Study on Detecting Dielectric Properties of Typical Electrical Insulation Materials by Terahertz Wave Spectroscopy

Hongwei Mei\(^1\), Member, IEEE, Lanxin Li\(^1\), Fanghui Yin\(^1\), Member, IEEE, Wei Hu\(^2\), Jianben Liu\(^2\), and Liming Wang\(^1\), Senior Member, IEEE

\(^1\)Graduate School at Shenzhen, Tsinghua University, Shenzhen, 518055, Guangdong Province, P. R. China
\(^2\)State Key Laboratory of Power Grid Environmental Protection, Wuhan Branch of China Electric Power Research Institute, Wuhan, 430074, Hubei Province, P. R. China

Corresponding author: Fanghui Yin (e-mail: AndyYinEE@gmail.com).

This work was supported in part by the Shenzhen Basic Research Project under Grant JCYJ20180306174040354 and in part by the Open Fund of State Key Laboratory of Power Grid Environmental Protection under Grant GYW51201801169.

ABSTRACT
The dielectric properties of the electrical insulation materials is of great importance to the safe operation of the power system. As a promising technique in the field of material testing and with the very adaptive physical modeling of wave transmission process, terahertz wave was used to measure the dielectric properties of five commonly used insulation materials by two methods in this paper. When excluding the echo pulse from the reference signal and the sample signal, a better signal-noise ratio and a wider effective frequency band of spectrums can be obtained. Alternatively, the dielectric properties can also be achieved by separating the main pulse and echo pulse from the sample signal. The latter method makes the sampling of reference signal unnecessary. Furthermore, the dielectric properties of materials were also measured on a relatively lower frequency band (1Hz-1MHz) by the broadband dielectric spectrometer. Compared with a relatively lower frequency band, due to the polarization, the dielectric constant of the tested insulation materials was lower on the terahertz band while the dielectric loss tangent was generally higher except the epoxy resin.

INDEX TERMS
Broadband dielectric spectrometer, Dielectric properties, Insulation materials, Terahertz wave.

I. INTRODUCTION
The electrical insulation materials play an important role in the insulation coordination of overhead power lines [1]. Their aging can cause potential risks to the safety and stability of power system. To select appropriate insulation materials or evaluate their aging degrees, the dielectric properties need to be measured. The broadband dielectric spectroscopy (BDS) is a common method and a powerful tool to explore dielectric properties of materials on timescales across several orders of magnitude [2]. It is based on the interaction of an external field with the electric dipole moment of the sample, often expressed by permittivity, and registers the relationship between the current and voltage (magnitude and phase) for a set of electrodes containing the material under investigation. Terahertz wave, also known as terahertz radiation, submillimeter radiation, or tremendously high frequency (THF), may also be used as an effective method to measure the dielectric properties of materials due to the technological advances for the last three decades [3-4]. Furthermore, the dielectric properties at terahertz frequencies can be used as reference parameters to evaluate material aging and performance improvement when adding reinforcing materials, detect potential defects, and so on.

Terahertz range refers to electromagnetic waves with frequencies between 0.1 THz and 10 THz (1 THz = 10^{12} Hz), or wavelengths between 3 mm and 30 μm. This frequency band is located right between the more well-known bands of microwaves and infrared radiation, and share some properties with each of them [5-7]. Due to their wavelengths, terahertz waves pose various advantages over traditional imaging wavelength as follows [8-13]: (1) excellent resolution both in time domain and frequency domain with pulse widths of less than 3 ps; (2) good temporal and spatial coherence; (3) unlike X-rays, terahertz waves do not have an
ionizing effect and are generally considered biologically innocuous; (4) good penetration which makes it capable of testing a wide variety of non-conducting materials; (5) unique interactions with matter, which can be exploited in various applications. For example, optical phonon resonances of crystalline materials and a part of vibrational and rotational excitations of molecules are in the terahertz range, making terahertz wave very promising for spectroscopy and material identification [14].

This paper measured the dielectric constant (also called relative permittivity) and dielectric loss tangent of five electrical insulation materials by both the BDS and the terahertz wave method. These five insulation materials, including epoxy resin, epoxy glass fiber, polyethylene (XLPE), electrical porcelain, and high temperature vulcanized (HTV) silicone rubber, are widely adopted in the power system. Among them, epoxy resin and epoxy glass fiber are normally used as the core rod of composite insulators and post insulators, XLPE is used in electric cables as external insulation, electrical porcelain is used in porcelain insulators and HTV is used as the sheath of composite insulators and post insulators. The test results obtained by terahertz wave method and BDS were compared and analyzed in the perspective of dielectric physics theory. According to the results of this study, it was found that the amplitude relationship of dielectric constant between the five materials at terahertz frequencies is consistent with that at power frequency. Thus, there’s a great prospect for terahertz technique to be applied in the insulation material test.

