superimposition of the geometry circuit module and the polarization circuit module with n ideal Debye physical processes. The derivation process of the analytical impedance expression based on EDCM has been

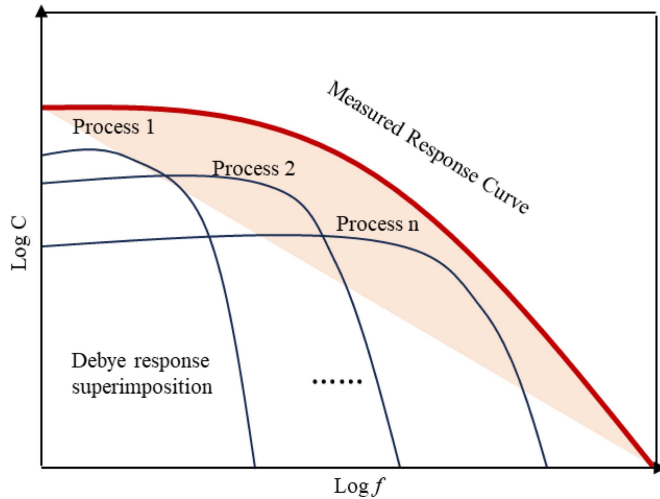


Fig. 15. Schematic diagram of the measured impedance curves superimposed by several ideal Debye response processes [69].

extensively reported by literature, such as [44], [45], [46], [47]. In the geometry circuit module, C_∞ and G ($1/G = R_g$) represent insulation bulk properties, the insulation capacitance and the insulation conductance. For another frequency-dependent circuit module, n RC branches with n ideal relaxation time constants $[\tau_1, \tau_2, \dots, \tau_n]$ are independently distributed into the polarization circuit module [65], [66], [67], [68]. Current research works shows that the EDCM is generally adopted by adding 6 RC relaxation branches within 6 decades of frequency [68]. To some extent, the number of RC relaxation branches is always determined based on experience and fitting accuracy.

In addition, the configuration of EDCM is dependent on the measured dielectric/impedance spectroscopy of insulation systems. The dielectric spectroscopy of insulation materials involves rich dielectric physics mechanisms, associating with the measurement voltage magnitude, voltage frequency, internal insulation physiochemical properties, and external factors like temperature, air pressure, and humidity. Therefore, the superimposed several RC branches that correspond to different time constants are applied to represent the measured impedance spectroscopy of insulation systems in Fig. 15 [69]. The EDCM formulation allows for a simplified understanding of dielectric dynamics by linking linear RC networks to polarization dynamics mechanisms of insulation materials. This makes it become a mathematical approximation approach to analyze the insulation dielectric properties under the multifrequency electric stresses. It must be noted that this approach provides only the approximation discretization analysis of the measured impedance spectroscopy curves of nonideal insulation materials, as the classical Debye model is inherently based on idealized assumptions [70], [71]. The EDCM in essence lacks the physical understanding of complex dielectric dynamics behaviors inside insulation materials.

B. Distributed Equivalent Debye Circuit Model

The electrical insulation systems used in different high-voltage power devices/assets will withstand the influence of

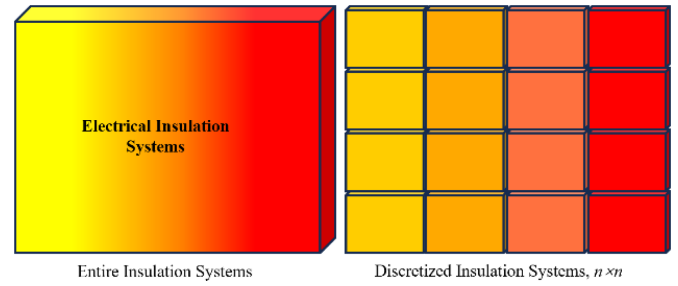


Fig. 16. Schematic diagram of the insulation system with spatial distribution states and its discretized insulation cells.

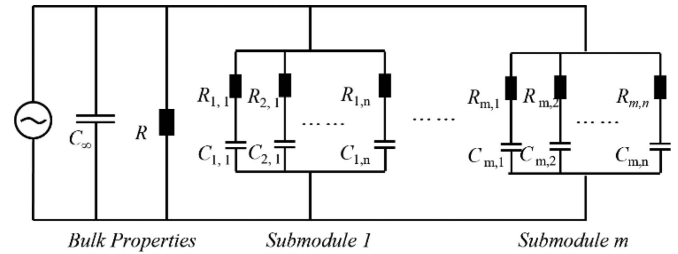


Fig. 17. One distributed circuit topology of D-EDCM [74].

gradient stresses, resulting in the nonuniform distribution of insulation health states. The space discretization strategy preliminarily aims to mesh insulation systems with spatial distribution states as illustrated in Fig. 16. The insulation systems with non-linear dielectric properties can be approximately discretized into a lot of small units with linear properties after discretization. For each small unit, the impedance properties of insulation systems can be characterized by linear RC circuit modules [70], [71]. The distributed EDCM (D-EDCM) is therefore established for characterizing the frequency-dependent impedance behaviors for nonuniform aged insulation systems.

The discretization circuit model (D-EDCM) was initially proposed to address the challenges of nonuniform aging in oil-paper insulation systems of high-voltage power transformers, where the insulation properties subject to stress gradients vary from layer 1 to layer m [72], [73], [74]. Fig. 17 exhibits the distributed circuit topology of D-EDCM discovered from the existing literature [74]. The D-EDCM incorporates multiple relaxation subsections, each representing the polarization part (comprising RC relaxation branches in parallel) as in the traditional EDCM. The geometry capacitance and resistance are preserved throughout the model to reflect the physical structure of the insulation system.

The D-EDCM is formed by an extremely complex RC network, where solving circuit parameters relies heavily on mathematical optimization techniques and the availability of detailed information on the intrinsic insulation states. The basic principle of the D-EDCM lies in the superposition of individual relaxation subsections, aiming to approximate the measured impedance spectroscopy of insulation systems. While the D-EDCM has been successfully validated, its practicality and feasibility for broader applications including and beyond oil-paper insulation systems require further investigation.

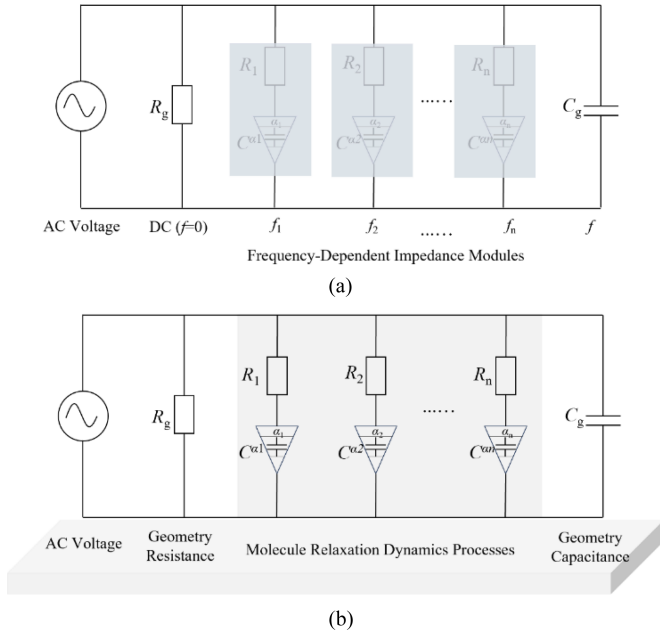


Fig. 18. One unification fractional-order equivalent circuit model with the basic function of generality and modularity. The FO-ECM can effectively capture nonideal underlying polarization dynamics mechanisms [54]. (a) Modular FO-ECM topology. (b) Specific FO-ECM with clear physics explanation.

Notably, the D-EDCM structure with a large amount of RC elements is complex, and its application (forward and inverse) faces huge challenges. If the D-EDCM is applied to solve forward issues such as insulation design with known material information, the specific D-EDCM structure necessitates additional modifications to be suitable for different application scenarios. However, for the inverse issues like the feature engineering and reliability analysis, the identification of unknown parameters inside D-EDCM will become very difficult. The D-EDCM may be difficult to play in its original imagination and target for engineering practicability.

C. Fractional-Order Equivalent Circuit Model

The fractional-order equivalent circuit model (FO-ECM), through incorporating a fractional-order capacitive element (Q , or C^α) can characterize the underlying physics meaning of insulation materials, which is a nonlinear impedance characterization approach. More details about the fractional-order calculus theory can be referred to papers [75], [76], [77].

Basic theory demonstrates that the FO-ECM can effectively capture frequency-dependent polarization behaviors inside insulation systems, as the RQ circuit module following power-law behaviors can represent nonideal physics mechanisms [77]. [54] proposed a unification FO-ECM for the frequency-dependent impedance properties characterization for polymeric insulation systems used in high-voltage power electronics applications as presented in Fig. 18. The proposed FO-ECM is modular, generic, and adjustable based on real impedance dynamics of the measured insulation systems. The FO-ECM is composed of two sections: frequency-independent geometry modules and

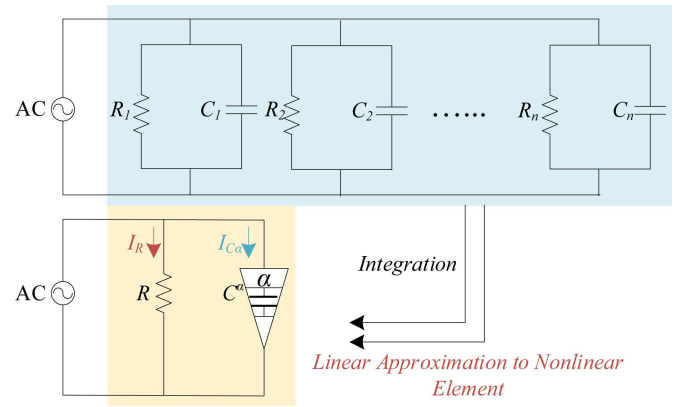


Fig. 19. Equivalence of one fractional-order RQ circuit module with several RC circuit modules in parallel [78].

frequency-dependent impedance modules. In comparison to the conventional EDCM, the novel FO-ECM with fewer circuit parameters, in essence, derived from fractional-order calculus theory, can accurately capture the underlying nonlinear impedance dynamics characteristics occurring in electrical insulation exposed to multifrequency voltages and harsh environmental factors.

Additionally, one RQ circuit module can be approximately equivalent to the superposition of multiple RC modules, as illustrated in Fig. 19 [78]. The FO-ECM can characterize the space distribution properties of the impedance dynamics behaviors of insulation systems. After this discretization, the overall nonlinear impedance can be translated into a summary of discretized spatial impedance as discussed in Section IV-B. Each discretized unit of insulation materials can be characterized by a linear RC model. [78], [79] first explored the feasibility of the equivalent circuit model incorporating a fractional-order RQ module to reconstruct the impedance distribution properties of insulation systems subjected to stress gradients.

D. DH Equivalent Circuit Block Model

Different from EDCM, D-EDCM, and FO-ECM, the DH model rooted in intrinsic dielectric physics mechanisms (conductance and polarization dynamics) is designed to analyze more complex dielectric responses that involve multiple relaxation processes and quasi-DC conductance behavior. Generally, there are five types of basic dielectric response processes that can occur in insulation materials, such as conductance process, infinite frequency capacitance, QDC relaxation, loss peak relaxation, and diffusion process [80]. Most importantly, the DH circuit model is highly dependent on the intrinsic physical mechanisms appearing inside insulation systems [80], [81], [82]. This work offers a brief introduction to the basic configuration of DH circuit model as shown in Fig. 20.

