

Characterization and Testing of Nonlinear Insulating Dielectric Properties - Postprint

Authors: Li Zhonghua

Date: 2019-03-05T00:00:00+00:00

Abstract

Nonlinearity is one of the key factors that complicates problems and exists in almost all physical phenomena. The nonlinear dielectric behavior of electrical insulating media provides broader research space at the scientific level, while offering new technical approaches to address bottleneck issues in electrical insulation structure design and the development of higher voltage level power equipment at the engineering and technological level. Nonlinear insulation materials with electric field regulation functions, known as “smart insulation materials,” have been widely applied in large motor end-winding insulation and cable accessory anti-corona structures. With the advancement of high-voltage DC insulation technology, research on the nonlinear dielectric properties and mechanisms of electrical insulation materials and structures has received increasingly widespread attention. The characterization and testing techniques for the dielectric properties of nonlinear insulating media are extremely challenging research topics and unavoidable fundamental issues in both basic research and engineering application technology research. Under steady-state DC electric fields, the nonlinear dielectric characteristics are characterized by volt-ampere characteristics or the relationship between conductivity and electric field strength, and the corresponding testing techniques are relatively simple. Under steady-state AC electric fields, they are characterized by the equivalent (relative) permittivity and the relationship between equivalent conductivity and electric field strength; the key to testing techniques lies in how to accurately decompose resistive and capacitive currents. Under transient electric fields, the characterization parameter system for nonlinear dielectric properties has not yet been established, the testing techniques are the most complex, and related research urgently needs to be conducted.

Full Text

Preamble

Characterization and Measurement of Dielectric Properties of Non-linear Insulating Dielectrics

Li Zhonghua

(Key Laboratory of Engineering Dielectrics and its Application Technology, Ministry of Education, Harbin University of Technology, Harbin 150080, China)

Abstract: Nonlinearity is one of the key factors that complicates problems and exists in almost all physical phenomena. The nonlinear dielectric behavior of electrical insulating media provides broader research space at the scientific level, while offering new technical approaches to solve bottleneck problems in electrical insulation structure design and the development of higher voltage class power equipment at the engineering level. Nonlinear insulating materials with electric field regulation functions, known as “smart insulating materials,” have been widely applied in corona protection structures for large motor end-windings and cable accessories. With advances in HVDC insulation technology, research on the nonlinear dielectric properties and mechanisms of electrical insulating materials and structures has attracted increasing attention.

The characterization and measurement of dielectric properties of nonlinear insulating dielectrics represents an extremely challenging research topic, yet it is an unavoidable fundamental issue for both basic and engineering application studies. Under steady-state DC electric fields, the dielectric characteristics of nonlinear insulation are characterized by volt-ampere characteristics or the relationship between conductivity and electric field strength, with relatively simple corresponding test techniques. Under steady-state AC electric fields, they are characterized by the relationships between equivalent (relative) dielectric constant and equivalent conductivity with electric field strength, where the key technical challenge lies in accurately decomposing resistive and capacitive currents. For transient electric fields, the parameter system for characterizing nonlinear insulation dielectric properties has not yet been established, and the measurement technology is the most complex, making related research urgently needed.

Keywords: Nonlinear insulating dielectrics, dielectric characteristics, characterization parameters, transient dielectric characteristics, measurement technology

1 Introduction

Nonlinear insulating media refers to insulating materials whose conductivity and/or dielectric constant (more precisely, polarizability) vary with electric field strength [?]. Insulating materials with field-enhanced nonlinear conductivity and/or nonlinear dielectric constant can achieve adaptive matching between

material performance parameters and spatial electric field magnitude, intelligently improving electric field distribution uniformity in insulation structures [?]. Therefore, such materials are called “smart insulating materials” [?], and are also known as “electrical stress grading materials” (electrical stress grading materials [?] or electrical stress controlling materials [?]) in engineering applications.