II. TEST FACILITIES AND SPECIMENS
The terahertz wave time-domain spectroscopy (THz-TDS) system was set up using a T-Ray 5000 spectrometer from Picometrix [15-17]. The THz-TDS test platform and its schematic diagram are shown in Fig. 1. The THz-TDS system is capable of generating, capturing, and analyzing terahertz wave. The entire platform is an all-fiber integrated system. Thus, there is no need for traditional complex optical components. The optical path could be freely converted and the flexibility of the operation is therefore greatly enhanced.

The T-Ray 5000 platform uses Vitesse 800 femtosecond laser as the excitation source to generate and detect the THz radiation. The width of the output femtosecond pulse is 100 fs, the center wavelength is 800 nm, the repetition frequency is 80 MHz, and the average power is up to 1 W. The workflow of the whole system is as follows: The femtosecond laser is split into pump light and probe light inside the control unit. On one hand, the pump light is transmitted to the THz emitter (the low-temperature-grown GaAs photoconductive antennas with a bias voltage) through the optical fiber, and terahertz wave is then radiated out with a time duration of about 5 ps, a spectral range of 0.02-2 THz, and an average power of about 100 nW. On the other hand, the probe light is transmitted to the THz receiver (the low-temperature-grown GaAs photoconductive antennas without bias voltage) after being subjected to a delay line in the control unit, and the instantaneous electric field strength of terahertz wave is obtained by measuring the photocurrent. By adjusting the delay time, the time-domain waveform of terahertz wave can be obtained.

The broadband dielectric spectrometer was used to measure the dielectric properties in the frequency range between 1 Hz and 1 MHz. Novocontrol GmbH is a professional manufacturer of physical quantity measuring instruments for dielectric materials. The Novocontrol
Broadband Dielectric Spectrometer can be combined with high-frequency analyzers (Keysight) to achieve an extremely wide frequency range (3 μHz to 3 GHz) [18-19]. It can measure dielectric materials with very low conductivity and loss (high resolution up to $10^{-5}$) and has an extremely wide range of impedance (10 MΩ to 100 TΩ). Besides, it can measure not only various solid and thin film materials, but also liquid, powder, and other sample materials. The fully automatic online control software accompanied can work in real-time measurement and analysis of more than thirty different parameters of the dielectric samples. The appearance of the Novocontrol Dielectric Spectrometer is shown in Fig. 2 and its parameters are listed in Table I.

### TABLE I

<table>
<thead>
<tr>
<th>Parameters of the Novocontrol Broadband Dielectric Spectrometer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency Range: 3 μHz to 40 MHz (up to 3GHz with Agilent E4991A)</td>
</tr>
<tr>
<td>Impedance Range: 0.01 Ω~100 TΩ</td>
</tr>
<tr>
<td>Capacitance Range: 1 fF~1 F</td>
</tr>
<tr>
<td>Phase difference Accuracy: $2 \times 10^{-3}$</td>
</tr>
<tr>
<td>Loss Accuracy (tanδ): $3 \times 10^{-5}$</td>
</tr>
<tr>
<td>Measuring Voltage: 0~3 V</td>
</tr>
<tr>
<td>DC-Bias Voltage: ±40 V</td>
</tr>
<tr>
<td>Temperature Range: -160 to 400 °C</td>
</tr>
<tr>
<td>Interface Bus: GPIB/IEEE488</td>
</tr>
</tbody>
</table>

To simplify the operation process and the theoretical analysis, five flat specimens of typical electrical materials were prepared as shown in Fig. 3. All those samples in the test were from CYG Insulator Co., Ltd, Dongguan, Guangdong Province, China. The thicknesses of epoxy resin, epoxy glass fiber, polyethylene, electrical porcelain, and HTV silicone rubber are 2.98 mm, 2.96 mm, 4.39 mm, 3.11 mm, and 3.01 mm, respectively.

### III. DIELECTRIC PROPERTIES ON TERAHERTZ BAND

In the measurement process on terahertz band, the optical characteristics of terahertz wave were utilized. Before dielectric properties investigation, optical parameters of materials including refractive index and absorption coefficient were measured. Many researchers have investigated the extraction of optical parameters of numerous materials under terahertz wave transmission mode. However, for most current algorithms and data-processing methods, the measured parameters have limited accuracy as the consequence of ignoring echo pulses in the terahertz signal. There may be two types of echo pulses in the measurements. The first type of echo pulse, or called as system echo pulse, is from the equipment system. Following the main pulse, it is emitted by the THz transmitter and is actually caused by the GaAs material of the emitter [20]. The second type of echo pulse, also called as reflected echo pulse, is generated when the main pulse passes through the sample. For materials with low absorption and high reflection index such as electrical porcelain, reflected echo pulse is generated by the reflection of the main pulse inside the sample as shown in Figure 4. For other four materials in the test, either the absorption is relatively high or the reflection index is low so that the reflection of the main pulse is greatly attenuated. Therefore, the echo pulses in the sample signals of these four materials are actually the system echo pulse. Whatever the type of echo pulse is, it needs to be handled to improve the model. In order to address this problem, two data-processing methods, which took into account the echo pulse, were proposed in this paper.