It is shown in Fig. 20 that the basic DH model as an example include five basic processes. Note that this basic DH-ECM can be evolved to a series of improved DH impedance circuit models. Although for the same insulation systems, the intrinsic dielectric dynamic characteristics vary under different environmental

TABLE I
COMPARISON ANALYSIS OF SEMI-EMPIRICAL EQUATIONS AND EQUIVALENT CIRCUIT MODELS FOR POLARIZATION DYNAMICS BEHAVIORS

Types	Models	Advantages	Shortcomings
Semi-empirical Equations	Debye Model	1. Simple Equation 2. Suitable for Ideal/Linear Insulation Materials	1. Cannot describe complex polarization dynamics of nonideal insulation materials 2. Ignores the distribution and asymmetry of relaxation processes
	Cole-Cole Model	1. Introduces α parameter to describe a broad relaxation distribution 2. Good fitting for many insulation dielectrics	1. α parameter has weak physical interpretation 2. Does not account for asymmetric relaxation behaviors
	Cole-Davison Model	1. Effectively describe the asymmetry of relaxation time distributions by introducing β parameter 2. Suitable for dielectrics with asymmetric relaxation processes	1. Limited capability for describing broad relaxation distributions 2. Higher mathematical complexity
	Havriliak–Negami Model	1. Add two parameters α and β to describe both broad and asymmetric relaxation distributions 2. Highly effective for complex insulation materials with complex structures	1. Complex equations with high difficulties to solve parameters 2. Strongly dependent on high-quality experimental data
	Dissado-Hill Model	1. Clear Physical Meaning, directly linking to microscopic structures and physical processes 2. Suitable for complex insulation materials with intricate molecule structures	1. High complexity with many parameters 2. High challenged optimization and fitting to solve model parameters 3. Strong dependency on high-precision experimental data
Equivalent Circuit Models	Equivalent Debye Circuit Model	1. Easy implementation for ideal insulation materials 2. Suitable for fast system-level computation with approximate accuracy	1. Cannot describe nonlinear dielectric dynamics behaviors 2. Neglect the distributed impedance effects of insulation systems in real power assets
	Distributed Equivalent Debye Circuit Model	1. Capable of fitting frequency response of complex insulation materials 2. Suitable for system-level simulation of insulation systems exhibiting multiple relaxation processes 3. Suitable for insulation system design stage	1. Higher mathematical and computational complexity 2. Require high-quality data for parameter optimization
	Fractional-order Equivalent Circuit Model	1. Broad applicability to describe complex polarization dynamics and broadband impedance properties following power-law behaviors 2. Suitable for modelling complex insulation systems over a wide frequency range 3. Appropriate for high-precision scenarios	1. High computational complexity but excellent for wide-frequency-range response modelling 2. Hard to directly link to microscopic material structures

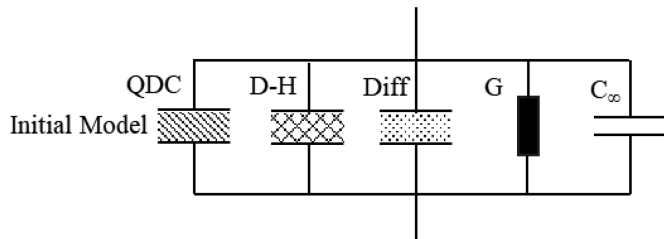


Fig. 20. DH equivalent circuit forms applied for the fitting of measured FDS curves with varied physics mechanisms [80], [81], [82].

conditions like temperature, which need to construct different DH impedance model topologies.

Notably, the DH circuit model is more applicable to characterize complex permittivity or complex susceptibility of insulation materials, instead of impedance properties of insulation systems, if without any prior knowledge of the specific geometry information of measured insulation systems. Additionally, the rich professional knowledge from researchers is a prerequisite for the construction of the DH circuit model. It is noteworthy that the DH model is not a circuit impedance model in the true sense. Instead, more specifically, it is a circuit block representation form.

E. Comparisons of Semi-Empirical Equations and ECMs

Semi-empirical equations and ECMs have continuously developed for nearly one century in the traditional high-voltage engineering. Two classical frequency-domain modelling approaches for electrical insulation materials/systems have distinct advantages and shortcomings, particularly tackling the challenges from the high-voltage power electronics applications. The comparisons between semi-empirical equations and ECMs have been summarized in Table I.

The semi-empirical equations are more suitable for insulation materials with known geometry information, which can be used to describe the underlying frequency-dependent polarization dynamics behaviors under different conditions. Among these semi-empirical equations, the fundamental Debye model is the simplest, which is only applicable for the ideal insulation materials. Notably, the current insulation materials are generally composites with complex intrinsic structures and multiple components. The intrinsic frequency-related dielectric dynamics for such insulation materials are extremely complex across a wide frequency range. Thus, the derived CC, CD, HN, and DH models are more suitable for describing the frequency-dependent polarization dynamics phenomena inside insulation materials with intricate molecule structures. Nevertheless, these models exist some shortcomings. One of the main challenges is to solve the unknown parameters in these models by fitting

the measured dielectric spectroscopy curves. In this regard, when the power electronics voltage waveforms have fast rising time, the high-frequency polarization properties of insulation materials are prominent. Thus, the extensions of these classical semi-empirical equations including multiple polarization terms in (5)–(8) should be considered. However, the selection of optimization algorithms and the set of the initialization conditions are crucial to solve many unknown parameters, like at least ten parameters. Additionally, the high-quality and high-precision measurement dielectric spectroscopy data is needed.

On the other hand, the equivalent circuit models are more suitable for the characterization of the frequency-dependent impedance dynamics characteristics of insulation systems in high-voltage power electronics applications. One of main advantages of ECMs is no need to obtain the geometry information of the measured insulation systems. The applicability is for high-voltage power electronics devices and assets. The EDCM and FO-ECM mainly characterize the overall polarization dynamics phenomena of electrical insulation by fitting the measured impedance spectroscopy. The EDCM as a linear model can approximate the measured impedance spectroscopy of insulation systems with no strong need to high accuracy. Different from the EDCM, the nonlinear FO-ECM has the capabilities to characterize the nonlinear polarization dynamics behaviors through accurately replicating the measured impedance spectroscopy curves. Additionally, the D-EDCM as a white-box approach is more suitable for the construction of system-level simulation model for insulation systems during the design stage. The D-EDCM can realize the effective connection between insulation systems and other components, like magnetic system, by using circuit simulator.

V. APPLICATIONS OF FREQUENCY-DOMAIN MODELS

Under the multifrequency power electronics applications driven by power semiconductor devices, this section mainly discusses how the semi-empirical equations and ECMs of frequency-dependent polarization behaviors can be applied to support the physics mechanisms understanding, system design, and reliability analysis for electrical insulation in high-voltage power electronics applications as summarized in Fig. 21.

A. Analysis of Dielectric Dynamics Mechanisms for Electrical Insulation

Current research works mainly integrate the classical semi-empirical equations and measured experimental data, aiming to identify the physical parameters of semi-empirical equations through reconstructing the measured dielectric spectroscopy. These semi-empirical equations are the function of complex permittivity or complex susceptibility of insulation materials, which are the macroscopic representation of microscopic charge carriers and dipoles. The investigation of frequency-dependent dielectric dynamics mechanisms of insulation systems mainly relies on two approaches: qualitative dielectric tools and quantitative empirical models.

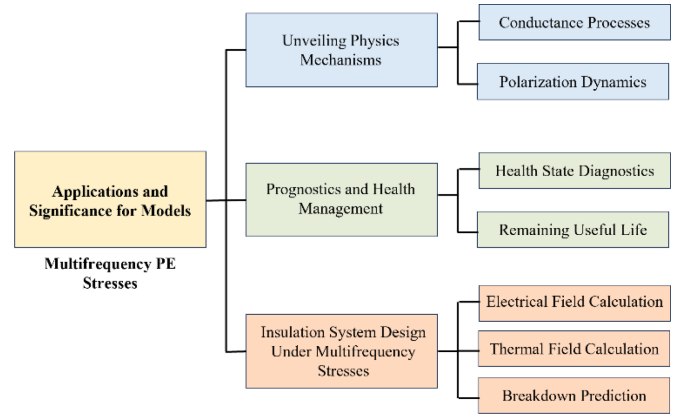


Fig. 21. Applications of frequency-dependent polarization models of insulation systems in high-voltage multifrequency power electronics applications.

1) *Qualitative Dielectric Tools*: The dielectric analysis tools include complex permittivity, conductivity $\sigma(\omega)$, dielectric loss tangent ($\tan\delta$), and electric modulus $M(\omega)$, aiming to comprehensively unravel frequency-dependent dielectric dynamics mechanisms of insulation systems exposed to multifrequency power electronics stresses. The transformation relationship of four dielectric quantities is presented in (9) and (10) [83]. Fig. 22 provides an illustration diagram for the relationship of four dielectric quantities from low temperature to high temperature. The conductivity $\sigma(\omega)$ is generally used to characterize quasi-DC conductivity and frequency-independent ac conductivity. The dielectric loss tangent ($\tan\delta$) in (10) is composed of conductance loss and polarization loss of insulation systems. It is noting that the insulation systems exhibit huge low-frequency permittivity under extreme operating scenarios, which will mask polarization dynamics behaviors. Therefore, the electric modulus was developed to eliminate the influence of huge permittivity, then to highlight the polarization dynamics, as illustrated in Fig. 22(e) [83]

$$\epsilon^*(\omega) = \frac{\sigma^*(\omega)}{j\omega\epsilon_0} = \frac{1}{M^*(\omega)} \quad (9)$$

$$\tan\delta = \frac{\epsilon''(\omega)}{\epsilon'(\omega)}. \quad (10)$$

2) *Quantitative Empirical Fitting Models*: The quantitative approaches are currently one mainstream direction to reveal dielectric dynamics mechanisms of insulation systems. The research steps are data processing, feature engineering, correlation models, and mechanism analysis, respectively. Fig. 23 provides a schematic process to interpret the quantitative empirical models by using the examples of the extended HN model with n polarization processes and two conductance forms.

Generally, the semi-empirical equations and equivalent circuit models are used to fit the measured dielectric/impedance spectroscopy of insulation systems under different health states. The physical parameters of semi-empirical equations and equivalent circuit models will be parameterized. Then, the correlation relationship between extracted parameters and insulation states is established to obtain the empirical models like linear

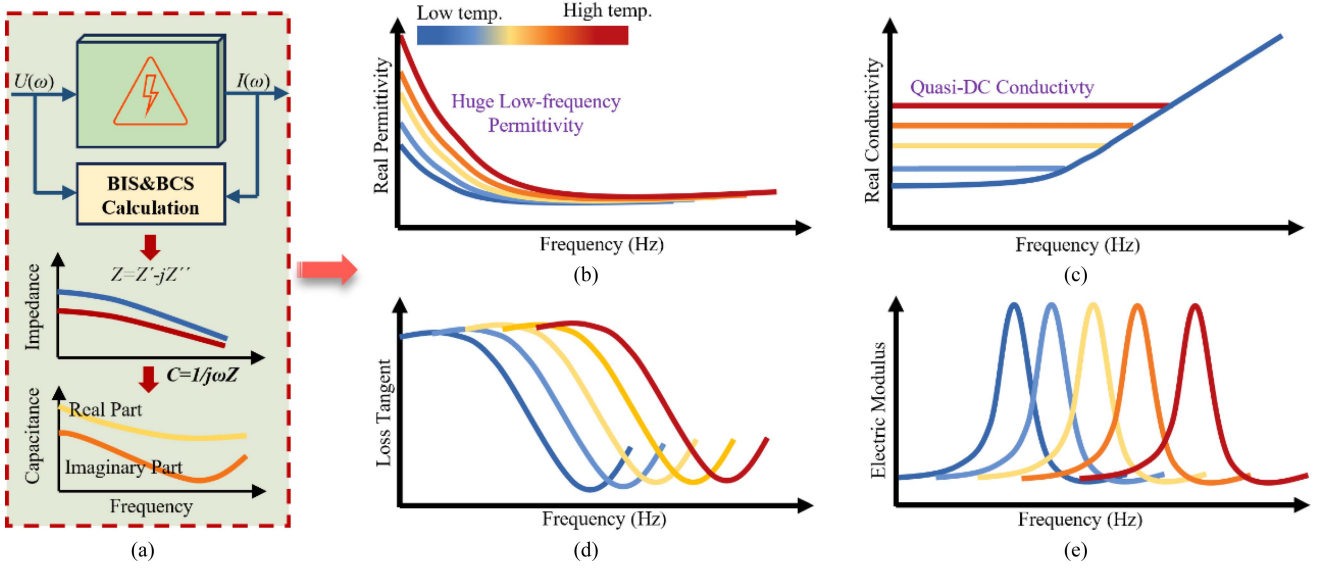


Fig. 22. Illustration diagram for the relationship of different dielectric quantities under different temperatures. Note that the frequency dependency of real dielectric curves could be very complicated. For example, in (c), the assumption is that temperatures have a noticeable effect on quasi-DC conductivity. (a) Schematic figure of broadband impedance/capacitance spectroscopy (BIS/BCS) measurement results. (b) Schematic figure of real permittivity over temperature and frequency. (c) Schematic figure of real conductivity over temperature and frequency. (d) Schematic figure of loss tangent over temperature and frequency. (e) Schematic figure of electric modulus over temperature and frequency.