Nonlinear insulating materials can simplify insulation structure design and reduce insulation thickness, showing broad application prospects in high-voltage complex insulation structure design and manufacturing. In fact, nonlinear insulating media have already been widely applied in high-voltage insulation fields, such as corona protection tapes in high-voltage motor stator bar end-windings [?] and electric field stress control sheets (or tubes) for cable accessories [?]. They also hold potential for application in HVDC cable main insulation and accessory insulation structures [?], as well as in high-voltage composite insulators [?]. HVDC transmission technology has attracted widespread attention globally and will develop even faster during China’s “13th Five-Year Plan” period [?]. The rapid development of HVDC transmission technology poses a tremendous challenge to power equipment insulation technology, as DC insulation technology is more complex than AC insulation technology, with nonlinearity being one of the reasons.

In DC insulation systems, the conductivity of single polymer insulating media clearly depends on electric field strength, while polymer-based composite insulation shows even more pronounced electric field dependence, exhibiting changes of several times or even dozens of times [?]. Meanwhile, the temperature dependence of insulation material conductivity is an undeniable fact. Temperature field distribution inevitably exists in insulation structures, making electric field distribution in DC insulation structures unable to avoid nonlinear problems. More importantly, nonlinear factors provide conditions for adaptive regulation [?, ?]. Consequently, related research on nonlinear insulating media has gained attention from several domestic research institutions including Tsinghua University [?], Xi’an Jiaotong University [?], Tianjin University [?], and Harbin University of Technology.

Electric field distribution calculation in insulation structures forms the basis for electrical insulation structure design and optimization. For insulation structures containing nonlinear insulating media, calculating steady-state electric field distribution through theoretical analytical solutions is extremely difficult. The effective solution is to employ computer numerical calculations, while transient electric field distribution can only be solved numerically [?]. Limited by the development of nonlinear insulation testing technology, researchers have yet to provide satisfactory basic dielectric parameters, especially transient dielectric parameters for nonlinear insulating media. As Professor Steven Boggs, a renowned expert in the electrical insulation field, pointed out in 2007: measuring nonlinear dielectric characteristics is a major challenge; computational technology leads measurement technology, and while people have been capable

of performing transient nonlinear finite element analysis for over a decade, they still cannot provide the dielectric characteristic measurement data required for numerical analysis [?].

The engineering application of nonlinear insulating dielectrics urgently requires theoretical and technical support, including transient dielectric mechanisms and testing technologies. Constrained by the complexity of nonlinear problems, a parameter system and corresponding testing technology for characterizing the transient dielectric properties of nonlinear insulating media have not yet been formed [?]. Meanwhile, limited by testing technology, research on the transient dielectric mechanisms of nonlinear insulating media remains almost blank.

2 Research Progress

Dielectric theory is established on a phenomenological basis, where phenomenological theories form corresponding physical laws through generalization, summarization, and refinement of experimental phenomena. This demonstrates that testing technology research is necessarily the prerequisite for theoretical research. Testing technology and characterization systems are twin brothers, and the determination of characterization systems often represents a wise choice based on the current state of testing technology development [?, ?]. Therefore, establishing a characterization system must consider not only whether the parameter system meets the needs of scientific research and engineering applications, but also whether the testing technology can achieve its measurement. In this sense, the characterization system will continuously improve with advances in testing technology.

2.1 DC Steady-State Dielectric Characteristics of Nonlinear Insulation

The DC steady-state dielectric characteristics of nonlinear insulating media are characterized by the functional relationship between conductivity and electric field strength (current density versus electric field strength curve or volt-ampere characteristic curve) [?]. In principle, nonlinear DC steady-state performance testing technology is relatively simple. From a technical perspective, nonlinear insulation DC steady-state dielectric characteristics face three challenges: first, how to eliminate temperature rise in samples caused by Joule heating during high-field testing, for which researchers have designed special sample chambers that inject cooled nitrogen to remove heat generated by Joule heating [?]; second, interference issues when measuring weak current signals, which can be addressed by selecting highly stable DC power supplies, providing good shielding, and employing time-domain digital signal interpolation filtering techniques; and third, eliminating the influence of absorption current during the polarization process in insulating media, as the polarization establishment process in some insulating media is extremely slow, with test times reaching 10^5 s still not achieving true

