IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 18 October 2022, accepted 3 November 2022, date of publication 17 November 2022, date of current version 23 November 2022.

Digital Object Identifier 10.1109/ACCESS.2022.3222860

TOPICAL REVIEW

A Review: Application of Terahertz Nondestructive Testing Technology in Electrical Insulation Materials

CHENJUN GUO[1], WENLONG XU[2], MINGMING CAI[2], SHUFAN DUAN[2], JIANBIAO FU[2], AND XINLONG ZHANG[2]
[1]Electric Power Research Institute, Kunming 650217, China
[2]State Key Laboratory of Power Transmission Equipment and System Security and New Technology, Chongqing 400044, China

Corresponding author: Xinlong Zhang (zxlcqu@cqu.edu.cn)

This work was supported by the National Natural Science Foundation of China under Grant 52077013.

ABSTRACT As the voltage level of the grid continuously rises, more and more new insulating materials with better performance are put into use. Nevertheless, air gaps often appear in insulating materials due to poor material quality, structural design flaws, etc. High-field-strength air gaps will produce partial discharge or even breakdown, resultingss in electrical equipment failure. In addition, during operation, organic insulating materials are simultaneously exposed to high temperatures, mechanical stress, electrical stress, and moisture. Consequently, aging is inevitable. The aging of insulation materials is the root cause of the reduced insulation properties of the degradation of the insulation properties of electrical equipment in long-term operation. In order to improve the safety performance of power equipment and assure the safety of power grids, the detection and identification of internal structural defects and aging states of insulating materials have always been hot issues in related fields. However, structural defects inside the insulation materials used in power equipment, which are tiny (microns to millimeters), are exceedingly challenging to detect. While there are various destructive methods for detecting the aging status, non-destructive in-line inspection methods are still less commonly reported. In recent years, some scholars have begun to try to use terahertz spectroscopy to detect insulating materials. Numerous scholars have discovered that terahertz spectroscopy can not only detect structural defects inside insulating materials but can also detect non-destructive testing on the degree of material aging and even the type of material, which has excellent engineering value and promotion prospects. In order to help relevant researchers understand the application of this emerging technology in the field of insulating materials, this paper reviews the basic principles of terahertz detection and its applications in air gap detection, moisture detection, and aging analysis of insulating materials. Existing problems and future development directions are discussed.

INDEX TERMS Aging, gap defects, moisture content, species identification, terahertz nondestructive testing.

I. INTRODUCTION

As the voltage level continues to increase, the power grid has ever-increasing requirements for the insulating performance and reliability of power equipment. Silicone rubber, epoxy resin, XLPE (cross-linked polyethylene), and other organic materials are widely utilized in high-voltage power equipment due to their superior insulating qualities and wide availability of raw ingredients [1]. These pieces of equipment include composite insulators, insulating paperboards, XLPE insulated cables, etc., as shown in Figure 1. However, due to the material's quality, the manufacturing process, and the influence of the electric field, temperature, and moisture that may be encountered during operation, air gaps may occur within the organic insulating material, and material properties also decline due to aging [2], [3], [4], [5], [6], [7]. Because of

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

the concentrated electric field at the air gap and the air gap's poor dielectric strength, it is quite likely that the internal air gap will produce partial discharge, accelerate the aging of the material, and eventually cause the breakdown of the material [8], [9], [10], [11], [12]. In addition, as the material ages, its insulating properties, mechanical properties, and thermal properties decrease to varying degrees, resulting in electrical failure, mechanical failure, and overheating failure of the equipment after a long-term operation, which poses a significant threat to the normal operation of the power system. Therefore, material properties are the core factors in the long-term safety of equipment operation and the dependability of power grid operation [13], [14], [15], [16], [17].

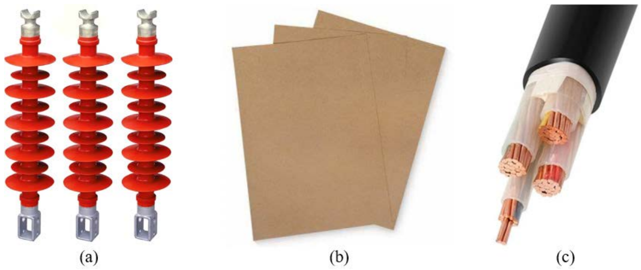


FIGURE 1. Application of organic insulating materials in High Voltage Equipment. (a) Composite insulators; (b) Insulating paperboard; (c) XLPE Insulated Cables.

Power system researchers have long placed a premium on non-destructive testing since it may rapidly and online detect internal flaws in materials and prevent catastrophic breakdowns caused by the continued operation of equipment with flaws. For non-destructive testing of insulating materials, researchers have recently proposed new technologies such as infrared thermal imaging detection technology, microwave detection technology, terahertz time-domain spectroscopy (THz-TDS) detection technology, nonlinear ultrasonic detection technology, and computed tomography (CT) detection technology [18], [19], [20], [21], [22]. The advantages and disadvantages of each nondestructive testing (NDT) technique are shown in Table 1. Terahertz spectrum detection technology is the only one that can detect moisture content and insulating materials in an aging state, as well as non-destructive identification of aging types. It significantly enhances the connotation of non-destructive testing in the sphere of electric power and has significant engineering and scientific value [23]. The applications of terahertz nondestructive testing technology to insulating materials are shown in Table 2. In addition, Mustafa et al. used Extended Voltage Response (EVR) and dielectric spectroscopy to identify the radiation aging state of the cable, which presented a new method for the study of the aging state of composite materials [24], [25], [26], [27].

This paper describes in detail the mechanism of terahertz time-domain spectroscopy and terahertz imaging technologies. Then, by investigating the classic cases of terahertz time-domain spectroscopy in the power field, the application of terahertz nondestructive testing technology in the detection of gap defects in insulating materials, water content analysis, aging analysis, and kind identification in practical engineering feasibility issues is analyzed. Finally, based on the existing limitations of terahertz time-domain spectroscopy technology, the future development direction of terahertz technology is prospected.

TABLE 1. Advantages and disadvantages of non-destructive testing technologies.

NDT	Advantage	Disadvantage
Infrared thermal imaging technology	Non-contact testing, Intuitive results	Vulnerable to the temperature of the test environment, High cost
Microwave detection	High penetrability, Low cost, Fast detection	Impossible to penetrate metal materials and composite materials with good electrical conductivity
THz-TDS	Fast detection, High precision, High security	Expensive equipment, susceptible to electromagnetic fields and humidity
Nonlinear ultrasonic	Superior detecting precision, Low cost, Fast detection	Contact testing, Unintuitive result
CT	Superior penetrability, intuitive imaging	Expensive apparatus, slow testing

TABLE 2. Applications of terahertz nondestructive testing technology to insulating materials.

Serial number	Application
1	Internal defect detection of organic insulating materials, including air gap defects and foreign body defects
2	Analysis of water content in organic insulating materials and prediction of water absorption of insulating materials
3	Aging Analysis and Type Identification of Insulating Materials

II. THE PRINCIPLE OF TERAHERTZ NONDESTRUCTIVE TESTING TECHNOLOGY

Terahertz radiation and detection are similar to other electromagnetic waves in principle. Still, due to their unique frequency bands, terahertz waves have the characteristics of high penetration, low energy, and transient properties [28], [29], [30]. Terahertz nondestructive testing technology has considerable application potential due to these characteristics. At the moment, terahertz radiation is mostly used for terahertz time-domain spectroscopy and terahertz imaging [31], [32], [33], [34].

The primary components of the terahertz time-domain spectroscopy system are a femtosecond laser, a beam splitter, a photoconductive antenna, a time delay control system, a parabolic mirror, a terahertz (THz) wave detector, and a computer. A femtosecond laser pulse is emitted by a femtosecond laser, and the pulse is split into two perpendicular beams by a beam splitter: a pump beam and a probe beam. Through the reflector and the time delay device, the pump beam is then focused on the substrate surface of the photoconductive antenna, stimulating the THz emitting element to form a THz pulse. A parabolic mirror collimates and focuses the THz pulse on the test sample. The THz pulse carrying sample information transmits through the sample, is collimated and concentrated by a second pair of parabolic mirrors, and collinearly travels through the detector with the probe beam. Finally, the detector transmits this signal to the computer for further data analysis and processing [35]. Thus, significant information about the sample can be acquired, and the measurement signal and the reference signal can be processed using a rapid Fourier transform to obtain the sample's refractive index, absorption coefficient, etc. [36]. When utilizing terahertz to detect composite materials, it is usual practice to extract the important optical parameters of the sample from the transmitted terahertz time domain spectrum. When the terahertz pulse is vertically incident on a non-polar material with a uniform thickness, the refractive index of air is taken as 1, and assuming that the material thickness is large, the reflected echo can be ignored. Terahertz transmission function to the material can be expressed as [37]

$$H(\omega) = 4n_s\big/(n_s+1)\cdot\exp\left[-i(n_s-1)\cdot\omega l\big/c\right] \cdot\exp\left[-K_s\cdot\omega l\big/c\right] \quad (1)$$

Two different parameters n_s and K_s are extracted from formula (1), as follows:

$$n_s = -c\big/\omega L\left\{\arg\left[H(\omega)\right] - \arg\left[4n_s\big/(n_s+1)\right]\right\} + 1 \quad (2)$$

Taking the logarithm of both sides of the formula (2) yields:

$$K_s = -c\big/\omega L\left\{\ln\left|H(\omega)\right| - \ln\left|4n_s\big/(n_s+1)\right|\right\} \quad (3)$$

In formulas (1)-(3): L—thickness of the material; n_s—complex refractive index of the material; K_S—the extinction coefficient; the speed of light c is a constant (3.0 × 108 m/s). The difference between polar objects and non-electric polar objects lies in the complex refractive index n_s. Since the attenuation of terahertz waves in polar objects is more significant, the size of the complex refractive index n_s is affected. Through the foregoing calculation procedure, the complex refractive index n_s and the extinction coefficient K_s may be derived, i.e., by realizing the use of terahertz to analyze and study the material to be tested, extract the distinctive parameters, and acquire the material's characteristics. The approach offers a high detection signal-to-noise ratio, a broad detection bandwidth, and a high detection sensitivity, and it is applicable to widely used in the detection of diverse samples.