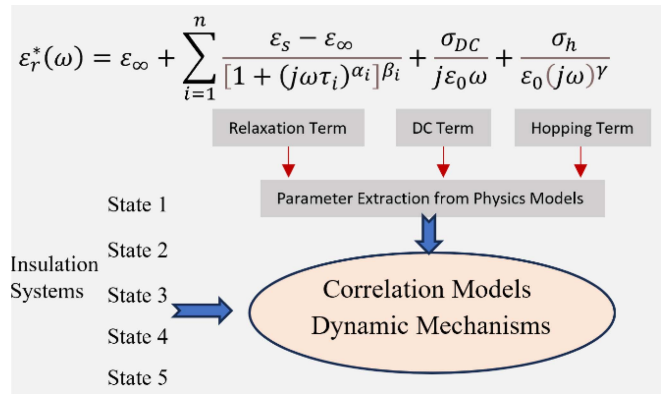


Fig. 23. Quantitative analysis process of underlying dielectric dynamics mechanisms for insulation systems by using semi-empirical equations or ECMs.

fitting functions. Ultimately, the underlying dynamics mechanisms of insulation systems can be unveiled under different insulation health conditions like thermal aging, humidity, and temperature.

Several application cases are introduced to deeply understand the dielectric dynamics mechanisms of insulation systems exposed to variable-frequency voltages. Wolny et al. [84] delved into the parameter estimations of the CC model, focusing on a single relaxation process within oil-paper insulation systems subjected to varied moisture contents and temperatures. The findings in paper [84] revealed a decline in both exponent and relaxation time constants as moisture content and temperature increased. Additionally, [49], [85] employed the improved CC model with double relaxation processes and hopping conductivity to evaluate the oil-paper insulation states under different

moisture contents. The investigation provided insights into the noticeable effects of moisture on the frequency-dependent dielectric dynamics behaviors of oil-paper insulation. [86] suggested that the CC model, particularly with two relaxation processes, offered a more comprehensive characterization of complex polarization dynamics processes for oil-paper insulation under different moisture and temperature conditions.

In [87], the impact of humidity on the dielectric dynamic mechanisms of rotating machines with epoxy/mica insulation is investigated based on the improved CC model with the dc-conductance process and double polarization processes. The results display the decrease in the interfacial relaxation time constant extracted from the improved CC model as a function of humidity. Furthermore, [88] applied the improved CC model with two relaxation processes to electrothermal aging influence on underlying dielectric dynamics behaviors of epoxy resin insulation materials. The correlation between relaxation time constant and aging degrees presents an exponential fitting function. The improved CC models with double relaxation processes, dc-conductance, and hopping conductance behaviors have been applied to unravel the aging mechanisms of oil-paper insulation [89]. As a result, the predominant trend in existing research mainly involves the improved semi-empirical equations to unveil dielectric dynamics mechanisms inside insulation systems affected by complex external stresses.

A significant challenge in current research lies in the prevalent application of the semi-empirical equations with fixed terms to investigate the dielectric dynamics mechanisms of insulation systems under various factors like humidity, aging, and temperature effects. However, the intrinsic conductance and relaxation processes vary with insulation states in the presence of different aging conditions and environmental factors. While the

same semi-empirical equations are utilized to elucidate physical mechanisms, it may contradict the essence of these models. It is concluded that it becomes imperative to identify the intrinsic dielectric dynamics processes like how types of polarization behaviors before using these semi-empirical equations. This identification process serves as the most fundamental basis for selecting appropriate semi-empirical equations that align with the dielectric response characteristics of the measured insulation systems.

The authors [80], [81], [82] applied DH models to unveil the complex dynamics mechanisms of different types of insulation materials. In contrast to the Debye-series models, DH models, rooted in the basic dielectric mechanisms of real insulation systems exhibit the flexibility to capture the unique physical mechanisms of insulation systems by changing DH equation terms [80], [81], [82]. This adaptability is evident in the inclusion of multiple models corresponding to the polarization processes inside the insulation system. For example, if the insulation material exhibits two polarization processes, two corresponding DH models would be incorporated. More importantly, the real DH model would refrain from adding a conductivity term if quasi-DC conductance phenomena were absent within the measured frequency regions. This can be found in papers [81], [82].

Two cases of uncoated and coated P(VDF-HFP) dielectric materials are introduced to illustrate the DH models' analysis processes to clearly present the dielectric dynamics behaviors as shown in Fig. 24 [81]. The distinctive conductance behaviors and polarization processes have been separated by using different DH models. The main differences of dielectric dynamics behaviors for uncoated and coated samples are the surface (the interface between electrodes and material) and bulk (material itself) properties. In comparison to the uncoated sample, the diffusion process element PL occurring in the coated insulation material has been added to replace the surface conductance element G_s of the uncoated material. The diffusion behaviors are dominated by Van der Waals and electrostatic forces [81]. Furthermore, regarding the bulk properties, the second quasi-DC (QDC₂) process occurring in the uncoated sample has been modified to dc conductance process (G). Based on DH theory, it is further shown that different insulation materials need distinct circuit blocks that accurately decipher unique dielectric response mechanisms presented from the measured dielectric spectroscopy curves. DH models have also applied to other insulation materials spanning from XLPE material, oil-paper insulation, to other polymers [90], [91].

B. Influence Analysis of Polarization Dynamics Behaviors on Electrical Field Profiles for Electrical Insulation

In contrast with power-frequency ac voltages, the design and optimization of electrical insulation exposed to multifrequency power electronics stresses must arouse enough attentions, as the switching impulses are posing huge challenges to electrical insulation materials particularly under stringent high-power density conditions. As comprehensively discussed in above sections, the multifrequency switching impulses stresses would stimulate the

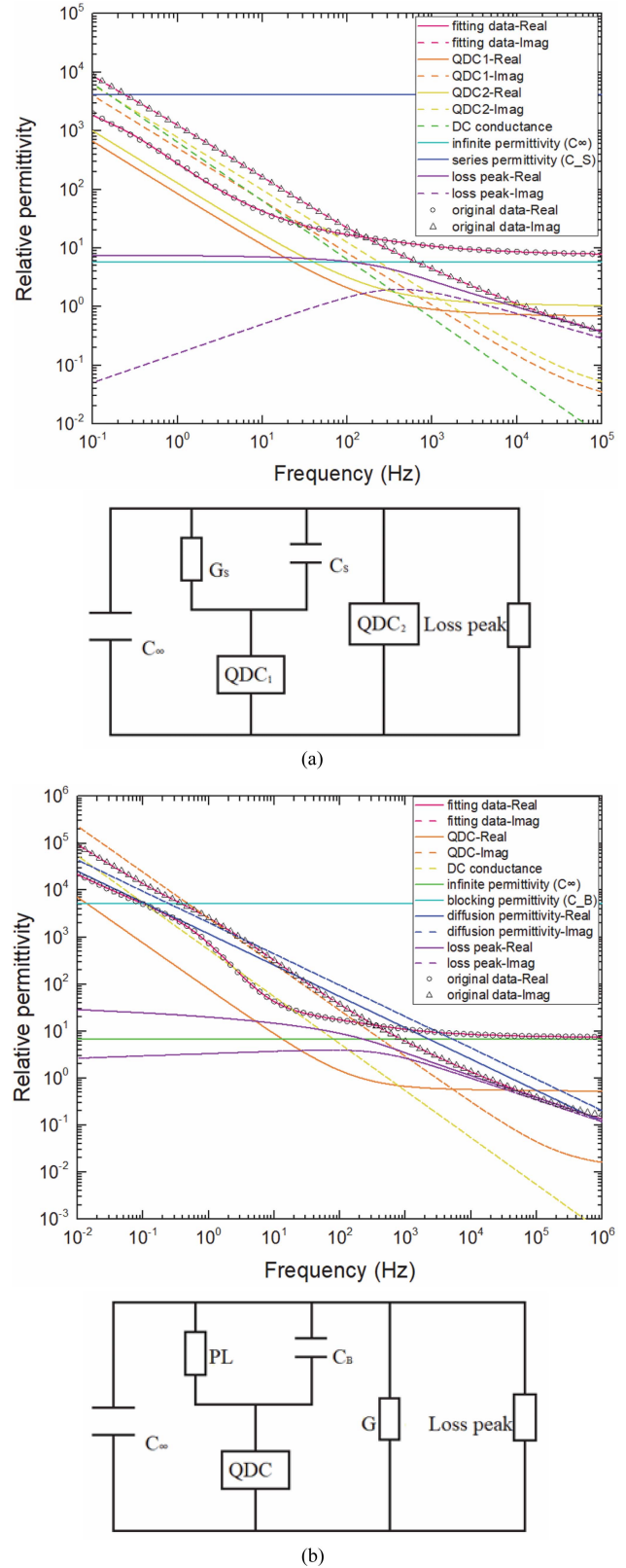


Fig. 24. Fitting processes of relative permittivity of the uncoated and coated insulation materials based on different DH models [81]. (a) Dielectric dynamics processes analysis and circuit model for uncoated P(VDF-HFP) sample with a thickness of 60 μm . (b) Dielectric dynamics processes analysis and circuit model for coated P(VDF-HFP) sample with a thickness of 60 μm .

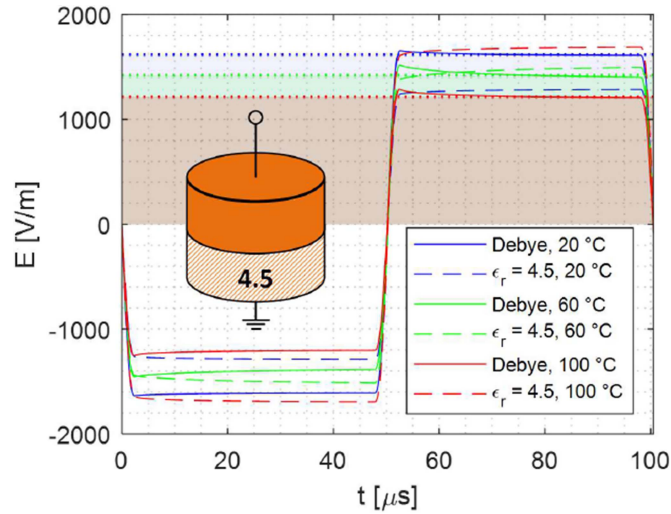


Fig. 25. Electric field distribution under switching voltage waveforms with the rising time of $5 \mu\text{s}$ for the stacked insulation systems under three different temperatures. The electric field was computed by the Debye polarization model and the traditional single real permittivity [96].

frequency-dependent polarization dynamics properties inside electrical insulation materials. This will cause two main consequences: change electric field distributions and generate more power loss inside insulation systems. Existing research shows that the partial discharge inception, insulation degradation, life reduction, and premature breakdown for electrical insulation systems become more prominent under complex electrothermal coupling stress [92], [93], [94]. The electric stress distributions dominated by polarization dynamics behaviors inside electrical insulation systems play a crucial role in guiding the rational and reliable design of insulation systems in high-voltage power electronics applications. Therefore, it is of great significance for the reliable insulation design in high-voltage power electronics applications to take frequency-dependent polarization dynamics processes into account.

Case 1: In papers [95], [96], and [97], the electric field distributions of polymeric insulation systems under switching voltage waveforms with different rising times of 5 and $0.2 \mu\text{s}$ are investigated by integrating the influence of polarization dynamics mechanisms behaviors. The electric field distribution results under switching transient voltages with different rising times of 5 and $0.2 \mu\text{s}$ as shown in Fig. 25 [96]. The temperature effects on polarization dynamics behaviors of insulation materials are considered as well. Furthermore, to provide key polarization parameters for electric field calculation, the polarization dynamics mechanisms are modelled by using the ideal semi-empirical Debye equation.