![FIGURE 4. Schematic diagram of terahertz wave transmission.](image)
can be determined according to the Fresnel equation [17-20].

Variables $E_0(\omega)$, $E_s(\omega)$, and $E_a(\omega)$ are defined as the spectral signals from the transmitting probe, the sample signal, and the reference signal, respectively. Normally, $n_1$ and $n_2$ are the refractive index of air and sample, respectively. $r_{12}$, $r_{21}$ are the reflection coefficients from air to sample, sample to air and $n_{12}$, $n_{21}$ are the transmission coefficients from air to sample and the sample to air, respectively. These variables can be determined according to the Fresnel equation [17-20]. For example, $r_{12} = (\bar{n}_1(\omega) - \bar{n}_2(\omega)) / (\bar{n}_1(\omega) + \bar{n}_2(\omega))$, where $\bar{n}_1(\omega)$ and $\bar{n}_2(\omega)$ are the complex refractive index of air and sample, respectively. Normally, $\bar{n}_1(\omega)$ is considered to be 1 and $\bar{n}_2(\omega) = n_2(\omega) - j\kappa_2(\omega)$, of which the real part and imaginary part respectively reflect the dispersion and absorption characteristics of the material. $p_1(\omega, x)$ and $p_2(\omega, x)$ are the propagation factors of the electromagnetic wave with the angular frequency of $\omega$ at the propagation distance $x$ in air and in the sample, respectively and their values can be calculated by $\exp(-j\bar{n}_1(\omega)\omega x / c)$ and $\exp(-j\bar{n}_2(\omega)\omega x / c)$, respectively.

Theoretical spectral signal of the reference signal is given by:

$$E_r(\omega) = E_0(\omega)p_1(\omega, x_1 + d + x_2) \quad (1)$$

where $x_1$ is distance between the transmitting probe and the sample, $x_2$ is the distance between the receiving probe and sample, and $d$ is the thickness of the sample. The theoretical spectral signal of the sample signal is:

$$E_s(\omega) = E_0(\omega)p_1(\omega, x_1) \; p_2(\omega, d) \underbrace{[1 + (r_{12} p_2(\omega, d))^2 + (r_{21} p_1(\omega, d))^2 + \cdots]}_2$$

where the value of $E_0(\omega)p_1(\omega, x_1 + x_2)p_2(\omega, d)\underbrace{[1 + (r_{12} p_2(\omega, d))^2 + (r_{21} p_1(\omega, d))^2 + \cdots]}_2$ represents the energy transmitted through the sample straightly without reflections inside the sample and the according pulse is normally defined as the main pulse. The rest components in (2) is the energy transmitted through the sample after been reflected one or more times inside the sample. Generally, for mathematical convenience, all echo pulses is ignored in the theoretical analysis and the transfer function is given as:

$$H(\omega) = \frac{E_s(\omega)}{E_r(\omega)} = \frac{n_{12} n_{21}}{p_1(\omega, d)} \quad (3)$$

The transmission coefficient and the propagation factor in (3) are functions of complex refractive index of material $\bar{n}_2(\omega)$. Thus, the transfer function could be further expressed as a function of $\bar{n}_2(\omega)$:

$$H(\omega) = \frac{4n_2(\omega)}{1 + \bar{n}_2(\omega)} e^{-\frac{j(n_2(\omega)-1)\omega d}{c}} \quad (4)$$

In the tests, the reference signal and sample signal were measured separately and then processed by the Fast Fourier Transform (FFT) to obtain the spectral signals $E_{r, m}(\omega)$ and $E_{s, m}(\omega)$. Because of the presence of echo pulse in the original signals, it was crucial to preprocess the original reference signal and sample signal with time-windows interceptions on time domain before FFT.