Terahertz imaging technology combines terahertz time-domain spectroscopy with a two-dimensional scanning procedure to acquire terahertz picture data by scanning the terahertz time-domain signal of each pixel point by point [38], [39]. Figure 2 shows the principle of terahertz time-domain spectrum imaging. Existing mainstream terahertz imaging techniques include continuous wave imaging, real-time imaging, tomography, near-field imaging, and pulsed wave imaging. Common methods for detecting tiny defects inside electrical equipment using terahertz imaging technology include continuous wave imaging and pulse wave imaging [40].

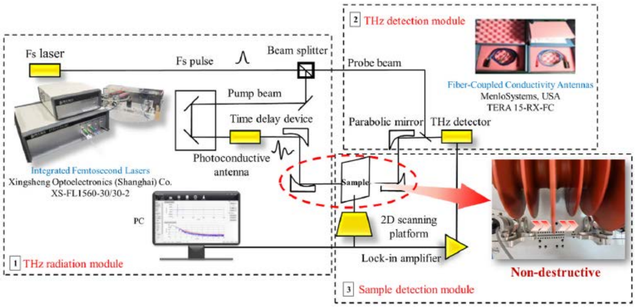


FIGURE 2. Terahertz imaging principle [39].

Terahertz continuous wave imaging is a point-by-point scanning method of imaging by recording the intensity information of successive terahertz waves through the sample or after reflection. Since the intensity information is collected, pausing at each scanning point is not necessary. At the same time, due to the large beam aperture, the scanning is significant, but the imaging resolution is relatively low, at the millimetre level.

THz-TDS is the most prevalent pulsed terahertz imaging technology. That is, single-point detection is performed on the sample by generating terahertz pulses via photoconductive or optical rectification, and then multi-point detection forms a two-dimensional matrix point with transmitted or reflected wave information. The principles of imaging have two methods: time-domain signal imaging and frequency-domain signal imaging. Among them, time-domain signal imaging is imaged because the reflected wave carries information such as phase, amplitude, etc. By processing the peak value, average signal intensity, and phase information of the time-domain signal, a two-dimensional image of the sample can be obtained. Frequency domain signal imaging is to perform a fast Fourier transform on the terahertz spectrogram to obtain frequency domain information, and then uses the spectral peaks of the collected frequency domain signals and information such as the frequency corresponding to the peaks to process data to obtain a two-dimensional image [41].

The terahertz pulse is shown in Figure 2, t_1 is the time interval of all zero crosses, t_2 is the time interval of positive and negative peaks, and both E_1 and E_2 are peaks. When a terahertz wave propagates in an insulating material, the zero crosspoints and peak value of the waveform will vary, which corresponds to the phase and amplitude of the wave. When extended to the frequency domain, these appear as spectral peaks and peak frequencies. By controlling the two-dimensional scanning stage, the moving sample is scanned, and the intensity and phase of the signal are extracted according to the analyzed frequency domain and time domain characteristic parameters. The feature parameter extracted each time is used as an imaging point, and its gray value is set [42]. Finally, a terahertz image is formed. Terahertz pulse imaging has a higher resolution than terahertz continuous wave imaging.

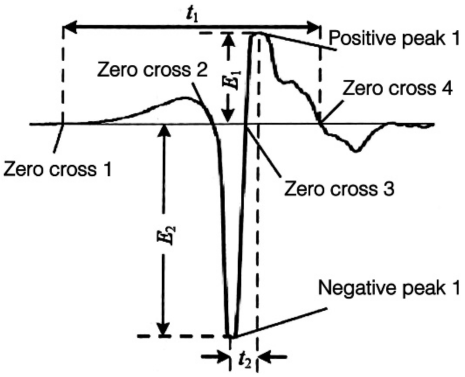


FIGURE 3. Terahertz pulse [42].

The above-mentioned terahertz testing technology provides distinct advantages over other non-destructive testing methods for finding interior defects in non-metallic materials. Terahertz inspection is not only easier to operate than conventional ultrasonic inspection, but it can also achieve imaging without touching the object's surface. And in some materials, sound waves are extremely attenuated, but terahertz waves are suitable for these materials. Compared to X-ray digital imaging technology, terahertz spectroscopy technology is safer, which causes no pathological reactions in the human body and has exceptionally little radiation damage. Passive infrared thermal imaging technology detects internal defects by capturing abnormal surface temperatures caused by partial discharges. However, the discharge voltage and intensity of partial discharges have no clear relationship with defect size and structure and surface temperature. Therefore, the technique is unable to obtain the size and structure of the defect. Compared to infrared thermal imaging detection technology, terahertz imaging technology can picture the internal flaws of equipment and materials with greater reliability and interference resistance. In comparison to microwaves, it compensates for the latter's poor ability to penetrate dielectric materials and can only be used for near-field detection.

III. INTERNAL GAP DEFECTS IN ORGANIC INSULATING MATERIALS

In the process of power system operation, the performance of insulating materials has a great impact on the operation of the overall power equipment and power system. Due to the preparation process and the influence of electrical, thermal, mechanical forces and other factors, insulating materials will produce defects or foreign matters in their interior, which will affect the electrical performance. Long-term operations may lose insulation capacity and cause economic and security losses. Therefore, a reliable nondestructive testing method for insulating material defects is very necessary. Common nondestructive testing techniques include the penetration method, ultrasonic method, eddy current method, X-ray method, and magnetic particle method. However, these traditional methods have their limitations in use. The penetrant method must be cleaned before detection, and the penetrant oil and developer used in the test are contaminated. When using the ultrasonic testing method, a coupling agent is required, and different probes are required for different defects. The eddy current method can only detect the surface and near-surface defects of conductive materials and can also identify the edge effect caused by the sudden change of part geometry. The cost of experimental equipment required by the X-ray method is large, and the experimental process is harmful to human body. The carbon powder method is only applicable to the detection of ferromagnetic materials, and has a small scope of application [43]. Compared with traditional methods, Terahertz spectroscopy technology is a new visual detection method that has the characteristics of high security, strong anti-interference ability, a wide application range, and can be applied to non-metallic media. Compared with traditional nondestructive testing methods, it has unique advantages. Therefore, it is suitable for defect detection of insulating materials [44].

A. AIR-GAP DEFECTS

Due to the thermal expansion and contraction effects, mechanical force, manufacturing process level, and other factors of insulating materials during operation, air gaps or internal cracks will be produced, which belong to common air gap defects. The refractive index of the terahertz wave will change in the insulating medium of air gaps or cracks, resulting in transmission and reflection changes. The amplitude and phase information of the wave will also change. Therefore, terahertz waves can be used to detect air gaps or cracks in insulating materials.

Wang et al. used the terahertz time-domain system to emit pulsed electromagnetic waves to test insulator models, which have different interface defects. They find that there is a significant difference in the position of the wave crest between defects and non-defects. It is proved that terahertz waves can be used to detect interface micro defects, and defects with thicknesses less than 1 mm can be identified. The methods include transmission detection and reflection detection. Transmission detection is judged by the position and amplitude of the peak, while reflection detection is judged by the peak. For actual composite insulators, the reflection method is more suitable for detection [45]. Cheng et al. used a reflective terahertz time-domain spectroscopy system to test composite insulator samples with artificial holes. By analyzing the amplitude and time delay of the time domain waveform, the 0.4 mm deep defect can be accurately located, and the minimum defect size that can be detected is 1.5 mm, with an error of less than 3%. When there are small defects in the composite insulator, there is a new reflection peak with a large amplitude in the terahertz waveform, and its position is determined by the thickness of silicone rubber [46]. Figure 3 shows the THz analysis result of the sample with artificial defects. Zhang et al. used terahertz time-domain spectroscopy to study the terahertz spectral characteristics of room temperature and high temperature cured epoxy resins. The former basically contains no bubbles, while the latter contains trace bubbles. Calculating the refractive index and absorption coefficient of the sample in the frequency band of 0.1∼1.5thz, the average refractive index of the former is about 1.7, which is higher than that of the latter about 1.65. And in both samples, the absorption coefficient is positively related to the frequency, there is no obvious absorption peak, and the absorption coefficient of the samples prepared at room temperature is higher [43]. Li et al. established a terahertz transmission model to analyze the terahertz time-domain spectrum of bubble defects in epoxy resin coating samples. The model can not only qualitatively distinguish whether there is a bubble stripping layer in the coating, but also quantitatively estimate its thickness and size. Bubble defects with a cross-section diameter of 3.5∼8 mm and a thickness greater than 0.6 mm can be detected [47].

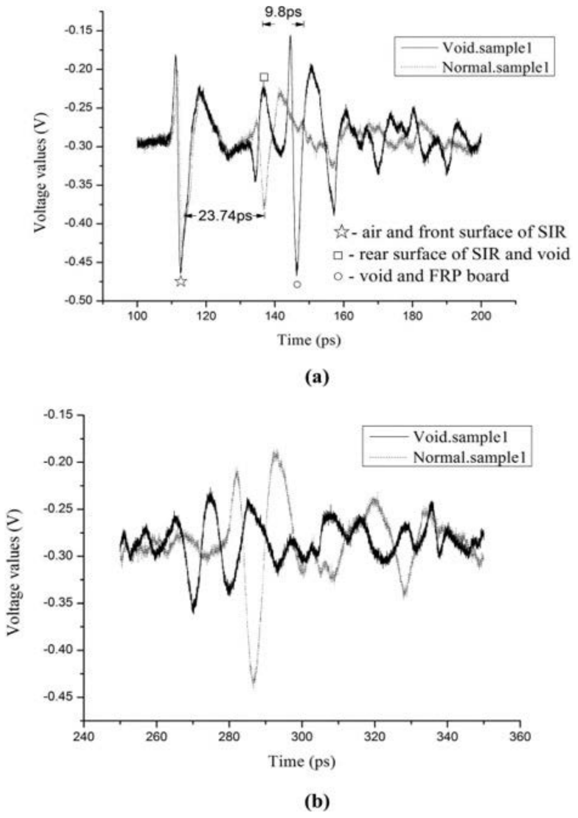


FIGURE 4. THz time-domain waveform results of sample with artificial defects. (a) 100–200 ps waveform; (b) 250–350 ps waveform [41].