It is shown from Fig. 25 that the electric field distributions calculated by considering polarization dynamics mechanisms are obviously different from those calculated by using a single real permittivity. The zoom figure under a transient voltage of $0.2 \mu\text{s}$ rising time is shown in Fig. 26, where the electric field overshoot phenomena during the voltage transient can be highlighted owing to include the contributions of

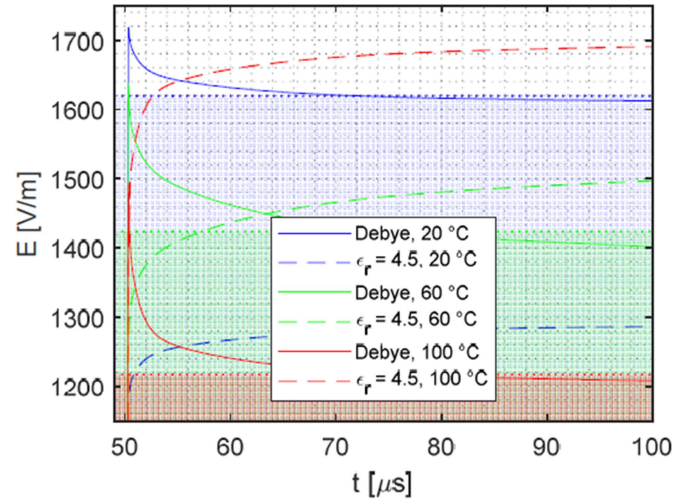


Fig. 26. Electric field distribution under switching voltage waveforms with the rising time of $0.2 \mu\text{s}$ for the stacked insulation systems under three different temperatures. The electric field was computed by the Debye polarization model and the traditional single real permittivity. This is a view of the half cycle [96].

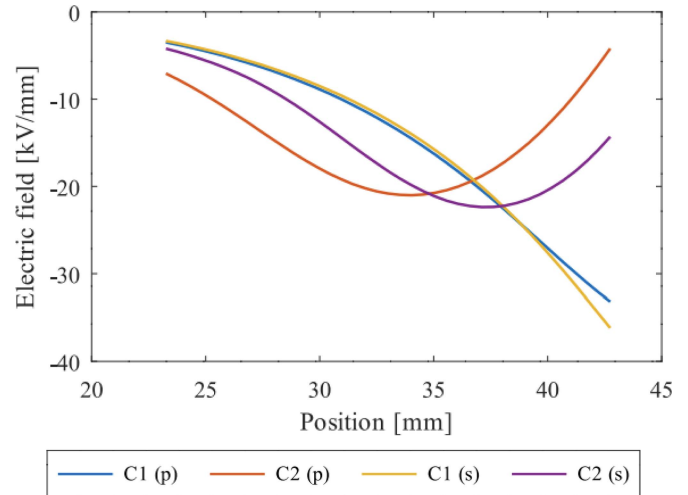


Fig. 27. Electric field profiles of insulation systems of two cables (C1 and C2) at 2 h after the polarity inversion. The electric field was computed using the polarization (p) model and the standard model (s) [98].

polarization dynamics mechanisms. The electric field magnitudes at the platform stage exhibit noticeable differences [95], [96], [97].

Case 2: In [98], to enhance the conventional electric field calculation accuracy for two HVDC cables (C1 and C2) exposed to different transient voltages (like polarity inversion), the improved calculation approach by integrating the intrinsic polarization dynamics effects was proposed to calculate the electric field distributions inside HVDC insulation systems. The EDCM approach in [98] was used to model the polarization dynamics mechanisms of insulation systems, aiming to provide the key polarization parameters for electric field calculation. The electrical field calculation results are displayed in Fig. 27.

Compared to the standard approach [C1(s) and C2(s)], the calculation results of the electric field profiles inside HVDC cables by considering polarization dynamics are different at 2

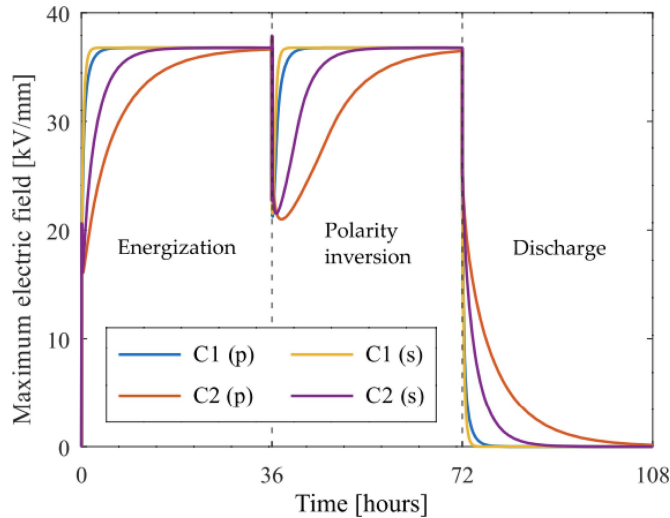


Fig. 28. Maximum electric fields in C1 cable and C2 cable during the different voltage forms, energization, polarity inversion, and discharge. The electric field was computed by the polarization (p) model and the standard model (s) [98].

h after the polarity inversion. It can be shown from Fig. 27 that the electric field strengths of insulation systems calculated by considering polarization dynamics behaviors decrease by about 7 times at positions between 40 and 45 mm, compared to the traditional standard method.

The maximum electric fields for two cables (C1 and C2) under different voltage transients are presented in Fig. 28 [98]. It can obtain valuable information that the maximum electric field calculated by considering polarization dynamics behaviors is lower than that computed by the traditional method during two key stages, energization and polarity inversion. Nevertheless, the maximum electric fields calculated by considering polarization dynamics behaviors are much higher, when occurring during the discharge stage.

In summary, hinted from the above two representative cases, the ideal semi-empirical Debye equation and equivalent Debye circuit model (EDCM) were preliminarily applied to model polarization dynamics mechanisms for the electric field profiles calculations under dc transient and switching voltage waveforms. These analysis results powerfully demonstrate that the polarization dynamics mechanisms indeed play a key role in the accurate electric field distribution of insulation systems, particularly under switching voltage waveforms with different rising times. Notably, the current research works only utilize the ideal Debye equations/models to characterize the polarization dynamics behaviors for the electric field profiles calculations of insulation systems. As discussed in previous section, the ideal Debye models can provide approximate modelling results for electrical insulation systems. Therefore, the electric field distribution calculations by integrating the accurate modelling techniques of polarization dynamics mechanisms need more research efforts to support the reliable design of insulation systems in high-voltage power electronics applications. The accurate characterization of polarization dynamics behaviors should be further considered by combining nonlinear models as listed in Table I.

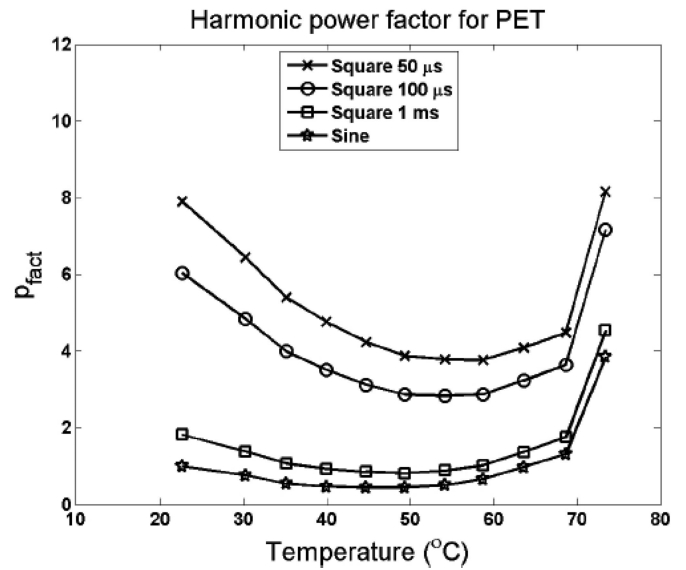


Fig. 29. Results of dielectric loss factors of insulation materials under different voltage waveforms [37].

C. Influence Analysis of Polarization Dynamics Behaviors on Power Loss Properties for Electrical Insulation

The polarization dynamics mechanisms take a prominent lead in the power loss properties inside insulation systems caused by multifrequency switching voltage waveforms. Note that the switching voltage waveforms with fast rising time would generate higher frequency components in frequency domain, which can also contribute more power loss inside insulation systems and then make dielectrics heating. [37] investigated the influences of square voltage waveforms with different rising times of $50 \mu\text{s}$, $100 \mu\text{s}$, and 1ms on power loss properties of epoxy resin insulation systems as shown in Fig. 29. Results display that the square voltage waveforms with fastest rising time of $50 \mu\text{s}$ can generate the largest power loss inside systems. In contrast, the power loss of insulation system exposed to the sinusoidal voltage waveform is minimum. The dielectrics heating (temperature increasing) caused by power loss could make the polarization dynamics behaviors more active and then change the macroscopic dielectric properties of insulation systems [41], [42]. Thus, the dielectric spectroscopy measurement of insulation systems under switching voltage waveforms is imperative, which can be beneficial for the selection of the appropriate frequency-domain modeling techniques for polarization dynamics behaviors. More details will be further analyzed in next section.

Additionally, the research team from ETH Zurich in paper [45] carried out the modeling and the computation of frequency-dependent dielectric losses of epoxy resin insulation systems in solid-state transformers under repetitive impulse voltages. The circuit topology and prototype of medium-voltage/medium-frequency (MV/MF) solid-state transformers are shown in Fig. 30. The researchers in paper [99] also applied the same approach to conduct the power loss calculations, then guide the insulation system design in power electronics transformers.

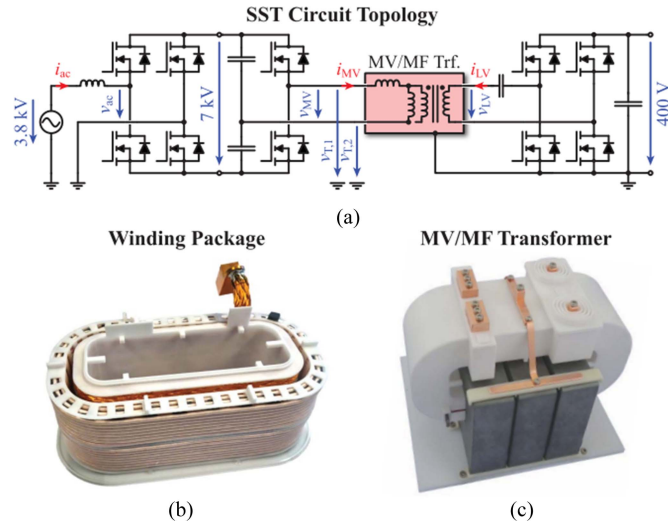


Fig. 30. Circuit topology and prototype of solid-state power electronics transformers [45]. (a) Solid-state transformer circuit topology. (b) Winding package. (c) Medium-voltage/medium-frequency transformer.

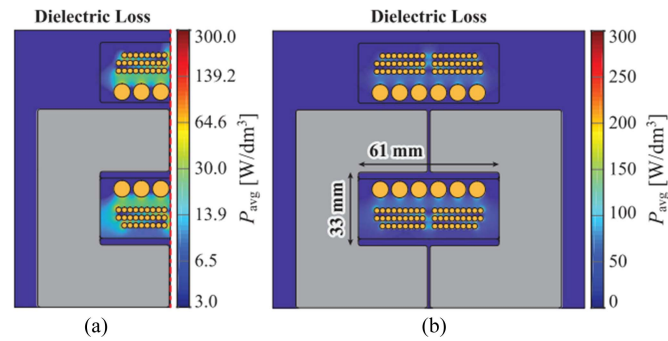


Fig. 31. Results of dielectric loss density inside insulation systems in power electronics transformers using logarithmic and linear scales [45]. (a) Dielectric loss result under the logarithmic scale. (b) Dielectric loss result under the linear scale.

Papers [45], [100] provide the simulation cases of dielectric loss density inside insulation systems as shown in Fig. 31. Results show that epoxy resin insulation systems can cause a significant increase of 17% in transformer losses at 25 kW rated conditions. The reasons are that the power loss inside insulation systems will increase due to the multifrequency switching voltage waveforms. Compared to the traditional case without considering multifrequency power loss, this will lead to an increase in the hot spot temperature of about 10 °C in solid-state transformers. [45], [100] also presented that an error of 9 W (65%) would occur, if the dielectric losses of insulation systems were simply calculated using fundamental frequency analysis.