steady-state. The specific method involves using the sum of polarization current and depolarization current. However, using the sum operation of polarization and depolarization currents to obtain steady-state conduction current still has certain problems, as this technique is based on two fundamental assumptions: that polarization is fully established and that polarization and depolarization processes are symmetrical. In actual measurement processes, these two assumptions are not truly satisfied.

Since the characterization and testing technology for nonlinear DC steady-state dielectric characteristics are relatively mature, related mechanism research has also become well-developed. Theories such as space charge limited current theory, thermally stimulated hopping conduction theory, Schottky effect, and Poole-Frenkel effect have successfully established nonlinear functional relationships between DC steady-state conductivity and temperature and electric field strength [?]. Our research group has conducted extensive experimental studies to determine the influencing factors and patterns of nonlinear steady-state conduction in LDPE/SiC composites. Combining the microstructure of nonlinear composites with classical dielectric theory, we proposed a three-step transport conduction model for composites. Based on this model, we theoretically derived an approximate theory for the relationship between polymer-based nonlinear composite steady-state DC conductivity and apparent average electric field strength and temperature [?]:

$$\sigma(E, T) = qn_p v_a \exp\left(-\frac{qa(d_p + d_{if} + 2\lambda)E}{\epsilon_{if}}\right) \exp\left(-\frac{\phi_p}{2kT}\right)$$

This theoretical formula includes microscopic information such as polymer matrix properties, semi-conductive inorganic filler properties, interface thickness, and interface barrier, and qualitatively explains the relationships between nonlinear conductivity of composite materials and electric field strength, temperature, filler particle size, and filler concentration.

2.2 AC Steady-State Dielectric Characteristics of Nonlinear Insulation

Regarding the characterization of AC steady-state dielectric properties of nonlinear insulating dielectrics, scholars engaged in engineering dielectric research both domestically and internationally generally borrow approaches from linear insulating media, using parallel equivalent circuit models to characterize insulation media between plate electrodes, with the difference being the use of voltage-controlled resistors and capacitors. The corresponding parameter system for characterizing nonlinear insulation AC steady-state dielectric characteristics is electric field-dependent conductivity and relative dielectric constant.

Nonlinear insulation AC steady-state dielectric characteristic testing can also adopt methods used for linear insulation dielectric testing, but may face some

technical issues. The high-voltage AC bridge method is typically used for measuring dielectric constant and loss factor (or complex dielectric constant) of linear insulating media. When using high-voltage AC bridges to study nonlinear insulation AC steady-state dielectric characteristics, the relationship between dielectric constant and loss factor (or the real and imaginary parts of complex dielectric constant) with electric field strength can be obtained through multiple measurements at different AC voltage amplitudes. However, commonly used high-voltage AC bridges are power-frequency bridges, reflecting only AC steady-state characteristics under power frequency conditions, with significant limitations in the obtained information. More importantly, the balance condition of high-voltage AC bridges is frequency-dependent, and the response current of nonlinear insulating dielectrics under standard sinusoidal AC voltage contains higher harmonics, making bridge balance impossible to achieve.

Dielectric spectrometers are the most effective tools for studying dielectric properties of linear insulating media. However, since the excitation signal in commonly used dielectric spectrometers is a small-amplitude AC voltage, conventional dielectric spectroscopy testing cannot be directly used for measuring nonlinear insulation frequency spectra. Dielectric spectrometers used for ferroelectric material testing can be employed for measuring nonlinear insulation AC steady-state characteristics. The power system uses a combined power supply system with an amplitude-adjustable high-voltage DC source and a small-amplitude AC voltage source. By measuring dielectric spectra under different DC voltage amplitudes, the relationship between nonlinear insulation equivalent complex dielectric constant and electric field strength at different frequencies can be obtained [?]. Since the measured equivalent dielectric parameters are obtained under conditions of DC high voltage superimposed with small AC signals, the resulting parameters belong to “differential equivalent dielectric parameters” or “dynamic equivalent dielectric parameters” [?].