In order to improve the imaging quality of terahertz detection technology, many scholars have studied it. Mei et al. based on the traditional terahertz detection method, used the time domain deconvolution method to process the terahertz waveform and reduce the overlap of reflected pulses, they successfully distinguish 0.173 mm air gap defects from insulating materials with double air gap defects [48]. The three characteristic parameters of maximum absolute value, signal power and envelope area can be used to identify double-layer defects with depths of 0.4 mm and 0.83 mm respectively. The imaging of the signal power and envelope area has advantages in defect morphology recognition and resolution [49]. The experiment expands the application scene and accuracy of terahertz time-domain spectroscopy. Zhang et al. proposed an imaging detection method based on waveform difference for corrosion defects. According to the characteristic information of terahertz waveform, the interface air gap and erosion defects are classified and diagnosed [42]. Jiang et al. used principal component analysis technology to fuse and image terahertz characteristic parameters, which improves the imaging performance of terahertz technology on composite insulators and obtains higher quality defect images [50]. The comparison diagram of the fusion imaging effect based on principal component analysis technology is shown in Figure 4.

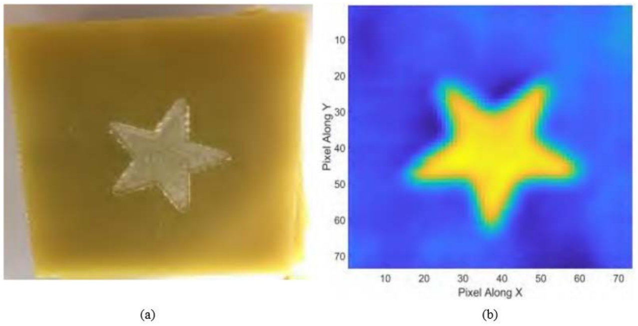


FIGURE 5. Comparison of fusion imaging effect based on principal component analysis technology. (a) Sample with air gap inside; (b) Fusion data imaging result [46].

In addition to utilizing terahertz time-domain spectroscopy to detect internal gap defects in insulating materials and improve imaging quality, researchers have proposed a variety of new terahertz detection methods based on terahertz detection technology. Zhang et al. verified that the superposition of terahertz waves in samples with internal air gap is approximately linear, and provided an internal air gap measurement method based on a waveform database to solve the problem that terahertz waves are difficult to measure the thickness of internal air gap [51]. Lee et al. detected the defects with the size of 0.5 mm in the cross-linked polyethylene plate according to the two-dimensional image of a continuous terahertz wave passing through the cross-linked polyethylene, proving that the continuous terahertz wave imaging system can detect the internal defects of insulating materials with efficient detection [52]. Cao et al. used terahertz time-domain spectroscopy to detect the internal defects of three-phase composite structures. They selected 0.348thz wave to pass through the sample along three mutually perpendicular directions can clearly show the location and geometry of gap defects [53]. A new idea of nondestructive testing of three-phase composites is provided.

B. FOREIGN BODY DEFECT

When the insulating material is polluted by particles and other impurities due to unqualified materials or improper manufacturing processes, it may lead to a decrease in hydrophobicity and the medium is prone to moisture. Partial discharges occur at defective areas, which may eventually form water trees and lose their insulating qualities in the long run. Therefore, it is necessary to detect foreign material defects in insulating materials.

Rheenen et al. prepared epoxy samples doped with graphene powder of different concentrations and measured the conductivity of the samples. The dielectric parameters, especially the absorption coefficient, were measured by terahertz transmission spectrum. It was found that with the increase in graphene concentration, the absorption of terahertz increased and the conductivity also increased [54]. Mori et al. Tested the optical absorption spectrum of epoxy resin nanocomposites containing MgO, SiO_2 and TiO_2 in the frequency range of 0.5∼5THz, and found that when micron level MgO and nano level SiO_2 fillers were added to the epoxy resin, they would absorb a lot, while small absorption occurred in epoxy resin nanocomposites containing TiO_2. As for using terahertz to explore the mechanics of nanocomposites rapidly [55]. Li et al. prepared nanocomposites with different filler contents based on epoxy resin, and studied their dispersion characteristics in the terahertz range. It is found that the dielectric constant of nanocomposites increases with the increase of the content of nanoparticles at 1THz, its dielectric constant shows different variation laws at 1Hz, the fitting damping coefficient has the opposite trend with the filler content, and there is a strong correlation between low-frequency dielectric constant and damping coefficient. Their research shows that terahertz time-domain spectroscopy is conducive to exploring the mechanism of nanocomposites [56]. Mizuuchi et al. used terahertz waves to detect epoxy resin samples with different defects and thicknesses inside: voids, metal fragments, and resin burrs. The image shows that the terahertz reflection intensity varies greatly with the type of defect. The reflection intensity of metal fragments is the highest, followed by voids, and resin burrs are the weakest. The delamination thickness can be estimated from the delay time difference of terahertz wave. It shows that terahertz wave technology can distinguish the defect types of insulating materials [57].

Kong et al. used terahertz time-domain spectroscopy to measure epoxy resin, silicone rubber, ceramics and their mixtures, and obtained the time domain, frequency domain, absorption spectrum and refractive index of the four groups of samples. It is found that these four parameters are significantly different from the samples after adding copper powder. Therefore, terahertz technology can be used to detect whether the solid powder of gas insulated switchgear (GIS) equipment contains metal foreign matters [58]. Li et al. analyzed the time-domain and frequency-domain waveform characteristics of terahertz pulse wave propagating in the insulation paperboard model mixed with metal foreign bodies through terahertz time-domain spectroscopy. It is found that when the thickness of paperboard coating is less than 5mm, the location and size of internal defects can be accurately obtained by using the amplitude and delay characteristics of terahertz time domain signal. Non-destructive testing of inner defects of insulation paperboard is realized effectively [22]. The imaging data diagram of terahertz pulse reflection wave is shown in Figure 5. Zong et al. detected the metal particles in the transformer by terahertz time-domain spectrometer and found that after adding metal particles, the time domain, frequency domain, absorption coefficient and refractive index of transformer oil were significantly different from those in the pure state. The absorption coefficient and refractive index decrease with the increase in copper content. It shows that the time domain, frequency domain, absorption coefficient and refractive index of the terahertz spectrum can effectively judge whether there are metal impurities in transformer oil [59]. The coefficient spectrum and refractive index spectrum of transformer oil with different copper content are shown in Figure 6.

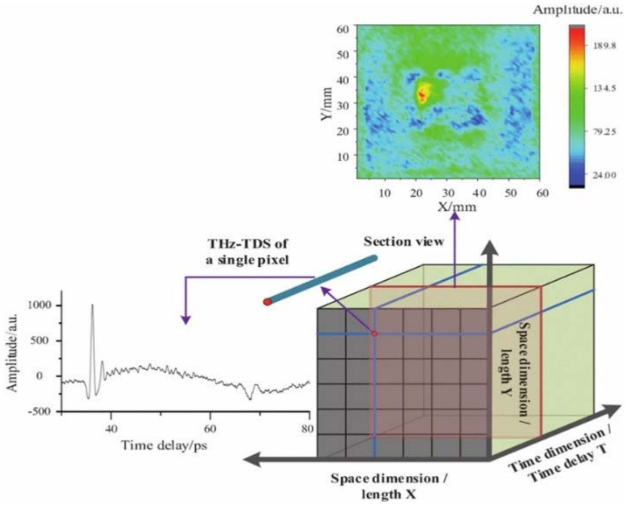
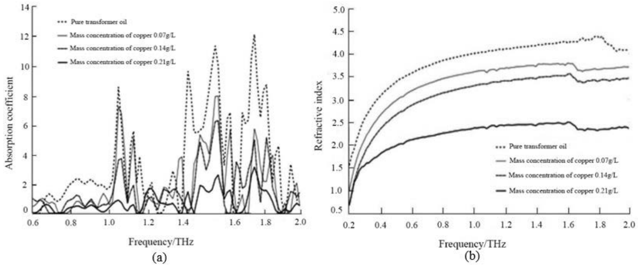


FIGURE 6. Imaging data map of THz pulse reflected wave [54].

IV. ANALYSIS OF MOISTURE CONTENT IN INSULATING MATERIALS

Moisture is an important cause of insulation deterioration of power equipment. Too much moisture will lead to insulation breakdown due to the excessive aging of materials, resulting in immeasurable damage and even harm to the entire power system. Therefore, it is very necessary to detect the moisture content in the material and evaluate and judge its current insulation state. Terahertz spectroscopy is ideally suited for non-destructive testing of insulating materials due to its ability to penetrate most materials without causing damage to



(a)

(b)

FIGURE 7. (a) Absorption spectrum of transformer oil with different copper content; (b) Refractive index spectrum of transformer oil with different copper content [55].

them [60]. Moreover, water molecules have a strong absorption effect in the terahertz frequency band [61], which enables the terahertz spectroscopy technology to precisely analyze the water content in insulating materials so as to find its problems early and prevent serious accidents, thereby improving the economics of equipment and the entire grid.

In general, the detection methods for water content in transformer oil include distillation, Karl Fischer titration, gravimetric, dielectric constant, and other approaches [62]. The disadvantages of the distillation method are time-consuming and imprecise. The Karl Fischer titration is the most common method for measuring the micro water content of transformer oil; this detection method must take into consideration a number of variables, and the chemical reagents used will pollute the environment. The gravimetric approach lacks precision. The dielectric constant method has high requirements for environmental factors [63]. Jiang et al. utilized terahertz spectroscopy technology for the detection of water content in transformer oil and constructed a system that may be employed for this purpose. The fundamental principle is to use optical rectification to generate terahertz waves, free space electrooptical sampling and detection of terahertz waves, terahertz pulses propagating in free space, collimated and focused by two sets of off-axis parabolic mirrors to the terahertz detection source, and the refractive index ellipsoid of the detection source changing [64]. Its phase will be modulated when the probe beam and the terahertz pulse propagate collinearly inside the probe source. By adjusting the position of the optical delay line, the time difference between the two pulses can be altered, and the time domain waveform of the terahertz electric field can be obtained by using the free space electrooptic sampling technique. They use DB-25# oil as the sample and the terahertz time-domain spectrum to determine the absorption coefficient and refractive index of transformer oil with various water concentrations, as illustrated in Figure 7 and Figure 8. It can be seen that the absorption coefficient and refractive index always maintain an upward trend with the increase of moisture content in different frequency bands. The test findings indicate a linear relationship between the absorption coefficient and refractive index of this transformer oil and its water content. The refractive index and absorption coefficient increases progressively as the water content increases. This provides a foundation for further developing terahertz spectroscopy for the detection of water content in transformer oil.