Based on existing research results, it can be found that much less research works emphasize the importance and influence of the polarization dynamics behaviors on the stress distributions of insulation system subjected to multifrequency switching voltage waveforms. It is worth noting that the polarization dynamics mechanisms play a more important role in the accurate calculation of transient electric field profiles and power loss for insulation systems, which can provide key guidelines for the design

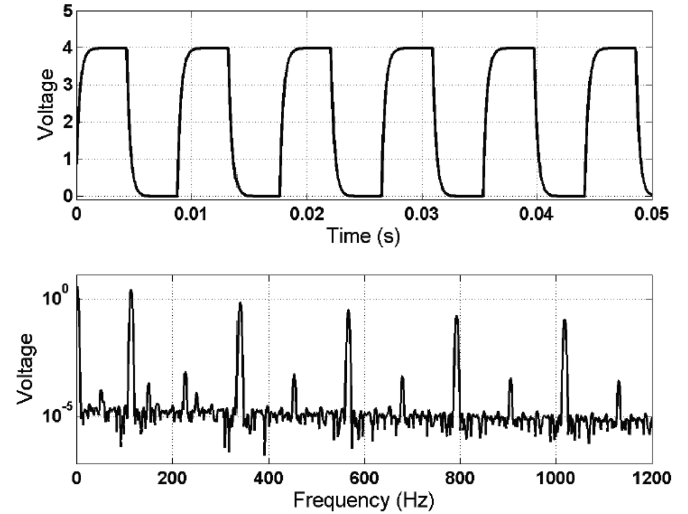


Fig. 32. Voltage waveform and corresponding frequency spectrum for dielectric spectroscopy measurement of insulation systems [37]. (a) Time-domain switching impulse voltage waveform. (b) Frequency-domain spectrum decomposed from time-domain voltage waveform.

and optimization of high-voltage power electronics applications under switching voltage waveforms with fast rising times.

D. Insulation Health Condition Assessment Methods Derived From Polarization Dynamics Behaviors

1) *Practical Considerations of Insulation Health Assessment*: The accurate acquisition of dielectric spectroscopy and impedance spectroscopy data for insulation systems is a critical prerequisite, which are the key basis to apply the frequency-domain polarization models summarized in this article. A key advantage of high-voltage power electronics applications lies in the use of transient voltage waveforms with multifrequency features. Compared to traditional high-voltage power equipment, these features enable the potential for online condition monitoring of electrical insulation systems, marking a significant step forward in insulation diagnostic technology. For instance, the switching voltage waveforms can be from power electronics system itself as shown in Fig. 32 [37]. From the perspective of frequency domain, these switching voltage waveforms have a wide range of frequency content. Therefore, after applying these transient voltage waveforms and acquiring transient response currents, the complex impedance of insulation systems can be calculated.

Recent studies have investigated dielectric spectroscopy measurement techniques for insulation systems under multifrequency transient conditions, including lightning and switching voltage waveforms [37], [101], [102], [103]. For example, Sonnerud et al. [37] utilized semi-square voltage waveforms to measure the broadband dielectric spectroscopy of insulation systems. The measured capacitance was compared with results obtained using the IDA200 Insulation Diagnostic Analyzer and the Hewlett-Packard 4192 LF Impedance Analyzer, as illustrated in Fig. 33 [37]. The comparative analysis demonstrated that semi-square voltage waveform excitation is an effective method

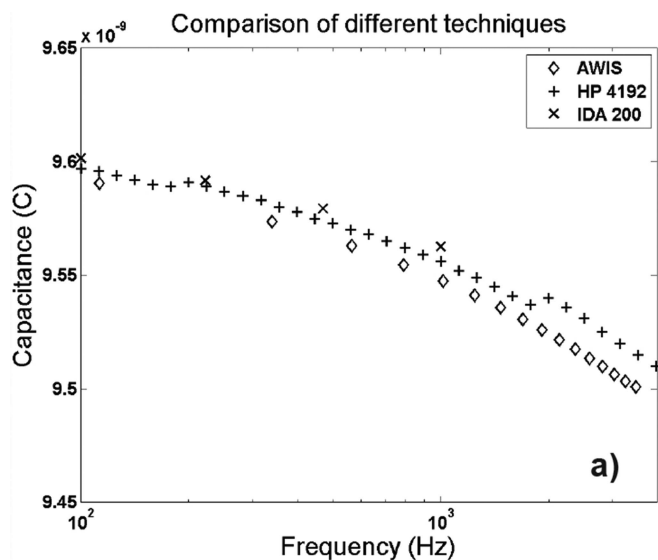


Fig. 33. Comparison results of insulation capacitance measured by different measurement setups [37].

for characterizing the frequency-dependent dielectric properties of insulation systems.

In addition, [101], [102] applied lightning impulse waveforms, typical in power systems, as voltage stimuli to measure the dielectric spectroscopy of transformer bushing insulation. The results successfully validated the feasibility of this approach. These findings provide a robust foundation for monitoring insulation condition and assessing the insulation health of high-voltage power electronics systems.

However, further research is required to extend these methodologies to high-voltage power electronics applications. Future efforts should focus on optimizing measurement techniques, expanding the applicable frequency range, and improving the accuracy of dielectric characterization for insulation systems under real-world operating conditions.

2) *Basic Procedure of Insulation Health Assessment*: Grey-box methods for health estimation and condition diagnostics have become a prevailing research direction, offering valuable physical insights into the reliability analysis of high-voltage power electronics applications. Semi-empirical equations and equivalent circuit models (ECMs), as key components of grey-box approaches, have been extensively studied to derive polarization dynamics information, supporting insulation health condition assessment.

This work provides a comprehensive introduction to the fundamental procedure for insulation health state estimation using grey-box frequency-domain modeling approaches, with a focus on semi-empirical equations and ECMs. The methodology comprises four main steps: parameterization (data fitting), feature extraction, regression analysis, and health state estimation, respectively.

Step 1. Parameterization (data fitting): The first step involves applying selected semi-empirical equations or ECMs to fit the measured frequency dielectric/impedance spectroscopy curves. The unknown parameters within these models are

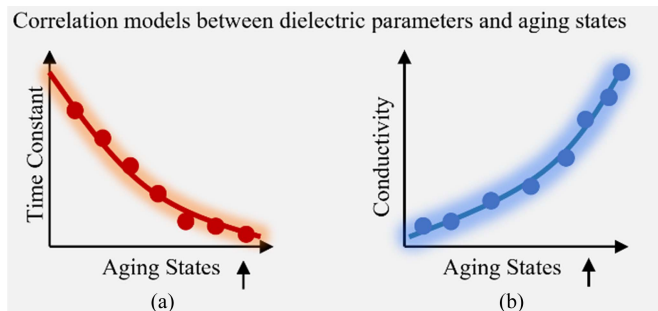


Fig. 34. Schematic diagram of the correlation models among aging states, relaxation time constants, and conductivity [49], [84], [85], [86], [87], [88]. The time constants are negatively correlated to aging states. The conductivity results are positively correlated to aging states. (a) Schematic figure of relationship between polarization time constant and aging states. (b) Schematic figure of relationship between conductivity and aging states.

determined using optimization algorithms. This process provides the foundation for extracting meaningful physical insights from the measured data.

Step 2. Feature extraction: To identify parameters most sensitive to insulation conditions, the correlation analysis techniques like Pearson's correlation coefficient should be employed. The parameters strongly correlated with insulation states are extracted as key features, serving as health indicators. This step ensures that only the most relevant information is utilized for subsequent analysis.

Step 3. Regression analysis: The relationship between key features and insulation states is established through regression analysis techniques, which may involve linear or nonlinear approaches, including Gaussian regression. Fig. 34 illustrates examples of positive and negative regression models. Furthermore, machine learning techniques play a pivotal role in enhancing the accuracy and robustness of the health state estimation process.

Step 4. Health state estimation: Finally, health state estimation models are developed by integrating laboratory results with small-sample field data. This step bridges the gap between controlled experimental conditions and real-world applications, ensuring practical applicability and reliability of the health state estimation models.

By following this systematic approach, the grey-box frequency-domain modeling methodologies of polarization dynamics behaviors inside electrical insulation systems provide a solid foundation for the construction of the robust health estimation framework of electrical insulation systems, paving the way for improved reliability and predictive maintenance in high-voltage power electronics applications.

In addition, Fig. 35 illustrates a schematic representation of the health condition diagnostics and lifetime prediction process for insulation systems. The health indicators, which effectively characterize insulation material performance, are derived from the underlying polarization dynamics of electrical insulation systems. Moreover, the evolution of these health indicators as a function of operating time can be modeled for high-voltage

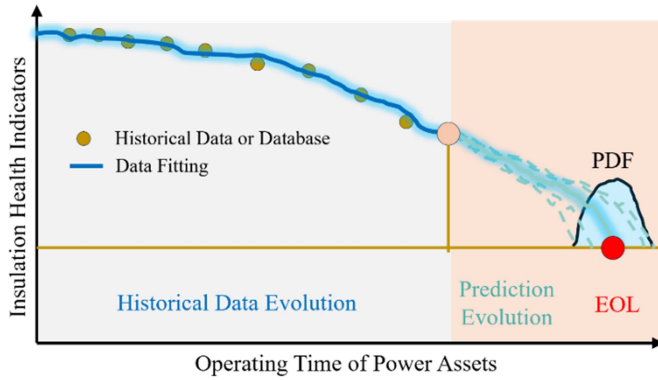


Fig. 35. Schematic diagram of the relationship of insulation health indicators and operating time of power assets. The relationship includes state diagnostics, state prediction, and prediction of EOL [104].

power applications. Using historical data and incorporating probability density functions, the end-of-lifetime (EOL) of insulation systems can be accurately predicted. However, this critical aspect of insulation diagnostics has not received sufficient attention in the context of high-voltage power electronics applications.

Notably, existing studies have primarily applied grey-box methods, such as semi-empirical equations and equivalent circuit models, to traditional high-voltage equipment like power transformers and power cables. These methods have proven effective in deriving physical insights for insulation health assessment as presented in Section V-A. However, high-voltage power electronics present unique challenges, including rapid switching transients, compact insulation designs, and broader frequency ranges. While the methodologies developed for traditional systems provide a solid foundation, their direct application to power electronics requires adaptation and further investigation.

VI. FUTURE RESEARCH DIRECTIONS

The traditional applications of semi-empirical and equivalent circuit models have primarily focused on underlying dielectric dynamics mechanisms analysis, and then guiding reliability analysis of insulation systems in power-frequency power equipment. Nonetheless, strongly driven by multifrequency power electronics applications, the role of frequency-dependent polarization dynamics behaviors in insulation systems becomes even more critical, which have more advantages in accurately calculating electrothermal fields under multifrequency voltage waveforms and acquiring reliable insulation design schemes. It is significant for the realization of high-power density and miniaturization of high-voltage and high-frequency power assets. Therefore, the intersection fields of electrical insulation and high-voltage power electronics applications still exist a series of new problems that need to be considered.

A. Suitability of Frequency-Dependent Polarization Models

The semi-empirical equations offer a more detailed polarization dynamics understanding for material specimens. The geometric information is required to derive the expressions

of complex permittivity or complex susceptibility. Instead, the equivalent circuit models provide a practical way to directly represent impedance dynamics without knowing geometric details of measured systems. Notably, both models also have common weaknesses and shortcomings that need to be solved.

- 1) How to choose a suitable model? For example, CC or HN model, RC or RQ branch?
- 2) How to determine the structures of selected models? For example, one polarization branch or two branches?
- 3) How can the parameters of these models be accurately solved? For instance, least squares method or physics-informed neural networks?

Additionally, the power electronics voltage waveforms with fast rising time would obviously influence the suitability and feasibility of these frequency-domain modelling techniques like CC model. The switching voltage waveforms with fast rising time can generate high-frequency components, the increase in the high-frequency sinusoidal waveform magnitude, and increase in dielectric heating. Thus, the voltage magnitude-frequency-thermal coupling effects on polarization dynamics behaviors of electrical insulation need to be emphasized under switching voltage waveforms with fast rising time. The coupling stress would amplify the frequency-dependent polarization dynamics behaviors, further influencing macroscopic properties of insulation systems. In this regard, the specific configuration of these frequency-domain models needs to be further confirmed based on the practical measured dielectric spectroscopy of insulation systems.

B. Electrothermal Field Calculation Considering Frequency-Dependent Polarization Mechanisms

To improve design robustness and ensure insulation reliability in high-voltage power electronics applications, it is essential to incorporate frequency-dependent polarization models in the calculation of electric fields under switching voltage waveforms. Accurate electrothermal field calculations require a thorough understanding of how polarization dynamics vary with factors such as electric stress, temperature, humidity, and pressure. In addition to experimental dielectric spectroscopy data, synthesized dielectric spectroscopy data based on the frequency-domain modelling approaches can play a critical role in enhancing the robustness of these electrothermal field calculations. By generating virtual datasets through advanced machine learning approaches, it becomes possible to simulate a wide range of operating conditions that may be challenging to replicate experimentally. This enables the development of more reliable insulation designs in high-voltage power electronics applications.