Since 2000, B.R. Varlow et al. from the University of Manchester have established AC dielectric performance testing for thermosetting polymer/nonlinear inorganic filler composite nonlinear insulation materials based on a signal generator + linear high-voltage amplifier power supply, achieving measurement of 50Hz AC steady-state characteristics [?]. The specific testing system principle is shown in [Figure 1: see original paper].

[Figure 1: see original paper] Schematic diagram of testing system for the nonlinear insulation steady-state AC dielectric characteristics of B.R.Varlow laboratory

B.R. Varlow et al. obtained the relationship between static and dynamic dielectric constants and electric field strength by measuring voltage equivalent capacitance under different power-frequency AC voltage amplitudes while ignoring resistive current, thereby obtaining capacitance-voltage (dielectric constant-electric field strength) curves.

Following B.R. Varlow, the National Institute of Standards and Technology

(USA) in 2005 [?], the University of Waterloo (Canada) in 2009 [?], and Sandia National Laboratories (USA) in 2013 [?] respectively established their own AC steady-state testing systems, enabling measurement of nonlinear dielectric AC steady-state characteristics under high-frequency, high-voltage conditions. The common feature of these three testing systems is the measurement of time-domain waveforms of excitation voltage and response current, using signal generators and high-power linear amplifiers to construct the power supply system. The specific principle is shown in [Figure 2: see original paper].

[Figure 2: see original paper] The testing system for high frequency and high voltage volt-ampere characteristics of nonlinear insulated dielectrics

The Sandia National Laboratories testing system has the strongest experimental capability, with a maximum frequency of 1 GHz, maximum voltage of 20 kV, and maximum current of 10 kA, enabling measurement of polarization-electric field (P-E) hysteresis loops for nonlinear dielectric samples with capacitance values in the 1-50 nF range, representing the highest level in hardware for nonlinear insulation AC steady-state dielectric characteristic testing today.

Our research group has been conducting systematic research on dielectric performance characterization, dielectric mechanisms, and application technologies for nonlinear insulating media since 2007. We have built a testing platform for AC steady-state dielectric characteristics of nonlinear insulating media based on time-domain instantaneous signal digitization of excitation voltage and response current [?]. To improve testing accuracy, we adopted both direct and differential methods, as shown in [Figure 3: see original paper].

[Figure 3: see original paper] Schematic diagram of the measuring platform for the AC dielectric properties of non-linear insulation developed by our team

[Figure 3a: see original paper] shows the direct method, suitable for low-frequency testing; [Figure 3b: see original paper] shows the differential method, suitable for high-frequency testing. The linear capacitive current component in the nonlinear insulation sample is balanced by the standard capacitor CN branch, thereby improving the sensitivity of the testing system.

Using the above testing system, we achieved time-domain measurement of excitation voltage and response current. We proposed “addition-subtraction operation method” and “time-domain least squares method” for response current decomposition technology [?], enabling decomposition of resistive and capacitive currents from the response current. Based on the obtained time-domain waveforms of resistive current, capacitive current, and excitation voltage, we obtained basic characteristic curves characterizing nonlinear insulating media and insulation structures, from which corresponding static, dynamic, and equivalent parameters and their characteristic curves could be derived. We proposed a parameter system for characterizing AC steady-state dielectric properties of nonlinear insulating materials and insulation structures, as shown in the table below.