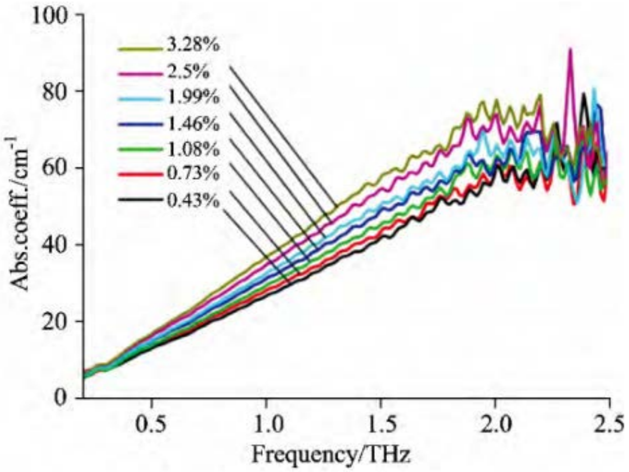


FIGURE 8. Absorption coefficient of DB-25# oil with different water content as a function of frequency [59].

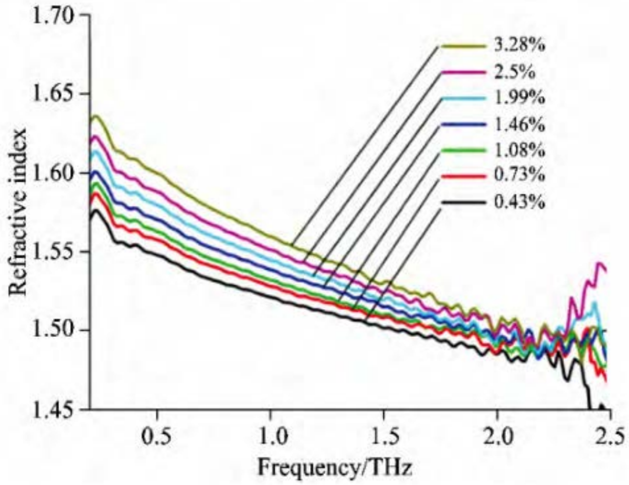
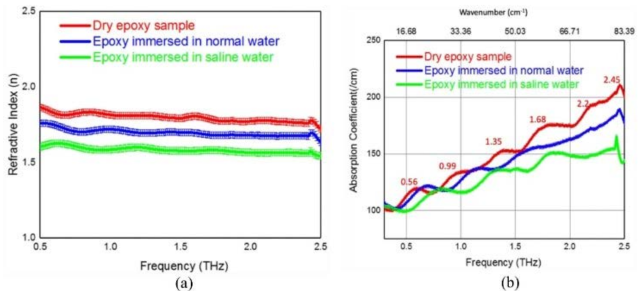


FIGURE 9. Refractive index of DB-25# oil with different water content as a function of frequency [59].

Epoxy resin is widely used in electrical equipment, and the detection of its water content is equally important. Lin et al. conducted a sensitivity analysis to quantify the water absorption of hydrothermally aged epoxy resin systems by terahertz time-domain spectroscopy [65]. They conducted transmission terahertz spectroscopy with a commercial THz-TDS setup (Terapulse 4000, Tera View Ltd., Cambridge, UK) and used a high-resolution sweep mode with 20 waveform averages; each measurement took around 40 seconds. By evaluating the refractive index and absorption index of various aged epoxy resin materials after the incidence of a terahertz wave, the size of their water content may be determined, but with some errors due to the lack of control over water molecules in the atmosphere and room humidity.

Sindhu et al. investigated the differences in epoxy resin's performance under various moisture conditions. In order to avoid the errors of water molecules in the atmosphere and room humidity during sample processing, the device was enclosed in a box made of plexiglass, and nitrogen gas was employed continuously to purge the air's humidity, further ensuring precise findings [66]. The results of the refractive index and absorption coefficient are shown in Figure 9. Evidently, the current research can be used to detect the moisture content in epoxy resins, but additional research is required to determine the precise distribution of moisture in epoxy resins and to develop more intuitive characteristic parameters. Liu et al. created an epoxy resin water absorption prediction model based on Langmuir's law and optimized it using terahertz technology. Epoxy resins that absorb water for 24 hours were examined by THz-TDS, and the experimental results were incorporated into the prediction model to predict the saturation water absorption of epoxy resins and to draw the water absorption curve. The deviation between the prediction curve and the actual water absorption curve was less than 5%. [67]



(a) (b)

FIGURE 10. **(a) Refractive index versus frequency curve of different samples; (b) Absorption coefficient versus frequency curve of different samples [66].**

The same trace moisture contained in the oil-paper insulation system of the transformer will accelerate the aging of oil paper and reduce its insulation properties, which is not conducive to safe and reliable operation [68], [69]. Terahertz spectroscopy can also analyze the moisture content of insulating oil paper. Yin et al. found that as the water content of oil-paper samples increased, so did their absorption of terahertz waves; as a result, the peak of the time-domain energy spectrum after terahertz wave projection would drop, and the peak time would be delayed as the water content increases [35]. The terahertz pulse reaches the detector earlier as the water content lowers. According to this principle, the magnitude of the energy spectrum's peak and the delay time in reaching the peak can be utilized to swiftly identify the micro-water content of oil paper. In addition, as the water content of oil-impregnated paper grows, so does the degree of polarization, resulting in a progressive increase in dielectric loss. The amplitude of its resonance term can indirectly reflect the number and bond energy of cellulose-water hydrogen bonds and water-water hydrogen bonds, characterize the water state and polarization behavior in oil paper, and is positively correlated with the water content of oil paper, so it can also be used as a characteristic quantity to detect the moisture content of oil paper. Cheng et al. also conducted relevant tests and preliminarily estimated the calculation formula for water content [70]. Moisture in the insulating cardboard causes the terahertz transmitted wave to change, which is reflected in the delay of the phase and the attenuation of the amplitude. The moisture content also affects the energy transmittance of the terahertz wave in the sample. The higher the moisture content, the lower the signal energy transmittance and the more delayed the phase. The frequency domain diagram of the test results is shown in Figure 10. The test results prove that this method can accurately reflect the moisture content of the insulating paperboard and its specific distribution within the insulating paperboard and can realize nondestructive testing.

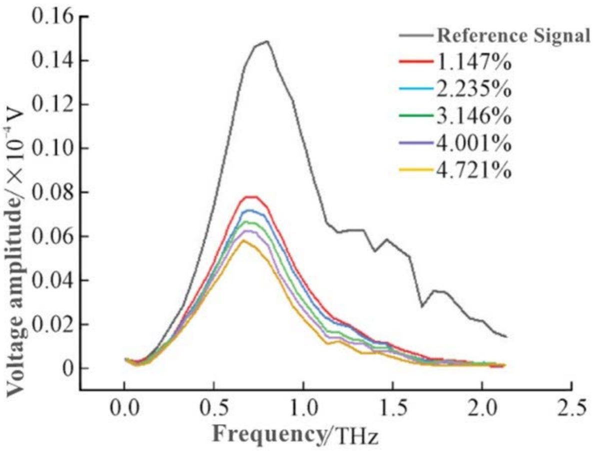


FIGURE 11. **Frequency-domain results of different moisture contents [70].**

Terahertz spectroscopy technology has a wide range of applications in the non-destructive testing of the moisture content of power equipment insulation materials, which is of great importance in the evaluation of power equipment performance. However, the current research in this field still needs further in-depth and application to the actual project.

V. AGING ANALYSIS AND SPECIES IDENTIFICATION

A. AGING ANALYSIS

Due to the long-term operation and the influence of complex working environment, the insulation aging of electrical equipment and its related components is growing in intensity, which leads to the reduction of insulation performance, affects the normal work of power equipment, and causes great hidden dangers and harms to the safety and stability of power grid operation. However, the traditional insulation aging diagnosis method has many limitations, such as it can't find the local insulation aging problem timely and is non-destructive. For maintaining the stability of the power grid, the blind overhaul or replacement strategy is generally adopted across the board, which will cause huge economic losses. Therefore, it is particularly important to study the method of timely, accurate and nondestructive detection of the aging of power equipment and its related components. Figure 11. shows the harms of electrical equipment aging. Because the rotation, vibration and weak interaction energy levels of many molecules (such as hydrogen bonds) are located in the terahertz band (0.1-10THz), THz-TDS can be used to analyze the properties of materials. The absorption spectrum can be obtained by Fourier transform of terahertz signal, and parameters such as absorption coefficient, extinction coefficient, return loss, refractive index, dielectric loss and complex dielectric constant can be obtained by combining with relevant mathematical models, which are used to evaluate the aging degree of materials.

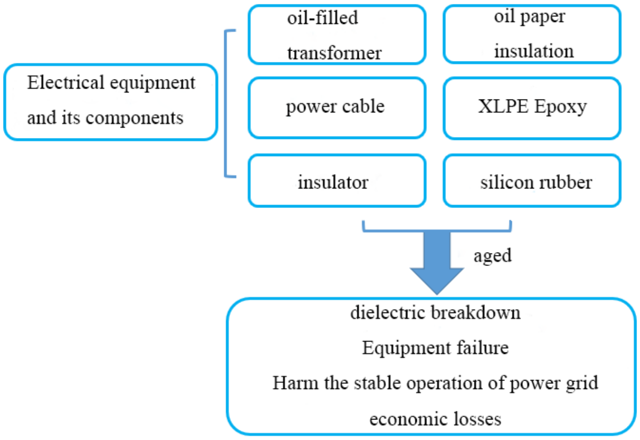


FIGURE 12. **The harms of electrical equipment aging.**

Zhang et al. carried out thermal oxidation experiments on natural vulcanized rubber, and measured the variation tendency of the terahertz dielectric spectrum of rubber. Combining the changing trend of complex dielectric constant and dielectric loss with the characteristics of rubber sample structure and the aging process, the polarization law of the sample under the action of the terahertz field was analyzed [71]. The results show that during sample aging, the main processes of chemical reactions are the breaking of the whole structure of macromolecular chains, the decrease of molecular weight and the weakening of intermolecular binding force, and the generation of polar small molecular groups (-OR group, -OH group, etc.), which leads to the enhancement of atomic polarization and orientation polarization in terahertz field. Against the backdrop of the aging of silicone rubber (SiR) in the nuclear power plant environment, Takuya Kaneko et al. analyzed four different aging processes (thermal aging, radiation aging, concurrent aging and hydrolysis aging) of SiR by terahertz absorption spectrum, Fourier transforms infrared spectrum and nuclear magnetic resonance. The results show that the aging mechanism of SiR depends on aging conditions [72]. In the process of thermal aging, the formation of cross-linked structures leads to absorption peaks at 4.0 and 4.6 THz in THz absorption spectrum. In the process of radiation aging, cyclic siloxane on SiR surface oxidizes and forms carbonyl groups on the surface. The increase of absorption in the whole frequency range of 0.5-5 THz is probably caused by carbonyl groups. In the process of hydrolytic aging, SiR is hydrolyzed and cross-linked, and the increase of absorption in the frequency range of 0.5-2.5 THz may be caused by the presence of water. The specific changes in THz absorption spectrum correspond to these aging processes, so THz absorption spectrum can be used to monitor the status of SiR.