C. Partial Discharge Inception Prediction

Partial discharge behavior in insulation systems remains a significant challenge in multifrequency power electronics applications. Despite advances in understanding, the integration of frequency-dependent polarization dynamics with gas discharge theory to accurately predict PDIV is still underdeveloped. Current approaches primarily focus on maximum electric field

estimation, but they lack comprehensive consideration of the interplay between polarization dynamics and discharge mechanisms, which is critical for improving prediction accuracy. A promising direction is to establish a more robust theoretical framework that combines the frequency-dependent behavior of insulating materials with well-established gas discharge theories. Such integration would not only enhance PDIV prediction but also provide deeper insights into the mechanisms underlying partial discharge phenomena in complex power electronics environments. For further reference, relevant theoretical foundations can be found in paper [105].

D. Health Condition Monitoring and Evaluation for Electrical Insulation

The condition-based health evaluation of insulation systems as a fragile component in high-voltage multifrequency power electronics applications is critical, which is more practical than the traditional time-based maintenance strategy. The polarization dynamics behaviors are the most fundamental representation of insulation performance. Thus, the underlying polarization dynamics processes derived from the broadband impedance spectroscopy would provide a comprehensive insight into the effective condition-based maintenance of high-voltage power electronics applications.

E. Qualification Test Methods for High-Voltage Power Electronics Applications

Electrical insulation challenges in high-voltage power electronics, particularly in power module packaging and inverter-fed electrical machines, have attracted significant attention. Qualification test methods and quality control standards for insulation systems under power electronics voltage waveforms represent critical development areas for advancing these applications [106], [107]. Of particular importance are the design of PD-free systems and the precise measurement of PDIV, which serve as benchmarks for ensuring insulation reliability and operational safety in power electronics systems. Future advancements in these areas will not only improve system performance but also provide a foundation for developing standardized test protocols tailored to the unique characteristics of power electronics waveforms.

F. Investigations and Selection of New Insulating Materials for High-Voltage Power Electronics Applications

Future high-voltage power electronics applications, including electrified transportation, renewable energy systems, and HVDC power transmission, will operate in extreme environments characterized by high electric fields, elevated temperatures, and high humidity. Addressing these challenges necessitates the development of new high-performance insulating materials that integrate multiple advantageous properties, such as high dielectric breakdown strength, superior mechanical performance, and enhanced thermal conductivity [106], [108], [109]. Moreover, sustainable development goals have driven research into bio-based and recyclable insulating materials, such as bio-derived epoxy resins. While these materials offer promising

environmental benefits, achieving synergistic improvements in multidimensional performance remains an intriguing and critical research topic.

VII. CONCLUSION

The reliability of electrical insulation in high-voltage power electronics applications is fundamental to the safe operation of advanced technologies, including electrified transportation, renewable energy systems, and HVDC transmission. This article provides a comprehensive review of physical mechanisms, frequency-domain modeling approaches, and practical applications of electrical insulation under multifrequency switching voltage waveforms. It underscores the critical role of frequency-dependent polarization dynamics in determining macroscopic dielectric properties of insulation materials and shaping their performance under real-world conditions. Key conclusions include the following.

- 1) The frequency-dependent polarization dynamics, influenced by switching voltage waveforms with varying rise times and frequencies, are critical for understanding insulation behavior in high-voltage power electronics. These dynamics, governed by interfacial, dipolar, atomic, and electronic polarization mechanisms, significantly impact dielectric properties such as permittivity and dielectric loss. This underscores the importance of incorporating accurate frequency-domain models, especially considering the impact of fast-rising waveforms on model selection and parameterization.
- 2) Semi-empirical equations (e.g., CC, HN) and equivalent circuit models (e.g., fractional-order circuits) offer robust tools for characterizing polarization dynamics of electrical insulation subjected to switching voltage waveforms. While semi-empirical equations provide deeper insights into material behavior, equivalent circuit models demonstrate superior adaptability for system-level applications. This dual approach enables more precise modeling and supports the development of high-reliability insulation systems tailored to multifrequency power electronics voltages. Additionally, classical models, such as the CC model, assume single relaxation processes and may not adequately capture the frequency response under fast rise times, which are associated with high-frequency transient dynamics. These extended models with multiple polarization terms are more suitable for conditions with rapid high-frequency voltage waveforms.
- 3) Polarization dynamics behaviors not only govern the coupled electrothermal behavior of insulation systems but also provide a foundation for advanced diagnostic techniques, such as condition-based health monitoring for high-voltage power electronics applications. By integrating these dynamics into modeling and experimental workflows, the accuracy of performance predictions and the robustness of system designs for electrical insulation in high-voltage power electronics can be significantly improved.
- 4) Despite the usefulness of current models, challenges in model selection, parameter optimization, and integration

with partial discharge prediction remain. Future research should focus on improving model accuracy, developing advanced qualification test methods, and investigating new insulating materials that meet the growing demands of high-power density and miniaturization in high-voltage power electronics.

The insights from this review highlight gaps in existing frequency-domain models of electrical insulation under switching voltage waveforms, providing a foundation for future research and offering valuable guidance for optimizing insulation design and ensuring reliability in high-voltage power electronics applications.

REFERENCES

- [1] J. Chen et al., "Review of inorganic non-metallic materials in power electronics packaging application," *IEEE Trans. Power Electron.*, vol. 40, no. 8, pp. 10509–10530, Aug. 2025, doi: [10.1109/TPEL.2025.3550882](https://doi.org/10.1109/TPEL.2025.3550882).
- [2] Z. Liu, L. Zhu, Y. Dang, and S. Ji, "Core loss calculation method considering leakage flux induced power loss for nanocrystalline core high-frequency transformer under load condition," *IEEE Trans. Power Electron.*, vol. 40, no. 9, pp. 13126–13141, Sep. 2025.
- [3] E. A. Jones, F. F. Wang, and D. Costinett, "Review of commercial GaN power devices and GaN-based converter design challenges," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 4, no. 3, pp. 707–719, Sep. 2016.
- [4] A. Saha and M. Ghassemi, "A review of electrical insulation challenges for electrical powertrain components in the future more and all electric aircraft under low-pressure conditions," *IEEE J. Emerg. Sel. Topics Power Electron.*, to be published, doi: [10.1109/JESTPE.2024.3491298](https://doi.org/10.1109/JESTPE.2024.3491298).
- [5] Z. Li, E. Hsieh, Q. Li, and F. C. Lee, "High-frequency transformer design with medium-voltage insulation for resonant converter in solid-state transformer," *IEEE Trans. Power Electron.*, vol. 38, no. 8, pp. 9917–9932, Aug. 2023, doi: [10.1109/TPEL.2023.3279030](https://doi.org/10.1109/TPEL.2023.3279030).
- [6] Z. Guo and A. Q. Huang, "Characterizations of partial discharge in modern power electronics," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 12, no. 6, pp. 5705–5714, Dec. 2024, doi: [10.1109/JESTPE.2024.3417803](https://doi.org/10.1109/JESTPE.2024.3417803).
- [7] Y. Zang et al., "Optical detection and characteristics of PCB partial discharge in more-electric aircraft under square wave voltage," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 12, no. 6, pp. 5558–5567, Dec. 2024, doi: [10.1109/JESTPE.2024.3371010](https://doi.org/10.1109/JESTPE.2024.3371010).
- [8] G. C. Montanari, "Time behavior of partial discharges and life of type II turn insulation specimens under repetitive impulse and sinusoidal waveforms," *IEEE Elect. Insul. Mag.*, vol. 33, no. 6, pp. 17–26, Nov./Dec. 2017.
- [9] M. S. Moonesan, S. H. Jayaram, and E. A. Cherney, "Time to failure of medium-voltage form-wound machine turn insulation stressed by unipolar square waves," *IEEE Trans. Dielect. Elect. Insul.*, vol. 22, no. 6, pp. 3118–3125, Dec. 2015.
- [10] P. Wang, G. C. Montanari, and A. Cavallini, "Partial discharge phenomenology and induced aging behavior in rotating machines controlled by power electronics," *IEEE Trans. Ind. Electron.*, vol. 61, no. 12, pp. 7105–7112, Dec. 2014, doi: [10.1109/TIE.2014.2320226](https://doi.org/10.1109/TIE.2014.2320226).
- [11] I. M. Jarrar, E. A. Cherney, and S. H. Jayaram, "Effect of repetitive impulse waveform characteristics on partial discharges in type II turn-to-turn insulation," *IEEE Trans. Dielect. Elect. Insul.*, vol. 29, no. 3, pp. 1183–1190, Jun. 2022.
- [12] R. Agarwal, H. Li, Z. Guo, and P. Cheetham, "The effects of PWM with high dv/dt on partial discharge and lifetime of medium-frequency transformer for medium-voltage (MV) solid state transformer applications," *IEEE Trans. Ind. Electron.*, vol. 70, no. 4, pp. 3857–3866, Apr. 2023, doi: [10.1109/TIE.2022.3174243](https://doi.org/10.1109/TIE.2022.3174243).
- [13] Z. Wang, X. Wei, F. F. da Silva, H. Sørensen, Z. Shen, and C. L. Bak, "Interactions analysis and life modeling for high-frequency transformers insulation under multistress," *IEEE Trans. Power Electron.*, vol. 40, no. 4, pp. 5646–5660, Apr. 2025.
- [14] H. Wang, G. Xiao, L. Wang, X. Dong, and Z. Ma, "High-frequency current transformer design and analysis for partial discharge detection of power electronic modules," *IEEE Trans. Power Electron.*, vol. 40, no. 5, pp. 7227–7238, May 2025.
- [15] M. Yang and B. T. Phung, "Motor winding insulation degradation under repetitive voltage pulses," *IEEE Access*, vol. 12, pp. 77658–77674, 2024.
- [16] H. Yao et al., "Dielectric characteristic analysis and insulation state evaluation of packaging material for power module with different aging degrees," *IEEE Trans. Dielect. Elect. Insul.*, vol. 31, no. 1, pp. 513–522, Feb. 2024.
- [17] Y. Gao et al., "Impacts of the bottom copper layer of direct-bond copper substrates on the partial discharge performance in power modules," *IEEE Trans. Power Electron.*, vol. 40, no. 4, pp. 5999–6009, Apr. 2025, doi: [10.1109/TPEL.2024.3516534](https://doi.org/10.1109/TPEL.2024.3516534).
- [18] Z. Li, Y. Han, Z. Xie, H. Ren, Q. Li, and Z. Wang, "High-frequency partial discharge characteristics of solid-state transformer interturn multilayer insulation under repetitive electrical stress," *IEEE Trans. Ind. Electron.*, vol. 71, no. 10, pp. 13331–13340, Oct. 2024.
- [19] M. Pastura et al., "Partial discharges in electrical machines for the more electric aircraft—Part I: A comprehensive modeling tool for the characterization of electric drives based on fast switching semiconductors," *IEEE Access*, vol. 9, pp. 27109–27121, 2021, doi: [10.1109/ACCESS.2021.3058083](https://doi.org/10.1109/ACCESS.2021.3058083).
- [20] L. Lusuardi, A. Rumi, A. Cavallini, D. Barater, and S. Nuzzo, "Partial discharge phenomena in electrical machines for the more electrical aircraft. Part II: Impact of reduced pressures and wide bandgap devices," *IEEE Access*, vol. 9, pp. 27485–27495, 2021, doi: [10.1109/ACCESS.2021.3058089](https://doi.org/10.1109/ACCESS.2021.3058089).
- [21] A. Rumi, L. Lusuardi, A. Cavallini, M. Pastura, D. Barater, and S. Nuzzo, "Partial discharges in electrical machines for the more electrical aircraft. Part III: Preventing partial discharges," *IEEE Access*, vol. 9, pp. 30113–30123, 2021, doi: [10.1109/ACCESS.2021.3058090](https://doi.org/10.1109/ACCESS.2021.3058090).
- [22] A. Cavallini, E. Concettoni, S. Luna, F. Rosignoli, and A. Rumi, "Challenges and opportunities in RPDIV testing of automotive electrical machines after assembly," in *Proc. IEEE Elect. Insul. Conf.*, 2023, pp. 1–4, doi: [10.1109/EIC5835.2023.10177369](https://doi.org/10.1109/EIC5835.2023.10177369).
- [23] H. Naderiallaf, M. Degano, and C. Gerada, "Modeling air pressure impact on PDIV for rectangular wire turn-to-turn insulation of inverter-fed motors under different voltage waveform excitations," *IEEE Access*, vol. 12, pp. 176232–176246, 2024.
- [24] H. Naderiallaf, Y. Ji, P. Giangrande, and M. Galea, "Modeling humidity impact on PDIV for turn-to-turn insulation of inverter-fed motors at different temperatures," *IEEE Trans. Dielect. Elect. Insul.*, vol. 31, no. 3, pp. 1573–1582, Jun. 2024.
- [25] J. Gao, A. Rumi, Y. He, and A. Cavallini, "Towards a holistic approach to inverter-fed machine design: FEM-based PDIV prediction of complete windings," *IEEE Trans. Dielect. Elect. Insul.*, vol. 30, no. 6, pp. 2870–2877, Dec. 2023, doi: [10.1109/TDEI.2023.3284414](https://doi.org/10.1109/TDEI.2023.3284414).
- [26] A. Rumi, P. Seri, and A. Cavallini, "Electric field distribution at high temperatures in impregnated enameled conductors used in electrical machines," in *Proc. 2023 Int. Symp. Elect. Insulating Mater.*, 2023, pp. 1–4, doi: [10.23919/ISEIM60444.2023.10329189](https://doi.org/10.23919/ISEIM60444.2023.10329189).
- [27] A. Rumi, J. Marinelli, and A. Cavallini, "Dielectric characterization of impregnating varnishes for inverter-fed motors," in *Proc. IEEE 4th Int. Conf. Dielect.*, 2022, pp. 389–392, doi: [10.1109/ICD53806.2022.9863563](https://doi.org/10.1109/ICD53806.2022.9863563).
- [28] M. Chen, Y. Wang, Y. Ding, L. Fan, and Y. Yin, "Self-adaptive field-grading coating for partial discharge mitigation of high voltage power module under high dv/dt square wave voltage," *IEEE Trans. Power Electron.*, vol. 39, no. 8, pp. 9079–9083, Aug. 2024, doi: [10.1109/TPEL.2024.3390672](https://doi.org/10.1109/TPEL.2024.3390672).
- [29] H. Wang, G. Xiao, L. Wang, F. Yan, Z. Ma, and Q. Yang, "Characteristics and mechanism of partial discharge behavior of power module under unipolar square voltage," *IEEE Trans. Ind. Electron.*, vol. 71, no. 8, pp. 9789–9799, Aug. 2024, doi: [10.1109/TIE.2023.3323749](https://doi.org/10.1109/TIE.2023.3323749).
- [30] Z. Han, Q. Li, Y. Guo, T. Liu, G. Dong, and H. Ren, "Influence of repetitive impulse waveforms on surface discharge characteristics and insulation life for polyimide film," *CSEE J. Power Energy Syst.*, vol. 10, no. 2, pp. 746–755, Mar. 2024.
- [31] Y. Lin et al., "Temperature- and degradation-dependent maximum electric field stress in wire-bonding power modules under PWM waves," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 10, no. 6, pp. 7653–7664, Dec. 2022, doi: [10.1109/JESTPE.2022.3195177](https://doi.org/10.1109/JESTPE.2022.3195177).
- [32] W. S. Zaengl, "Applications of dielectric spectroscopy in time and frequency domain for HV power equipment," *IEEE Elect. Insul. Mag.*, vol. 19, no. 6, pp. 9–22, Nov./Dec. 2003.
- [33] X. Dai et al., "Unraveling high temperature-induced glass transition effect on underlying multimescales dynamic mechanisms of epoxy resin insulation in power electronic applications," *IEEE Trans. Dielect. Elect. Insul.*, vol. 31, no. 5, pp. 2290–2298, Oct. 2024, doi: [10.1109/TDEI.2024.3403075](https://doi.org/10.1109/TDEI.2024.3403075).