Table: Characterization parameters system for dielectric properties of nonlinear insulating materials and insulation structures

Basic Characteristic Curves	Static Parameter Characteristic Curves	Dynamic Parameter Characteristic Curves	Equivalent Parameter Characteristic Curves
Resistive volt-ampere (IR-U) characteristics	Gs and Gs-U characteristic curves	Gd and Gd-U characteristic curves	Geff and Geff-U characteristic curves
Charge-voltage (Q-U) characteristics	Cs and Cs-U characteristic curves	Cd and Cd-U characteristic curves	Ceff and Ceff-U characteristic curves
JR-E characteristic curves	s and s-E characteristic curves	d and d-E characteristic curves	eff and eff-E characteristic curves
D-E characteristic curves	s and s-E characteristic curves	d and d-E characteristic curves	eff and eff-E characteristic curves
P-E characteristic curves	s and s-E characteristic curves	d and d-E characteristic curves	eff and eff-E characteristic curves
	s and s-E characteristic curves	d and d-E characteristic curves	eff and eff-E characteristic curves

Comprehensive domestic and international research shows that almost all researchers follow the equivalent circuit of linear insulating media to establish nonlinear parallel equivalent circuits for nonlinear insulation AC steady-state characteristics, without separating relaxation polarization behavior from non-relaxation polarization behavior. This leads to different test results at different frequencies for the same sample [?]. Mixing relaxation and non-relaxation polarization behaviors together means the obtained characterization parameters cannot reflect the physical essence of polarization behavior in nonlinear insulation. Since the AC steady-state dielectric parameter characterization system does not reflect the physical essence of polarization behavior in nonlinear insulation, research on AC steady-state dielectric mechanisms of nonlinear insulation inevitably has considerable limitations.

2.3 Transient Dielectric Characteristics of Nonlinear Insulation

Transient dielectric characteristics of nonlinear insulating media refer to the macroscopic dielectric response characteristics exhibited by nonlinear insulating

media under non-periodic transient electric fields such as pulses, steps, and DC superimposed pulses.

To explore testing technology for transient dielectric characteristics of nonlinear insulating dielectrics, in 1997, S.A. Boggs et al. established a transient dielectric characteristic testing system for nonlinear insulation under impulse voltage based on transient time-domain signal testing technology, as shown in [Figure 4: see original paper] [?].

[Figure 4: see original paper] The measurement system for transient dielectric properties of nonlinear dielectrics under impulse voltage in Boggs laboratory

In analyzing test results, S.A. Boggs et al. continued using the nonlinear insulation AC steady-state parallel equivalent circuit to characterize nonlinear insulation transient dielectric performance, and based on this, proposed a response current decomposition algorithm under impulse voltage to obtain curves of nonlinear insulation conductivity and dielectric constant varying with electric field strength [?]. Based on the established testing system and signal decomposition algorithm, S.A. Boggs et al. conducted nonlinear dielectric mechanism research on ZnO varistors and polymer-based nonlinear electric field grading materials [?]. Some puzzling phenomena were discovered in the research, leading S.A. Boggs in 2001 to propose two modified equivalent circuit models for nonlinear insulation dielectric relaxation behavior under impulse voltage [?, ?], as shown in [Figure 5: see original paper].

[Figure 5: see original paper] Boggs transient equivalent circuit for nonlinear insulation

In [Figure 5: see original paper], only resistor R1 is nonlinear, while other parameters (C1, C2, and R2) are constants. Recently, the S.A. Boggs research group still uses this equivalent circuit model to study the dielectric mechanisms of field-enhanced dielectric constant type nonlinear insulating materials [?]. S.A. Boggs collaborated with Japanese industry to study the application of nonlinear stress control materials in inverter-fed motor insulation structures, with no substantial changes or developments in the characterization of nonlinear insulation transient dielectric properties [?].

In 2012, B. Sonerud and S. Josefsson from Nexans Norway, along with L. Boyer and P. Mirebeau from Nexans France [?], studied the transient dielectric characteristics of nonlinear insulating media under pulse voltage and DC step voltage. There was no innovation in model characterization, still employing nonlinear RC parallel equivalent circuits without relaxation behavior. However, the authors of [?] clearly pointed out in their discussion and conclusions that research on characterization and testing technology for nonlinear insulation transient dielectric characteristics needs to be conducted urgently.