Chang et al. measured the thermal aging process of carbon black and silica filled natural rubber (NR) periodically by terahertz time-domain spectroscopy, and quantitatively evaluated the aging degree of the samples by analyzing parameters such as terahertz dielectric constant and optical refractive index [73]. The results indicate that as thermal aging progresses, the terahertz extinction coefficients of the NR filled with carbon black grow significantly after around 30 days. In other words, after about 30 days of thermal aging, the NR filled with carbon black goes through a change in its aging state. And the variation rules of the extinction coefficient are shown in Figure 12. Chang's research has proved the feasibility of terahertz dielectric spectroscopy as a nondestructive testing tool to determine the thermal aging state of rubber.

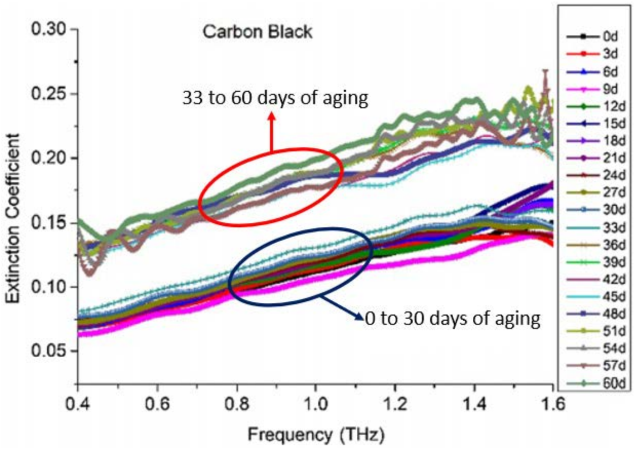


FIGURE 13. **Extinction coefficient versus terahertz frequency of NR filled with carbon black in different aging states [73].**

Yang and Wu studied the relationship between the relative dielectric constant of silicone rubber and the molecular chain length through molecular simulation calculations, and put forward a molecular chain breaking model. It was calculated that the dielectric constant of silicone rubber increased with the decrease of the average molecular chain length [74], [75]. Then, the relationship between the aging degree of silicone rubber and the terahertz input return loss was obtained through the simulation calculation of the electromagnetic model of the terahertz signal incident on the silicone rubber sheet. Finally, the reliability of the relationship between the aging degree of silicone rubber and the terahertz input loss was verified by the terahertz reflection experiment. Figure 13. shows the relationship between the aging degree of silicone rubber and terahertz input return loss.

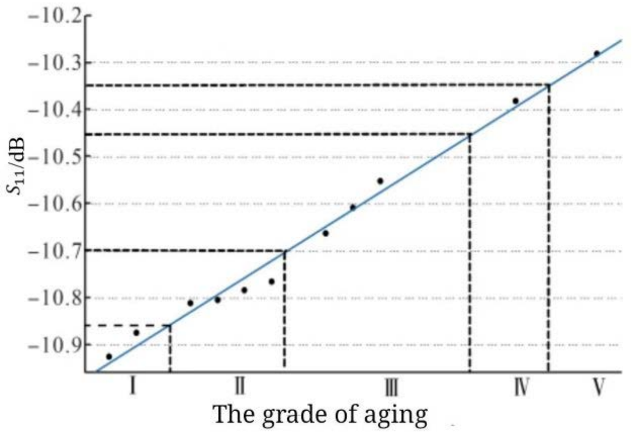
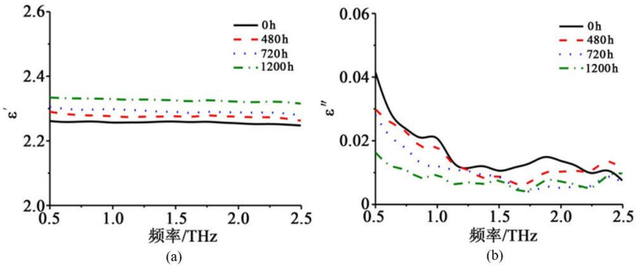


FIGURE 14. **Return loss parameters corresponding to different aging grades [75].**

Yu et al. carried out thermal aging experiments on XLPE cable insulation, using terahertz time-domain spectrometer to test the time-domain signals of reference samples and XLPE samples, respectively, and using differential scanning calorimeter and Fourier transform infrared spectroscopy to study the changes in the chemical structure of samples during aging [76]. The results show that during thermal aging, the molecular chain of XLPE is broken and oxidized, its chemical structure is destroyed, and the movement ability of molecular chain segments is enhanced, which leads to a real increase in the dielectric constant of XLPE at terahertz frequency. Aging results in the decrease of the crystallinity of XLPE, the weakening of lattice vibration intensity, and the decrease of the imaginary part of the dielectric constant. Figure 14. shows the variation of the dielectric constant with frequency.



(a)

(b)

FIGURE 15. **Changes of dielectric constant of XLPE samples with aging time in the range of 0.5∼2.5THz. (a) ε'; (b) ε'' [76].**

Ohki et al. prepared two kinds of epoxy resins (HE and SE), after thermal aging experiment or radiation aging experiment, and measured their terahertz absorption spectra in the frequency range of 0.5∼5.0 THz [77]. The results show that the intensity of terahertz absorption in SE is closely related to the intensity of infrared absorption (mIR) due to the formation of carbonyl groups. In contrast, there is no obvious difference between THz and mIR absorption spectra of HE.

Lee et al. analyzed the thermal aging process of cellulose insulation paper by terahertz time-domain spectroscopy, and found that the refractive index decreased rapidly at 400° and above, which was close to the temperature at which the glycosidic bond in cellulose broke [78]. Subsequently, Lee et al. confirmed that the abrupt change in refractive index caused the thermal aging and continuous thermal breakdown of the cellulose platen. Therefore, they speculated that the changes in refractive index and extinction degree that always appeared in the experimental results were caused by the breakage of glycosidic bonds in cellulose. Wang found that the average refractive index of unaged cellulose insulation paper was 1.531 in the range of 0.1-1.80 THz by analyzing the THz optical parameters of cellulose insulation paper with different thermal aging degrees, and it increased with the aging degree [79]. Figure 15. shows the variation of refractive index with frequency.

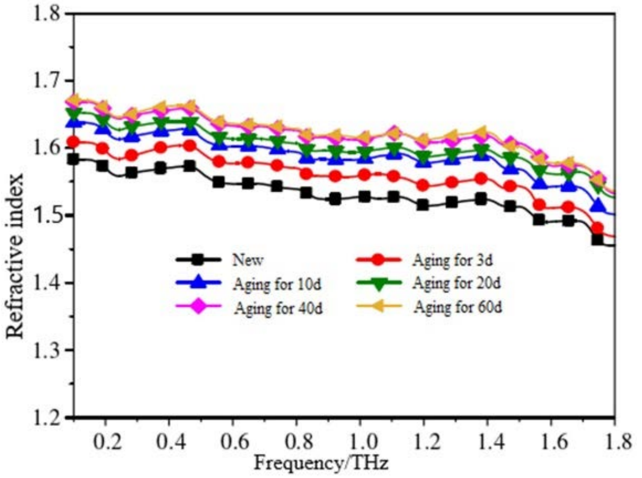
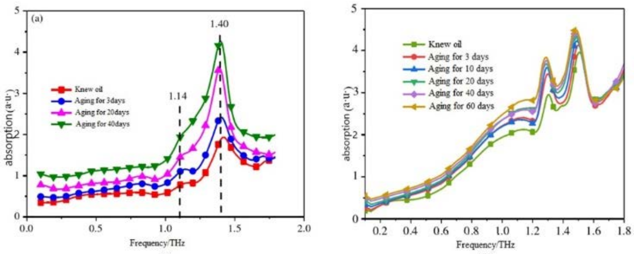


FIGURE 16. **Refractive index diagram of mineral oil impregnated cellulose insulation paper with different thermal aging degrees [79].**

Wang et al. carried out thermal aging experiments and THz-TDS analysis on mineral insulating oil paper and FR3 vegetable insulating oil paper, respectively, and used the improved electromagnetic wave transfer function to process the signal to eliminate the echo oscillation in the frequency domain spectrum signal. Finally, the terahertz optical parameters of insulating oil and paper were calculated [80]. By comparing and analyzing the absorption spectrum and refractive index spectrum of mineral insulating oil in different aging states, it is found that there are two different absorption peaks in mineral insulating oil and FR3 plant insulating oil, which can be used as the characteristic absorption peaks of both of them in THz band, as Figure 16. shows. However, with the aggravation of aging, the absorption peaks become stronger and stronger, and at the same time, a violent chemical reaction takes place in the oil, which leads to the increasing content of aging by-products such as water in the oil. In order to further verify the reasons for the change of optical parameters in THz spectrum of FR3 insulating oil, Wang prepared samples with the same aging degree and different moisture content through the natural moisture absorption test of natural ester insulating oil. Further analysis of the influence of moisture content in insulating oil on THz optical parameters found that moisture is the main factor affecting THz optical parameters of insulating oil [79].