- [34] S. K. Ojha, P. Purkait, and S. Chakravorti, "Evaluating the effects of temperature on moisture dynamics and relaxation mechanism in transformer oil-paper insulation," *IEEE Trans. Dielect. Elect. Insul.*, vol. 31, no. 1, pp. 151–159, Feb. 2024.
- [35] H. Liu, B. Du, M. Xiao, Z. Ran, and Y. Ma, "Dielectric properties of polymer films in strong electromagnetic field for energy storage capacitor," *IEEE Trans. Dielect. Elect. Insul.*, vol. 29, no. 5, pp. 1745–1753, Oct. 2022.
- [36] S. V. Suraci, X. Colin, and D. Fabiani, "Multiscale modeling of permittivity of polymers with aging: Analysis of molecular scale properties and their impact on electrical permittivity," *IEEE Trans. Dielect. Elect. Insul.*, vol. 29, no. 5, pp. 1795–1802, Oct. 2022.
- [37] B. Sonerud, T. Bengtsson, J. Blennow, and S. M. Gubanski, "Dielectric response measurements utilizing semi-square voltage waveforms," *IEEE Trans. Dielect. Elect. Insul.*, vol. 15, no. 4, pp. 920–926, Aug. 2008.
- [38] J. Hao, R. Liao, G. Chen, Z. Ma, and L. Yang, "Quantitative analysis ageing status of natural ester-paper insulation and mineral oil-paper insulation by polarization/depolarization current," *IEEE Trans. Dielect. Elect. Insul.*, vol. 19, no. 1, pp. 188–199, Feb. 2012.
- [39] D. Mishra, N. Haque, A. Baral, and S. Chakravorti, "Assessment of interfacial charge accumulation in oil-paper interface in transformer insulation from polarization/depolarization current measurements," *IEEE Trans. Dielect. Elect. Insul.*, vol. 24, no. 3, pp. 1665–1673, Jun. 2017.
- [40] T. K. Saha and P. Purkait, "Investigation of polarization and depolarization current measurements for the assessment of oil-paper insulation of aged transformers," *IEEE Trans. Dielect. Elect. Insul.*, vol. 11, no. 1, pp. 144–154, Feb. 2004.
- [41] F. Kremer and A. Schönhal, *Broadband Dielectric Spectroscopy*. Berlin, Germany: Springer, 2003.
- [42] K. Jonscher, *Dielectric Relaxation in Solids*. Hampshire, U.K.: Chelsea Dielectrics Press Limited, 1983.
- [43] J. Hao et al., "Physical mechanism analysis of conductivity and relaxation polarization behavior of oil-paper insulation based on broadband frequency domain spectroscopy," *IEEE Trans. Dielect. Elect. Insul.*, vol. 28, no. 5, pp. 1571–1578, Oct. 2021.
- [44] S. Wang et al., "Polymer-based dielectrics with high permittivity and low dielectric loss for flexible electronics," *J. Mater. Chem. C*, vol. 10, no. 16, pp. 6196–6221, 2022.
- [45] T. Guillod, R. Faerber, D. Rothmund, F. Krismer, C. M. Franck, and J. W. Kolar, "Dielectric losses in dry-type insulation of medium-voltage power electronic converters," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 8, no. 3, pp. 2716–2732, Sep. 2020.
- [46] X. Dai, J. Hao, and C. L. Bak, "A health indicator sensitive to non-uniforming aging patterns of polymeric insulation systems," in *Proc. IEEE Int. Conf. High Voltage Eng. Appl.*, 2024, pp. 1–4.
- [47] H. Peng et al., "High-frequency modeling of permanent magnet synchronous machines using grey box models," *IEEE Trans. Transp. Electrific.*, vol. 10, no. 4, pp. 8150–8160, Dec. 2024, doi: [10.1109/TTE.2024.3363511](https://doi.org/10.1109/TTE.2024.3363511).
- [48] C. Wu, M. Arab, J. Ronzello, and Y. Cao, "Charge transport dynamics and space charge accumulation in XLPE composites with 2D platelet fillers for HVDC cable insulation," *IEEE Trans. Dielect. Elect. Insul.*, vol. 28, no. 1, pp. 3–10, Feb. 2021.
- [49] J. Gao, L. Yang, Y. Wang, C. Qi, J. Hao, and J. Liu, "Quantitative evaluation of ageing condition of oil-paper insulation using frequency domain characteristic extracted from modified Cole-Cole model," *IEEE Trans. Dielect. Elect. Insul.*, vol. 22, no. 5, pp. 2694–2702, Oct. 2015.
- [50] Z. Lyu, Z. Liang, H. Yao, Y. Zhang, and W. Wei, "Condition assessment of XLPE cable insulation based on improved fractional Zener model," *IEEE Trans. Dielect. Elect. Insul.*, vol. 31, no. 3, pp. 1499–1508, Jun. 2024.
- [51] D. K. Das-Gupta and P. C. N. Scarpa, "Modeling of dielectric relaxation spectra of polymers in the condensed phase," *IEEE Elect. Insul. Mag.*, vol. 15, no. 2, pp. 23–32, Mar./Apr. 1999.
- [52] D. Wang, J. Zhang, L. Zhou, H. Tang, J. Wu, and Z. Guo, "Estimation method for non-uniform state of MOIP in traction transformer via curve reconstruction of frequency domain spectrum," *IEEE Trans. Transp. Electrific.*, vol. 10, no. 1, pp. 2008–2019, Mar. 2024, doi: [10.1109/TTE.2023.3288896](https://doi.org/10.1109/TTE.2023.3288896).
- [53] T. Zhang Tao and W. Yang, "Modelling and calculation for dielectric response circuit of oil-paper insulation transformers," in *Proc. Int. Conf. Electric Inf. Control Eng.*, 2011, pp. 1472–1475.
- [54] X. Dai, A. Cavallini, J. Hao, R. Liao, C. L. Bak, and H. Wang, "A modular fractional-order circuit model for broadband impedance characterization of polymeric insulation systems," in *Proc. IEEE 5th Int. Conf. Dielectrics*, 2024, pp. 1–4.
- [55] T. Zhang, X. Li, H. Lv, and X. Tan, "Parameter identification and calculation of return voltage curve based on FDS data," *IEEE Trans. Appl. Supercond.*, vol. 24, no. 5, Oct. 2014, Art. no. 9002405.
- [56] P. Debye, "Zur theorie der spezifischen waerme," *Annalen Der Physik (German)*, vol. 39, no. 4, pp. 789–839, 1912.
- [57] S. Cole and R. H. Cole, "Dispersion and absorption in dielectrics I. Alternating current characteristics," *J. Chem. Phys.*, vol. 9, no. 4, pp. 341–351, 1941.
- [58] D. W. Davidson and R. H. Cole, "Dielectric relaxation in glycerol propylene glycol and n-propanol," *J. Chem. Phys.*, vol. 19, pp. 1484–1490, 1951.
- [59] S. Havriliak and S. Negami, "A complex plane representation of dielectric and mechanical relaxation processes in some polymers," *Polymer*, vol. 8, pp. 161–210, 1967.
- [60] G. Williams and D. C. Watts, "Non-symmetrical dielectric relaxation behaviour arising from a simple semi-empirical decay function," *Trans. Faraday Soc.*, vol. 66, pp. 80–85, 1970.
- [61] A. Dissado and R. M. Hill, "A cluster approach to the structure of imperfect materials and their relaxation spectroscopy," *Proc. Roy. Soc. London U.K. Math. Phys. Sci.*, vol. 390, pp. 131–180, 1983.
- [62] L. A. Dissado and R. M. Hill, "Anomalous low-frequency dispersion. Near direct current conductivity in disordered low-dimensional materials," *J. Chem. Soc. Faraday Trans. 2, Mol. Chem. Phys.*, vol. 80, pp. 291–319, 1984.
- [63] N. Chalashkanov and L. Dissado, "Dielectric measurements in the frequency domain—Dos and don'ts," *IEEE Elect. Insul. Mag.*, vol. 38, no. 5, pp. 28–38, Sep./Oct. 2022.
- [64] Q. Xu, S. Wang, F. Lin, and H. Li, "Extracting frequency spectroscopy of oil-immersed paper based on Havriliak–Negami model without known insulation structure of transformer," *IEEE Trans. Instrum. Meas.*, vol. 71, 2022, Art. no. 6003312.
- [65] X. Dai, C. L. Bak, and H. Wang, "Performance analysis of high-order RC circuit models applied to insulation broadband impedance reconstruction in multifrequency applications," in *Proc. IEEE Int. Conf. High Voltage Eng. Appl.*, 2024, pp. 1–4.
- [66] Y. Deng et al., "Nonlinear dielectric response characteristics of damp oil-paper insulation and application of H-W model in time-frequency conversion," *IEEE Trans. Dielect. Elect. Insul.*, vol. 27, no. 6, pp. 2078–2086, Dec. 2020.
- [67] L. Yang, J. Chen, S. Wang, and J. Gao, "Dielectric response measurement of oil-paper insulation based on system identification and its time-frequency-domain conversion method," *IEEE Trans. Dielect. Elect. Insul.*, vol. 25, no. 5, pp. 1688–1698, Oct. 2018.
- [68] F. Yang and L. Du, "A circuital model-based analysis of moisture content in oil-impregnated-paper insulation using frequency domain spectroscopy," *IEEE Access*, vol. 8, pp. 47092–47102, 2020.
- [69] H. Zhao et al., "Deciphering the intricate dielectric relaxation processes of cellulose paper: Extraction of distribution of relaxation time and analysis of degradation characteristics," *Carbohydrate Polymers*, vol. 324, 2024, Art. no. 121497.
- [70] I. Wirth, M. H. Zink, A. Kuechler, F. Berger, and T. Schnitzler, "Implementation of conduction and polarization mechanisms in transient FEM simulations of HVDC insulation systems," in *Proc. VDE High Voltage Technol.; ETG-Symp.*, 2018, pp. 1–6.
- [71] K. Andreas et al., "FEM model for describing the dielectric behavior of oil-impregnated pressboard under DC stresses," in *Proc. Papers 33rd Int. Sci. Conf. "Sci. Pract."*, 2015, pp. 62–66.
- [72] A. Baral and S. Chakravorti, "A modified maxwell model for characterization of relaxation processes within insulation system having non-uniform aging due to temperature gradient," *IEEE Trans. Dielect. Elect. Insul.*, vol. 20, no. 2, pp. 524–534, Apr. 2013, doi: [10.1109/TDEI.2013.6508755](https://doi.org/10.1109/TDEI.2013.6508755).
- [73] Z. Ding, X. Fan, B. Song, H. H. Goh, Y. Zhang, and J. Liu, "NSGA-II model-based dielectric frequency response parameters for aging and moisture analysis of transformer insulation," *IEEE Trans. Instrum. Meas.*, vol. 71, 2022, Art. no. 3518710.
- [74] X. Fan, F. Liang, H. Luo, C. Li, J. Liu, and J. He, "Adaptive-optimization-based digital simulation database for nonuniform aging diagnosis of transformer insulation system," *IEEE Trans. Ind. Electron.*, vol. 71, no. 6, pp. 6315–6324, Jun. 2024.