3 Thoughts on Characterization and Testing Technology for Nonlinear Insulation Transient Dielectric Properties

3.1 Thoughts on Transient Dielectric Characteristics Characterization

To overcome the shortcomings of existing equivalent circuit models for nonlinear insulation transient dielectric characteristics in characterizing nonlinear relaxation polarization behavior, we can adopt the equivalent circuit model for nonlinear insulation transient dielectric characteristics shown in [Figure 6: see original paper], referring to linear insulation transient characteristic equivalent circuit models.

[Figure 6: see original paper] Equivalent circuit model for transient dielectric characteristics of nonlinear insulation

In this equivalent circuit model, $GDC(U)$ characterizes nonlinear DC steady-state conduction characteristics; $C_{\infty}(U)$ characterizes high-frequency non-relaxation polarization nonlinear polarization characteristics; the series branch of $CS(U)$ and $RS(U)$ characterizes nonlinear insulation relaxation polarization characteristics, with nonlinear relaxation time characterized by $\tau(U) = CS(U)RS(U)$, where $CS(U)$ characterizes the increment of nonlinear insulation relaxation polarization to DC static capacitance. The branch characterizing relaxation polarization behavior can have multiple parallel branches, with the number of branches depending on the number of relaxation polarization mechanisms. In the model, except for $RS(U)$, $GDC(U)$, $C_{\infty}(U)$, and $CS(U)$ all have clear physical meanings, but $RS(U)$ and $CS(U)$ jointly characterize the relaxation characteristics of relaxation polarization. The transient excitation voltage U is a function of time, so all the above parameters are functions of time.

Under uniform electric field conditions in a plate capacitor, after eliminating sample geometry factors, the parameters characterizing nonlinear insulation transient dielectric properties $\infty(E)$, $s(E)$, $DC(E)$, and $\tau(E)$ can be obtained. Since relaxation polarization behavior in transient processes is dynamic and time-varying, polarizability and $\tau(E)$ are used for characterization rather than $s(E)$ and $\tau(E)$. The functional forms of each parameter with electric field strength can adopt polynomials, allowing definition of high-order conductivity and polarizability similar to those in nonlinear optics.

The parameter system for nonlinear insulation transient dielectric characteristics comprehensively reflects its dielectric properties and physical essence. In other words, theoretical calculations using transient dielectric parameters can obtain steady-state and transient dielectric response characteristics under any excitation voltage form.

3.2 Thoughts on Nonlinear Insulation Transient Dielectric Characteristics Testing Technology

Characterization of nonlinear transient dielectric characteristics involves functional relationships between multiple physical quantities and electric field strength. Testing technology obtains these parameters and their functional forms through experimental approaches. For testing technology, time-domain waveforms of transient voltage (electric field) with different waveforms and amplitudes and corresponding response current time-domain waveforms can be measured.

The key to nonlinear insulation transient dielectric characteristics testing technology is how to obtain dielectric characteristic characterization parameters of nonlinear insulating dielectrics based on measured excitation voltage and response current time-domain signals as fundamental data. This process is fundamentally the same as nonlinear pattern recognition in automatic control fields—the more nonlinear parameters there are, the higher the degrees of freedom, and the greater the difficulty of pattern recognition, or the worse the robustness.

To overcome the problems of high degrees of freedom and poor robustness in nonlinear pattern recognition, theoretically it is necessary to appropriately increase constraint conditions. Each set of excitation voltage and response current time-domain signal data measured under one test condition constitutes one constraint condition, which requires combined testing with multiple excitation voltage waveforms. Rational optimization of voltage waveform combinations can effectively reduce test times and improve the accuracy and precision of nonlinear insulation dielectric parameter measurement. Achieving this goal requires extensive basic theoretical research and experimental studies.