(a) (b)

FIGURE 17. **Absorption coefficient of insulating oil in THz band (a) Mineral insulating oil (b) FR3 type vegetable insulating oil [79].**

B. SPECIES IDENTIFICATION

When using terahertz time-domain spectroscopy to analyze the aging degree of materials, as many components in materials are the same, in the terahertz spectrum of different types of the same materials, the peaks in some areas are relatively close, and the characteristic peaks may also be relatively close, which is difficult to distinguish. It is necessary to use the method of spectral feature extraction to establish a suitable classification model for data processing. At the same time, the measured data of THz spectrum may have some problems, such as unobvious absorption characteristics, a large amount of data, high dimensions and so on. It is necessary to extract the features of the data and reduce the dimension of the data, so as to simplify the data and suppress the interference of some noise, which is very important for the classification and identification of the spectrum.

Miao et al. studied four kinds of epoxy resins with different epoxy values by terahertz time-domain spectroscopy, calculated the refractive index and absorption coefficient of the samples in the 0.2∼2.6THz band, and distinguished the four samples by their different absorption coefficients and refractive indexes in the THz band [81]. On this basis, the epoxy resin was identified qualitatively by a simple least square regression method.

Yin et al. detected four kinds of rubber samples based on the THz-TDS system, respectively used kernel principal component analysis (KPCA) and kernel canonical correlation analysis (KCCA) to extract the characteristics of THz spectra of rubber, introduced PCA and CCA as a comparison, combined with support vector machine (SVM) to establish a classification model, and finally used partial least squares discriminant method (PLS-DA) to identify rubber [82]. The results show that SVM combined with the feature extraction method can classify rubber spectra, KPCA-SVM has the best classification effect on absorption spectra, while PLS-DA has a better classification effect on refraction spectra than SVM, and KPCA has a better feature extraction effect on spectra than standard KCCA. It provides a new method for the identification and analysis of experimental rubber. In order to improve the accuracy of classification, Yin et al. introduced the modeling method of improved particle swarm optimization support vector machine (MPSO-SVM) into the qualitative analysis of terahertz spectrum. The accuracy of classification was measured by confusion matrix, and the results showed that the accuracy of comprehensive classification was over 81.25%. In addition, the recognition time of (MPSO-SVM) method was also accelerated, and the overall time consumption was less than 9.4s [83].

VI. CONCLUSION

At present, preliminary research has indicated that THz time-domain spectroscopy technology has certain effects in the detection of gap defects in insulating materials, moisture content analysis, aging analysis, and species identification. However, the application time of THz detecting technology in the electrical field is brief. There are still certain problems to be solved for the extensive applications in the power field:

1) MINIATURIZATION OF APPARATUS

The current terahertz detection system is mainly composed of a THz wave source, a terahertz signal detection system, and a data acquisition system. The size is relatively substantial overall. Under the condition of maintaining precision, it is required to improve equipment integration to reduce size.

2) INTERFERENCE RESISTANT OF THE EQUIPMENT

Electromagnetic fields can cause electromagnetic interference to terahertz waves, but there is typically a strong electromagnetic field near high-voltage power equipment, so the interference of electromagnetic fields will be inevitable. A worthwhile study is how to eliminate the effects of electromagnetic fields.

3) SOURCE ANALYSIS OF MATERIALS

Due to the wide number of producers of electrical insulating materials, their quality, particularly their aging properties, is often uneven. The origin of the material can currently only be demarcated by lots of destructive refinement analysis in the laboratory. Using the terahertz technology to trace the origin of material is also crucial for equipment manufacturing and testing equipment admission.

REFERENCES

[1] S. Li, S. Yu, and Y. Feng, "Progress in and prospects for electrical insulating materials," *High Voltage*, vol. 1, no. 3, pp. 122–129, Oct. 2016, doi: 10.1049/hve.2016.0034.

[2] M. Ramesh, L. Cui, and R. S. Gorur, "Impact of superficial and internal defects on electric field of composite insulators," *Int. J. Electr. Power Energy Syst.*, vol. 106, pp. 327–334, Mar. 2019, doi: 10.1016/j.ijepes.2018.10.013.

[3] C. Aj, M. A. Salam, Q. M. Rahman, F. Wen, S. P. Ang, and W. Voon, "Causes of transformer failures and diagnostic methods—A review," *Renew. Sustain. Energy Rev.*, vol. 82, pp. 1442–1456, Feb. 2018, doi: 10.1016/j.rser.2017.05.165.

[4] C. Zhou, H. Yi, and X. Dong, "Review of recent research towards power cable life cycle management," *High Volt.*, vol. 2, no. 3, pp. 179–187, Sep. 2017, doi: 10.1049/hve.2017.0037.

[5] C. H. de Tourreil, "Response of composite insulators to dynamic mechanical loads," *IEEE Trans. Power Del.*, vol. 5, no. 1, pp. 379–383, Jan. 1990, doi: 10.1109/61.107301.

[6] S. C. Zhong, "Progress in terahertz nondestructive testing: A review," *Frontiers Mech. Eng.*, vol. 14, pp. 273–281, Sep. 2019, doi: 10.1007/s11465-018-0495-9.

[7] R. S. A. Afia, E. Mustafa, and Z. A. Tamus, "Mechanical stresses on polymer insulating materials," in *Proc. Int. Conf. Diag. Electr. Eng.*, Sep. 2018, pp. 1–4, doi: 10.1109/DIAGNOSTIKA.2018.8526097.

[8] S. R. White, N. R. Sottos, P. H. Geubelle, J. S. Moore, M. R. Kessler, S. R. Sriram, E. N. Brown, and S. Viswanathan, "Autonomic healing of polymer composites," *Nature*, vol. 409, no. 6822, pp. 794–797, Feb. 2001, doi: 10.1038/35057232.

[9] M. Batalovic, H. Zildzo, H. Matoruga, M. Matoruga, and S. Berberovic, "Detection of defect presence inside the insulation of cable accessories through changes in cable capacitance," in *Proc. 28th Int. Conf. Inf., Commun. Autom. Technol. (ICAT)*, Oct. 2019, pp. 1–4, doi: 10.1109/ICAT47117.2019.8938874.

[10] P. D. Bastidas and S. M. Rowland, "Interfacial aging in composite insulators as a result of partial discharge activity," in *Proc. IEEE Electr. Insul. Conf. (EIC)*, Jun. 2017, pp. 13–16, doi: 10.1109/EIC.2017.8004690.

[11] Z. Zhang, P. D. S. Assala, and L. Wu, "Residual life assessment of 110 kV XLPE cable," *Electr. Power Syst. Res.*, vol. 163, pp. 572–580, Oct. 2018, doi: 10.1016/j.epsr.2017.12.027.

[12] S. Zhang, L. Cheng, R. Liao, Y. Liu, X. Wang, T. Wang, and J. Fu, "Process improvement to restrain emergency heating defect of composite insulator," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 29, no. 2, pp. 446–453, Apr. 2022, doi: 10.1109/TDEI.2022.3157929.

[13] M. Kohtoh, S. Kaneko, S. Okabe, and T. Amimoto, "Aging effect on electrical characteristics of insulating oil in field transformer," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 16, no. 6, pp. 1698–1706, Dec. 2009, doi: 10.1109/TDEI.2009.5361592.

[14] M. Amin, M. Akbar, and M. Salman, "Composite insulators and their aging: An overview," *Sci. China, E, Technol. Sci.*, vol. 50, no. 6, pp. 697–713, Dec. 2007, doi: 10.1007/s11431-007-0053-x.

[15] P. Pahlavanpour and M. A. Martins, "Insulating paper ageing and furfural formation," in *Proc. Electr. Insul. Conf. Electr. Manuf. Coil Winding Technol. Conf.*, Sep. 2003, pp. 283–288, doi: 10.1109/EICEMC.2003.1247898.

[16] J. Li, X. Zhao, G. Yin, S. Li, J. Zhao, and B. Ouyang, "The effect of accelerated water tree ageing on the properties of XLPE cable insulation," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 18, no. 5, pp. 1562–1569, Oct. 2011, doi: 10.1109/TDEI.2011.6032825.

[17] Y. Wang, C. Feng, R. Fei, and Y. Luo, "Thermal-ageing characteristics of dry-type transformer epoxy composite insulation," *High Perform. Polym.*, vol. 32, no. 7, pp. 741–752, Sep. 2020, doi: 10.1177/0954008320906439.

[18] Y. Wei, S. Zhang, Y. Luo, L. Ding, and D. Zhang, "Accurate depth determination of defects in composite materials using pulsed thermography," *Compos. Struct.*, vol. 267, Jul. 2021, Art. no. 113846, doi: 10.1016/j.compstruct.2021.113846.

[19] B. Lutz, L. Cheng, Z. Guan, and L. Wang, "Microwave-based detection of internal defects in composite insulators for outdoor application," in *Proc. IEEE Int. Conf. Condition Monitor. Diagnosis*, Sep. 2012, pp. 1175–1178, doi: 10.1109/CMD.2012.6416370.

[20] T. Kim, S. Sanyal, M. Rabelo, I.-H. Choi, Y. G. Yoon, T. K. Oh, and J. Yi, "Non-destructive analysis of power insulators by frequency response function and three dimensional-computed tomography," *Mech. Syst. Signal Process.*, vol. 177, Sep. 2022, Art. no. 109310, doi: 10.1016/j.ymssp.2022.109310.

[21] H. Wang, L. Cheng, R. Liao, S. Zhang, and L. Yang, "Nonlinear ultrasonic nondestructive detection and modelling of kissing defects in high voltage composite insulators," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 27, no. 3, pp. 924–931, Jun. 2020, doi: 10.1109/TDEI.2019.008523.

[22] J. Li, L. Yang, Y. He, W. Li, and C. Wu, "Terahertz nondestructive testing method of oil-paper insulation debonding and foreign matter defects," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 28, no. 6, pp. 1901–1908, Dec. 2021, doi: 10.1109/TDEI.2021.009655.

[23] Y. H. Tao, A. J. Fitzgerald, and V. P. Wallace, "Non-contact, non-destructive testing in various industrial sectors with terahertz technology," *Sensors*, vol. 20, no. 3, p. 712, Jan. 2020, doi: 10.3390/s20030712.

[24] E. Mustafa, R. S. A. Afia, and Z. A. Tamus, "Application of non-destructive condition monitoring techniques on irradiated low voltage unshielded nuclear power cables," *IEEE Access*, vol. 8, pp. 166024–166033, 2020, doi: 10.1109/ACCESS.2020.3022953.