- [75] S. Holm, "Natural occurrence of fractional derivatives in physics," in *Proc. Int. Conf. Fractional Differentiation Appl.*, 2023, pp. 1–5.
- [76] S. Holm, *Waves With Power-Law Attenuation*. Berlin, Germany: Springer, 2019.
- [77] S. Holm, "The constant phase element is not a generalized capacitor," in *Proc. 19th Biennial Baltic Electron. Conf.*, 2024, pp. 1–4.
- [78] X. Dai, J. Hao, Z. Jian, K. Hassan Al Hosani, and R. Liao, "Insights into non-uniform aging effects on broadband dielectric behaviors for high-voltage XLPE cable insulation: A novel fractional-order circuit modeling approach," *IEEE Trans. Dielect. Elect. Insul.*, vol. 32, no. 3, pp. 1793–1801, Jun. 2025, doi: [10.1109/TDEI.2024.3466127](https://doi.org/10.1109/TDEI.2024.3466127).
- [79] X. Dai, J. Hao, M. E. Moursi, R. Chen, R. Liao, and C. L. Bak, "Dielectric mechanisms and health state estimation for high-voltage XLPE cable insulation under nonuniform thermal aging," *IEEE Trans. Dielect. Elect. Insul.*, to be published, doi: [10.1109/TDEI.2025.3542752](https://doi.org/10.1109/TDEI.2025.3542752).
- [80] Y. Gao et al., "Numerical calculation method for constructing equivalent circuit model in the analysis of dielectric response," in *Proc. IEEE Int. Conf. High Voltage Eng. Application*, 2020, pp. 1–4.
- [81] Q. Wang et al., "Interfacial and bulk polarization of P(VDF-HFP) investigated by dielectric spectroscopy," *IEEE Trans. Dielect. Elect. Insul.*, vol. 28, no. 4, pp. 1247–1254, Aug. 2021.
- [82] Y. Gao, X. Liang, L. A. Dissado, S. J. Dodd, and N. M. Chalashkanov, "Dielectric response of filled high temperature vulcanized silicone rubber," *IEEE Trans. Dielect. Elect. Insul.*, vol. 23, no. 6, pp. 3683–3695, Dec. 2016.
- [83] F. Tian and Y. Ohki, "Electric modulus powerful tool for analyzing dielectric behavior," *IEEE Trans. Dielect. Elect. Insul.*, vol. 21, no. 3, pp. 929–931, Jun. 2014.
- [84] S. Wolny, A. Adamowicz, and M. Lepich, "Influence of temperature and moisture level in paper-oil insulation on the parameters of the Cole-Cole model," *IEEE Trans. Power Del.*, vol. 29, no. 1, pp. 246–250, Feb. 2014.
- [85] C. Qi, L. Yang, W. Li, J. Hao, Z. Ma, and J. Bai, "Extraction method for frequency domain characteristic parameters of oil impregnated insulation paper," in *Proc. Int. Conf. High Voltage Eng. Application*, 2012, pp. 110–114.
- [86] J. Liu, L. Zhou, G. Wu, Y. Zhao, P. Liu, and Q. Peng, "Dielectric frequency response of oil-paper composite insulation modified by nanoparticles," *IEEE Trans. Dielect. Elect. Insul.*, vol. 19, no. 2, pp. 510–520, Apr. 2012.
- [87] Y. Xiaobing and C. Baojiang, "Effect of humidity on the properties of frequency domain spectroscopy of rotating machines epoxy/mica insulation," in *Proc. IEEE Int. Conf. High Voltage Eng. Appl.*, 2016, pp. 1–4.
- [88] Y. Mi, L. Liu, S. Deng, L. Gui, and W. Ouyang, "Electrothermal aging characteristics of epoxy resin under bipolar exponential decay pulse voltage and its insulation life evaluation based on Cole-Cole model," *IEEE Trans. Dielect. Elect. Insul.*, vol. 26, no. 3, pp. 784–791, Jun. 2019.
- [89] J. Hao et al., "Synergistic enhancement effect of moisture and aging on frequency dielectric response of oil-immersed cellulose insulation and its degree of polymerization evaluation using dielectric modulus," *Cellulose*, vol. 28, no. 1, pp. 1–17, Jan. 2021.
- [90] Y. Zhang et al., "Study on nonuniform thermal aging state of XLPE based on Dissado–Hill model," *IEEE Trans. Plasma Sci.*, vol. 50, no. 11, pp. 4566–4575, Nov. 2022.
- [91] W. Liao, L. Zhou, C. Zhang, D. Wang, J. Zhang, and L. Guo, "A method for discriminating the moisture status of OIP bushing based on Dissado-Hill and GWO-HMM model," *IEEE Trans. Ind. Appl.*, vol. 58, no. 2, pp. 1512–1520, Mar./Apr. 2022.
- [92] L. Benmamas, P. Teste, E. Odic, G. Krebs, and T. Hamiti, "Contribution to the analysis of PWM inverter parameters influence on the partial discharge inception voltage," *IEEE Trans. Dielect. Elect. Insul.*, vol. 26, no. 1, pp. 146–152, Feb. 2019.
- [93] M. Florkowski, "Magnetic field effects on partial discharges in electrical insulation subjected to PWM excitation," *IEEE Trans. Power Electron.*, vol. 39, no. 2, pp. 2741–2750, Feb. 2024.
- [94] T. J. Å. Hammarström, "Partial discharge characteristics within motor insulation exposed to multi-level PWM waveforms," *IEEE Trans. Dielect. Elect. Insul.*, vol. 25, no. 2, pp. 559–567, Apr. 2018.
- [95] M. Eckert and J. Pihera, "Dielectric model of polarization mechanisms in time domain FEM simulation," in *Proc. 23rd Int. Symp. High Voltage Eng.*, 2023, pp. 270–275.
- [96] M. Eckert and J. Pihera, "Dielectric model of polarization mechanisms in time domain field simulation including temperature dependence," in *Proc. IEEE 5th Int. Conf. Dielect.*, 2024, pp. 1–4.
- [97] M. Eckert and J. Pihera, "Polarization and electric field distribution of stacked dielectrics at transient excitation," in *Proc. Int. Conf. Diagnostics Elect. Eng. (Diagnostika)*, 2024, pp. 1–5.
- [98] P. Cambareri, C. de Falco, L. D. Rienzo, P. Seri, and G. C. Montanari, "Electric field calculation during voltage transients in HVDC cables: Contribution of polarization processes," *IEEE Trans. Power Del.*, vol. 37, no. 6, pp. 5425–5432, Dec. 2022.
- [99] W. Wang et al., "An improved design procedure for a 10 kHz, 10 kW medium-frequency transformer considering insulation breakdown strength and structure optimization," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 10, no. 4, pp. 3525–3540, Aug. 2022.
- [100] T. Guillod, R. Färber, F. Krismer, C. M. Franck, and J. W. Kolar, "Computation and analysis of dielectric losses in MV power electronic converter insulation," in *Proc. IEEE Energy Convers. Congr. Expo.*, 2016, pp. 1–8.
- [101] R. Nikjoo, N. Taylor, and H. Edin, "Dielectric response measurement by impulse stimulus on AC: Measurement considerations, and laboratory testing on a bushing," *IEEE Trans. Dielect. Elect. Insul.*, vol. 24, no. 1, pp. 511–518, Feb. 2017, doi: [10.1109/TDEI.2016.006084](https://doi.org/10.1109/TDEI.2016.006084).
- [102] R. Nikjoo, N. Taylor, R. C. Kiiza, and H. Edin, "Dielectric response of aged transformer bushings utilizing power system transients," in *Proc. IEEE PES ISGT Europe*, 2013, pp. 1–5, doi: [10.1109/ISGTEurope.2013.6695398](https://doi.org/10.1109/ISGTEurope.2013.6695398).
- [103] R. Nikjoo, N. Taylor, R. C. Kiiza, and H. Edin, "Dielectric response of oil-impregnated paper by utilizing lightning and switching transients," *IEEE Trans. Dielect. Elect. Insul.*, vol. 22, no. 1, pp. 335–344, Feb. 2015, doi: [10.1109/TDEI.2014.004664](https://doi.org/10.1109/TDEI.2014.004664).
- [104] X. Dai, "Dielectric dynamics mechanism and grey-box equivalent circuit modelling for high-voltage polymeric insulation systems in multifrequency power electronics applications," Ph.D. Thesis, Aalborg Univ., Aalborg, Denmark, 2025.
- [105] L. Lusuardi, A. Cavallini, M. G. de la Calle, J. M. Martínez-Tarifa, and G. Robles, "Insulation design of low voltage electrical motors fed by PWM inverters," *IEEE Elect. Insul. Mag.*, vol. 35, no. 3, pp. 7–15, May/June 2019.
- [106] A. Cavallini, P. Seri, N. Frost, and S. Jayharam, "Towards the standardization of impulse tests used for quality control of electrical machines used in road transportation," in *Proc. IEEE Elect. Insul. Conf.*, 2024, pp. 417–420, doi: [10.1109/EIC58847.2024.10579276](https://doi.org/10.1109/EIC58847.2024.10579276).
- [107] A. Cavallini, "High power density motors for transport electrification: State-of-the-art and challenges," in *Proc. 10th Int. Conf. Condition Monit. Diagnosis*, 2024, pp. 238–241, doi: [10.23919/CMD62064.2024.10766263](https://doi.org/10.23919/CMD62064.2024.10766263).
- [108] A. Rumi, J. G. Marinelli, D. Barater, A. Cavallini, and P. Seri, "The challenges of reliable dielectrics in modern aerospace applications: The hazard of corona resistant materials," *IEEE Trans. Transp. Electrification*, vol. 8, no. 4, pp. 4646–4653, Dec. 2022, doi: [10.1109/TTE.2022.3191064](https://doi.org/10.1109/TTE.2022.3191064).
- [109] S. Diahm, Z. Valdez-Nava, T. T. Le, L. Lévêque, L. Laudebat, and T. Lebey, "Field grading composites tailored by electrophoresis—Part 3: Application to power electronics modules encapsulation," *IEEE Trans. Dielect. Elect. Insul.*, vol. 28, no. 2, pp. 348–354, Apr. 2021, doi: [10.1109/TDEI.2020.009032](https://doi.org/10.1109/TDEI.2020.009032).