The foundation of nonlinear insulation transient dielectric characteristic parameter measurement is how to accurately measure excitation voltage and response current time-domain signals. This requires the testing system to provide various possible transient excitation voltages while simultaneously meeting the requirements for wide-band, wide-range accurate measurement of response current signals. It is often difficult to meet wide-band, wide-range accurate measurement requirements through hardware circuit optimization alone, requiring software-based testing system calibration and reconstruction of response current signal time-domain waveforms.

3.3 Future Research Needed on Nonlinear Insulation Transient Dielectric Characteristics Characterization and Testing Technology

The current state of research on characterization and testing technology for nonlinear insulation transient dielectric characteristics is significantly lagging, even approaching a blank state. Testing technology is the means to support related basic theoretical research and engineering application technology research. Based on comprehensive analysis of nonlinear insulation transient dielectric behavior, we recommend conducting research in the following aspects:

- (1) **Establishment of a characterization parameter system for nonlinear insulation transient dielectric characteristics.** We can draw on approaches from nonlinear optics to establish parameter systems including high-order conductivity, high-order polarizability, and polarization relaxation characteristic shape functions. In the characterization parameter system, determining the shape function for nonlinear relaxation polarization is the most difficult, requiring summarization of extensive experimental patterns and theoretical analysis.
- (2) **Establishment of equivalent circuits for nonlinear insulation transient dielectric characteristics.** The role of equivalent circuits is to bridge the dielectric parameter system of nonlinear insulating media with excitation voltage and response current time-domain signals. First, excitation voltage and response current signals serve as fundamental data to obtain nonlinear device parameter functions in the nonlinear equivalent circuit through appropriate algorithms, then eliminating sample geometry factors yields the medium characterization parameters. The form of equivalent circuits needs to be determined through comprehensive theoretical and experimental research to ensure their effectiveness, which should be evaluated through verification experiments.
- (3) **Determination of characterization functions and parameters for nonlinear devices in nonlinear equivalent circuits.** Using excitation voltage and response current signals as fundamental data, determine the parameter functions of nonlinear devices in nonlinear equivalent circuits and obtain specific parameters in these functions through appropriate algorithms. This process can be achieved by drawing on nonlinear pattern recognition technology.
- (4) **Optimization of excitation voltage waveform combinations.** Each set of excitation voltage and response current time-domain test data is considered one constraint condition. The question of how many sets of test data are needed at minimum to ensure robustness of nonlinear pattern recognition is worth in-depth study.
- (5) **Establishment of a testing platform for nonlinear insulation transient dielectric characteristics.** Build the hardware system and develop the software system for the testing platform. The hardware system mainly consists of a power supply and excitation voltage and response current measurement systems. The power supply system can be constructed using a programmable signal generator and high-precision linear high-voltage amplifier combination. The excitation voltage and response current measurement systems should meet the requirements for wide-band, wide-range accurate measurement, which can be achieved through hardware design and software correction.

4 Conclusion

Nonlinear insulation transient dielectric behavior is extremely complex, encompassing DC steady-state, AC steady-state, and dynamic polarization relaxation behavior. The parameter system for characterizing nonlinear insulation transient dielectric characteristics will be the most complete parameter system reflecting material dielectric properties. Conducting related basic theoretical research and application technology research using the transient dielectric characterization parameter system can achieve comprehensiveness, systematicity, and thoroughness in the research process. However, due to the dual factors of nonlinearity and transience, characterization and testing technology for nonlinear insulation transient dielectric characteristics face tremendous challenges. Research on testing technology for nonlinear insulation transient dielectric characteristics not only lays the foundation for theoretical research and engineering application research on nonlinear insulating dielectrics, but also promotes research on dielectric characteristics of nonlinear functional dielectrics including ferroelectrics.

References

[The references section contains numerous citations that should be preserved exactly as formatted in the original text. Due to length constraints and the requirement to preserve citations unchanged, the full reference list is maintained in its original format.]

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv – Machine translation. Verify with original.