[25] E. Mustafa, R. S. A. Afia, and Z. Á. Tamus, "Dielectric loss and extended voltage response measurements for low-voltage power cables used in nuclear power plant: Potential methods for aging detection due to thermal stress," *Electr. Eng.*, vol. 103, no. 2, pp. 899–908, Apr. 2021, doi: 10.1007/s00202-020-01121-4.

[26] E. Mustafa, R. S. A. Afia, A. Nawaz, O. Nouini, and Z. Á. Tamus, "Implementation of non-destructive condition monitoring techniques on low-voltage nuclear cables: II. thermal aging of EPR/CSPE cables," *Energies*, vol. 15, no. 9, p. 3231, Apr. 2022, doi: 10.3390/en15093231.

[27] E. Mustafa, R. S. A. Afia, O. Nouini, and Z. Á. Tamus, "Implementation of non-destructive electrical condition monitoring techniques on low-voltage nuclear cables: I. Irradiation aging of EPR/CSPE cables," *Energies*, vol. 14, no. 16, p. 5139, Aug. 2021, doi: 10.3390/en14165139.

[28] T. Izutsu, D. Odaka, M. Komatsu, Y. Ohki, M. Mizuno, Y. Nakamura, and N. Chiwata, "A new method for estimating the content of vinyl acetate in ethylene-vinyl acetate copolymer," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 23, no. 3, pp. 1260–1265, Jun. 2016, doi: 10.1109/TDEI.2015.005546.

[29] W. Withayachumnankul and M. Naftaly, "Fundamentals of measurement in terahertz time-domain spectroscopy," *J. Infr. Millim. THz Waves*, vol. 35, no. 8, pp. 610–637, Aug. 2014, doi: 10.1007/s10762-013-0042-z.

[30] J. Dong, B. Kim, A. Locquet, P. Mckeon, N. Declercq, and D. S. Citrin, "Nondestructive evaluation of forced delamination in glass fiber-reinforced composites by terahertz and ultrasonic waves," *Compos. B, Eng.*, vol. 79, pp. 667–675, Sep. 2015, doi: 10.1016/j.compositesb.2015.05.028.

[31] Q. Wang, L. Xie, and Y. Ying, "Overview of imaging methods based on terahertz time-domain spectroscopy," *Appl. Spectrosc. Rev.*, vol. 57, no. 3, pp. 249–264, Mar. 2022, doi: 10.1080/05704928.2021.1875480.

[32] R. M. Smith and M. A. Arnold, "Terahertz time-domain spectroscopy of solid samples: Principles, applications, and challenges," *Appl. Spectrosc. Rev.*, vol. 46, no. 8, pp. 636–679, Nov. 2011, doi: 10.1080/05704928.2011.614305.

[33] M.-G. Bae, I.-S. Lee, and J. W. Lee, "Defect detection in XLPE material using terahertz wave-based non-destructive testing," *New Phys., Sae Mulli*, vol. 71, no. 3, pp. 305–309, Mar. 2021, doi: 10.3938/NPSM.71.305.

[34] S. Xie, F. Yang, X. Huang, X. Yu, and B. Gao, "Air gap detection and analysis of XLPE cable insulation based on terahertz time domain spectroscopy," *Trans. China Electrotechn. Soc.*, vol. 35, no. 12, pp. 2698–2707, 2020, doi: 10.19595/j.cnki.1000-6753.tces.190662.

[35] J. Yin, L. Cheng, H. Wang, R. Liao, and Z. Cheng, "Study on polarization characteristics and rapid detection method of micro water content in the terahertz band containing micro-water oil-immersed insulating paperboard," *Trans. China Electrotech. Soc.*, vol. 35, no. 13, pp. 2940–2949, 2020, doi: 10.19595/j.cnki.1000-6753.tces.190824.

[36] Z. Zhou, Z. Zhang, J. Liu, H. Mei, S. Gao, and L. Wang, "Application of terahertz wave technology in insulation detection of grid equipment," *High Voltage App.*, vol. 55, no. 10, pp. 216–223, 2019, doi: 10.13296/j.1001-1609.hva.2019.10.035.

[37] Y.-S. Lee. *Principles of Terahertz Science and Technology*. Accessed: Jul. 17, 2022. [Online]. Available: https://sc.panda321.com/extdomains/books.google.com/books/about/Principles_of_Terahertz_Science_and_Tech.html?hl=zh-CN&id=4ZqkuUURxFcC

[38] B. B. Hu and M. C. Nuss, "Imaging with terahertz waves," *Opt. Lett.*, vol. 20, no. 16, pp. 1716–1718, Apr. 1995, doi: 10.1364/OL.20.001716.

[39] L. Cheng, Y. Liu, Z. Cheng, R. Chen, S. Zhang, R. Liao, and Y. Yuan, "A novel aging characterization method for silicone rubber based on terahertz absorption spectroscopy," *Polym. Test.*, vol. 115, Nov. 2022, Art. no. 107723, doi: 10.1016/j.polymertesting.2022.107723.

[40] Z. Tang and Y. Li, "Review of terahertz technology in electrical equipment insulation defect detection," *High Voltage App.*, vol. 2022, pp. 1–9, Jan. 2022.

[41] L. Xu, "High resolution terahertz image processing," M.S. dissertation, Dept. Phys. Electron., Univ. Chin. Acad. Sci., Beijing, China, 2013. Accessed: Jul. 17, 2022. [Online]. Available: https://kns.cnki.net/kcms/detail/detail.aspx?dbcode=CMFD&dbname=CMFD201401&filename=1014018661.nh&uniplatform=NZKPT&v=vEBhmpKwyOAVzmy1znz-Vh6lLfxv57KbpxHCM3gq4qwL5lQK-WQ5uDl-eycsggOo

[42] Z. Zhang, H. Mei, J. Liu, W. Wu, L. Wang, L. Li, H. Jiang, and G. Yuan, "Detection method of interfacial defects of composite insulators based on THz wave," *Proc. CSEE*, vol. 40, no. 3, pp. 989–999, 2020, doi: 10.13334/j.0258-8013.pcsee.190699.

[43] J. Zhang, "Study on terahertz spectral properties of epoxy resin adhesives," *Spectroscope Spectral Anal.*, vol. 36, no. 4, pp. 919–923, 2016.

[44] Z. Cheng, "Experimental research on insulation material defect detection based on terahertz imaging technology," M.S. dissertation, Dept. Mech. Eng., North China Electr. Power Univ., Beijing, China, 2021, doi: 10.27139/d.cnki.ghbdu.2021.000160.

[45] R. Wang, Z. Zhang, C. Yang, Z. Nie, L. Wang, X. Peng, Z. Huang, and D. Yang, "Study on detection of insulator defects in time domain terahertz wave," in *Proc. IEEE Conf. Electr. Insul. Dielectr. Phenomena (CEIDP)*, Oct. 2018, pp. 297–300, doi: 10.1109/CEIDP.2018.8544879.

[46] L. Cheng, L. Wang, H. Mei, Z. Guan, and F. Zhang, "Research of nondestructive methods to test defects hidden within composite insulators based on THz time-domain spectroscopy technology," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 23, no. 4, pp. 2126–2133, Aug. 2016, doi: 10.1109/TDEI.2016.7556487.

[47] Y. Li, C. Zhang, X. Zhao, T. Zhang, and C. Cao, "Terahertz time-domain spectrum detection of non-metallic coating defects," *Chin. J. Sci. Instrum.*, vol. 41, no. 11, pp. 129–136, 2020, doi: 10.19650/j.cnki.cjsi.J2006852.

[48] H. Mei, H. Jiang, F. Yin, L. Li, and L. Wang, "Detection of small defects in composite insulators using terahertz technique and deconvolution method," *IEEE Trans. Instrum. Meas.*, vol. 69, no. 10, pp. 8146–8155, Oct. 2020, doi: 10.1109/TIM.2020.2987407.

[49] H. Jiang, H. Mei, X. Bian, L. Li, L. Wang, and L. Wang, "Detection of double-layer air gap defects based on terahertz imaging method," in *Proc. IEEE Int. Instrum. Meas. Technol. Conf. (I2MTC)*, May 2021, pp. 1–5, doi: 10.1109/I2MTC50364.2021.9459793.

[50] H. Jiang, H. Mei, J. Liu, D. Chen, L. Wang, and L. Wang, "Research on terahertz fusion parameter imaging method of composite insulator internal defects based on PCA technology," *Proc. CSEE*, vol. 2021, pp. 1–10, Jan. 2021.

[51] Z. Zhang, L. Wang, H. Mei, and W. Wu, "Quantitative detection of interfacial air gap in insulation equipment based on terahertz wave contrast method," *IEEE Trans. Instrum. Meas.*, vol. 68, no. 12, pp. 4896–4905, Dec. 2019, doi: 10.1109/TIM.2019.2898048.

[52] I.-S. Lee and J. W. Lee, "Nondestructive internal defect detection using a CW–THz imaging system in XLPE for power cable insulation," *Appl. Sci.*, vol. 10, no. 6, p. 2055, Mar. 2020, doi: 10.3390/app10062055.

[53] B. Cao, S. Li, Y. Kang, J. Lu, X. Yang, and H. Dong, "Insulation delamination detection of three-phase composite structure based on terahertz time-domain spectral," in *Proc. Int. Conf. Electr. Mater. Power Equip. (ICEMPE)*, Apr. 2021, pp. 1–4, doi: 10.1109/ICEMPE51623.2021.9509103.

[54] A. D. van Rheenen, B. B. Johnsen, and M. W. Haakestad. *Transmission of Terahertz Waves Through Graphene/Epoxy Samples—Correlation With Electrical Conductivity*. Accessed: Jul. 29, 2022. [Online]. Available: https://sc.panda321.com/scholar?hl=zh-CN&as_sdt=0%2C5&q=Transmission+of+Terahertz+Waves+through+Graphene%2FEpoxy+Samples+%E2

[55] K. Mori, T. Seki, N. Hirai, and Y. Ohki, "Terahertz absorption spectra of several polymer nanocomposites indicating polymer-filler interactions," *AIP Adv.*, vol. 9, no. 10, Oct. 2019, Art. no. 105109, doi: 10.1063/1.5117182.

[56] Z. Lian, D. Chen, and S. Li, "Investigation on the correlation between dispersion characteristics at terahertz range and dielectric permittivity at low frequency of epoxy resin nanocomposites," *Polymers*, vol. 14, no. 4, p. 827, Feb. 2022, doi: 10.3390/polym14040827.

[57] R. Mizuuchi, Y. Hisazato, H. Cho, Y. Nakamura, Y. Sumimoto, and K. Wada, "Non-destructive inspection method for defects in epoxy resin by using THz wave," in *Proc. 8th Int. Conf. Condition Monitor. Diagnosis (CMD)*, Oct. 2020, pp. 400–403, doi: 10.1109/CMD48350.2020.9287268.

[58] X. Kong, "Research on the detection of metal foreign objects in GIS equipment based on terahertz time domain spectroscopy," *Electr. Eng.*, vol. 2021, no. 23, pp. 140–143, 2021, doi: 10.19768/j.cnki.dgjs.2021.23.046.

[59] P. Zong, Z. Li, and R. Liu, "Based on terahertz time-domain spectroscopy detection and research of metal impurities in transformer oil," *Shanxi Electr. Power*, vol. 2022, no. 2, pp. 18–22, 2022.

[60] K. Bandara, T. K. Saha, and C. Ekanayake. (2015). *Influence of Moisture and Ageing on Dielectric Response of Ester and Mineral Oil Impregnated Pressboard Insulation*. Accessed: Sep. 17, 2022. [Online]. Available: https://www.webofscience.com/wos/alldb/full-record/WOS:000380532100117

[61] T. Yasui and T. Araki, "Sensitive measurement of water content in dry material based on low-frequency terahertz time-domain spectroscopy," *Proc. SPIE*, vol. 6024, pp. 69–74, Dec. 2005, doi: 10.1117/12.666812.

[62] X. Kong, "Terahertz time-domain spectroscopy detection of water content in transformer oil," *Guangdong Chem. Ind.*, vol. 48, no. 16, pp. 240–242, 2021.

[63] M. Koch and T. Prevost, "Analysis of dielectric response measurements for condition assessment of oil-paper transformer insulation," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 19, no. 6, pp. 1908–1915, Dec. 2012, doi: 10.1109/TDEI.2012.6396947.

[64] Q. Jiang, Y. Wang, Z. Wen, and J. Wang, "Moisture content determination of transformer oil by using terahertz time-domain spectroscopy," *Spectrosc. Spectr. Anal.*, vol. 38, no. 4, pp. 1049–1052, Apr. 2018.

[65] H. Lin, B. P. Russell, P. Bawuah, and J. A. Zeitler, "Sensing water absorption in hygrothermally aged epoxies with terahertz time-domain spectroscopy," *Anal. Chem.*, vol. 93, no. 4, pp. 2449–2455, Feb. 2021, doi: 10.1021/acs.analchem.0c04453.

[66] P. S. Sindhu, N. Mitra, D. Ghindani, and S. S. Prabhu, "Epoxy resin (DGEBA/TETA) exposed to water: A spectroscopic investigation to determine water-epoxy interactions," *J. Infr., Millim., THz Waves*, vol. 42, no. 5, pp. 558–571, May 2021, doi: 10.1007/s10762-021-00788-5.

[67] H. Dong, Y. Liu, Y. Cao, J. Wu, S. Zhang, X. Zhang, and L. Cheng, "Terahertz-based method for accurate characterization of early water absorption properties of epoxy resins and rapid detection of water absorption," *Polymers*, vol. 13, no. 23, p. 4250, Dec. 2021, doi: 10.3390/polym13234250.

[68] A. Setayeshmehr, A. Akbari, H. Borsi, and E. Gockenbach, "On-line monitoring and diagnoses of power transformer bushings," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 13, no. 3, pp. 608–615, Jun. 2006, doi: 10.1109/TDEI.2006.1657975.

[69] Q. Dai, B. Qi, R. Zhou, Q. Pan, K. Zhu, C. Li, and M. Fu, "The influence of mass moisture invading on electrical features for oil-impregnated paper bushing," in *Proc. IEEE Conf. Electr. Insul. Dielectr. Phenomena (CEIDP)*, Oct. 2016, pp. 319–322, doi: 10.1109/ceidp.2016.7785641.

[70] L. Cheng, Y. Xia, S. Gao, J. Zhao, J. Wang, and Z. Cheng, "Application of terahertz time domain spectroscopy in moisture content detection of insulating pressboard," *Smart Power*, vol. 48, no. 8, pp. 104–109, 2020.

[71] X. Zhang, T. Chang, H. Cui, X. Yang, L. Liu, and Y. Zhang, "Terahertz dielectric spectroscopy of natural vulcanized rubber by thermal oxidation," *Infr. Laser Eng.*, vol. 47, no. 10, pp. 291–296, 2018.

[72] T. Kaneko, S. Ito, T. Minakawa, N. Hirai, and Y. Ohki, "Degradation mechanisms of silicone rubber under different aging conditions," *Polym. Degradation Stability*, vol. 168, Oct. 2019, Art. no. 108936, doi: 10.1016/j.polymdegradstab.2019.108936.

[73] T. Chang, X. Zhang, and H.-L. Cui, "Thermal aging analysis of carbon black and silica filled natural rubber based on terahertz dielectric spectroscopy," *Infr. Phys. Technol.*, vol. 105, Mar. 2020, Art. no. 103195, doi: 10.1016/j.infrared.2020.103195.

[74] H. Yang, Z. Wu, W. Dong, J. Dang, and H. Ren, "Analysis of the influence of silicone rubber aging on the transmission parameters of terahertz waves," *Energies*, vol. 14, no. 14, p. 4238, Jul. 2021, doi: 10.3390/en14144238.

[75] X. Zhang, J. Huang, Z. Wang, C. Miao, Z. Wu, and Y. Cheng, "Aging detection of silicone rubber composite insulators based on terahertz technology," *J. GUANGXI Univ. Sci. Technol.*, vol. 32, no. 4, pp. 1–8, 2021, doi: 10.16375/j.cnki.cn45-1395/t.2021.04.001.

[76] S. Yu, Y. Zhang, H. He, and X. Yu, "Effect of thermal-oxidative ageing on dielectric properties of XLPE in terahertz frequency domain," *Insulating Mater.*, vol. 53, no. 2, pp. 53–58, 2020, doi: 10.16790/j.cnki.1009-9239.im.2020.02.008.

[77] Y. Ohki, H. Ishii, M. Hayashi, and N. Hirai, "THz spectroscopic study of degradation of epoxy resins," in *Proc. Int. Conf. Electr. Mater. Power Equip. (ICEMPE)*, Apr. 2021, pp. 1–4, doi: 10.1109/ICEMPE51623.2021.9509210.

[78] I.-S. Lee and J. Wook Lee, "Effects of thermal aging on cellulose pressboard using terahertz time-domain spectroscopy," *Current Appl. Phys.*, vol. 19, no. 11, pp. 1145–1149, Nov. 2019, doi: 10.1016/j.cap.2019.07.012.

[79] L. Wang, "State detection of transformer insulating oil and paper based on terahertz spectrum," M.S. dissertation, Dept. Agricult. Electric. Automat., Southwest Univ., El Paso, TX, USA, 2020, doi: 10.27684/d.cnki.gxndx.2020.003135.

[80] W. Liang, Q. Zhipeng, L. Ze, and G. Li, "THz optical parameters of FR3 natural ester insulating oil after thermal aging," *Optik*, vol. 239, Aug. 2021, Art. no. 166873, doi: 10.1016/j.ijleo.2021.166873.

[81] Q. Miao, K. Zhao, L. Tian, G. Zhao, and L. Liu, "Research on spectroscopy of epoxy resin and its mixture in terahertz range," *Mod. Sci. Instrum.*, vol. 15, no. 6, pp. 31–33, 2011.

[82] X. Yin, N. Wang, and J. Chen, "Rubber classification and recognition based on THz time-domain spectroscope system," *Foreign Electron. Meas. Technol.*, vol. 35, no. 6, pp. 19–23, 2016, doi: 10.19652/j.cnki.femt.2016.06.006.

[83] X. Yin, Y. Liu, W. He, M. Feng, and Y. Shi, "Classification and recognition of vulcanized rubber and its auxiliary based on MPSO-SVM," *LASE, Technol.*, vol. 45, no. 1, pp. 7–12, 2021.

CHENJUN GUO was born in 1988. He is currently pursuing the Ph.D. degree. He is also a Senior Engineer. He is mainly engaged in the research of high-voltage test technology, high-voltage insulation technology, and external insulation state monitoring and evaluation.

WENLONG XU was born in Chongqing, China, in 2000. He received the bachelor's degree in electrical engineering and automation from Southwest University, China, in 2022. He is currently pursuing the master's degree in electrical engineering with Chongqing University, China. He is also working as a Researcher at the State Key Laboratory of Power Transmission Equipment and System Security and New Technology, Chongqing University.

MINGMING CAI was born in Liaoning, China, in 2000. She received the bachelor's degree in marine electrical and electronic engineering from Dalian Maritime University, China, in 2022. She is currently pursuing the master's degree in electrical engineering with Chongqing University, China. She is also working as a Researcher at the State Key Laboratory of Power Transmission Equipment and System Security and New Technology, Chongqing University. Her research interests include terahertz technology, online monitoring, and external insulation of electric equipment.

SHUFAN DUAN was born in Sichuan, China, in 1999. He received the bachelor's degree from the School of Electrical Engineering, Chongqing University, China, in 2021. He is currently pursuing the master's degree in electrical engineering with Chongqing University, China. He is also working as a Researcher at the State Key Laboratory of Power Transmission Equipment and System Security and New Technology, Chongqing University. He is majoring in high voltage and insulation technology.

JIANBIAO FU was born in Suihua, Heilongjiang. He received the bachelor's degree in electrical engineering from the Harbin University of Science and Technology, in 2020. He is currently pursuing the master's degree in electrical engineering.

XINLONG ZHANG was born in Tangshan, Hebei, China. He received the bachelor's degree in electrical engineering and automation from Hainan University, in 2018. He is currently pursuing the master's degree in electrical engineering with Chongqing University, China. He is also working as a Researcher at the State Key Laboratory of Power Transmission Equipment and System Security and New Technology, Chongqing University. He is primarily involved in nondestructive testing research and electrical equipment evaluation.

• • •