Let

$$H(\omega) = \frac{E_{s, m}(\omega)}{E_{r, m}(\omega)} = \rho(\omega) \angle -\varphi(\omega) \quad (5)$$

then, the optical parameters of materials could be derived as follows:

$$n_2(\omega) = 1 + \frac{c\rho(\omega)}{\omega d} \quad (6)$$

$$\alpha_2(\omega) = \frac{2k_2(\omega)\omega}{c} = \frac{2\ln\left[\frac{4n_2(\omega)}{\rho(\omega)[n_2(\omega)+1]^2}\right]}{d} \quad (7)$$

$$k_2(\omega) = \frac{c\alpha_2(\omega)}{2\omega} \quad (8)$$

where $n_2(\omega)$, $k_2(\omega)$ and $\alpha_2(\omega)$ are the real part of the complex refractive index, the extinction coefficient, and the absorption coefficient respectively; $c$ is the speed of light; and $d$ is the thickness of sample.

Based on (6)-(8) and the relationship that $\varepsilon_2(\omega) = \bar{n}_2(\omega)^2$, the dielectric properties could be given by:
where $\varepsilon_{2r}(\omega)$ and $\varepsilon_{2i}(\omega)$ are the real part and imaginary part of the sample’s complex relative permittivity $\varepsilon_{2}(\omega)$, respectively, and $\tan\delta$ is its dielectric loss tangent.

A strategy to obtain the average refractive index value (the average value of the modulus of complex refractive index) based on the time-domain waveform of reference signal and sample signal was also proposed. According to the theory of electromagnetic wave propagation, the average refractive index $n$ could be calculated by the time delay $\Delta t$ between the main pulse of reference signal and sample signal as follows:

$$n = \frac{c\Delta t}{d} + 1$$

The tests of the average refractive index $n$ on terahertz band were carried out based on the T-Ray 5000 platform with the temperature setting at 20 °C and the relative humidity less than 10%. In this paper, the epoxy resin was served as an example to demonstrate the data-processing method. The reference signal and sample signal were shown in Fig. 6. The whole time length of the time-domain waveform of terahertz wave received at the software was 700 ps.

For visual convenience, Fig. 6 shows only part of the whole waveform, about 300 ps, to clarify the process of time-windows interception. It is obvious that the system echo pulses are contained in both the reference signal and sample signal. To intercept the portion of time-domain wave, $t_1$ and $t_2$ are used to represent the time windows for reference signal and sample signal, respectively. The principle for the selection of time window is that the time window begins a few picoseconds before the main pulse appears and ends a few picoseconds before the echo pulse appears. By the interception of time-domain waveform, the echo pulse in reference signal and sample signal can be excluded. It should be noted that it is essential to add a series of zeros to extend the time length of the intercepted waveform up to 700 ps as shown in Fig. 7.

![FIGURE 6. The interception process of original reference signal and sample signal of epoxy resin.](image)

For visual convenience, Fig. 6 shows only part of the whole waveform, about 300 ps, to clarify the process of time-windows interception. It is obvious that the system echo pulses are contained in both the reference signal and sample signal. To intercept the portion of time-domain wave, $t_1$ and $t_2$ are used to represent the time windows for reference signal and sample signal, respectively. The principle for the selection of time window is that the time window begins a few picoseconds before the main pulse appears and ends a few picoseconds before the echo pulse appears. By the interception of time-domain waveform, the echo pulse in reference signal and sample signal can be excluded. It should be noted that it is essential to add a series of zeros to extend the time length of the intercepted waveform up to 700 ps as shown in Fig. 7.

![FIGURE 7. The preprocessed reference signal and sample signal of epoxy resin.](image)

![FIGURE 8. The spectrum of real part of refractive index of each material at different frequencies.](image)

<table>
<thead>
<tr>
<th>Material</th>
<th>Average Refractive Index</th>
<th>Average Dielectric Constant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epoxy resin</td>
<td>2.35</td>
<td>5.52</td>
</tr>
<tr>
<td>Epoxy glass fiber</td>
<td>2.26</td>
<td>5.12</td>
</tr>
<tr>
<td>Polyethylene (XLPE)</td>
<td>1.51</td>
<td>2.27</td>
</tr>
<tr>
<td>Electrical porcelain</td>
<td>3.10</td>
<td>9.59</td>
</tr>
<tr>
<td>Silicone rubber (HTV)</td>
<td>1.89</td>
<td>3.36</td>
</tr>
</tbody>
</table>

After the reference signal and sample signal being processed by FFT, the spectrum of optical parameters and dielectric properties of each material could be measured by
(6) - (11) and the average refractive index by (12). The measured optical parameters and dielectric parameters of all five materials are shown in Fig. 8 and 9 and listed in Table II. It should be noted that the first method can be applied to all the five materials.

![Figure 8: Dielectric properties of epoxy resin](a)

![Figure 9: Dielectric properties of epoxy glass fiber](b)

![Figure 9: Dielectric properties of polyethylene (XLPE)](c)

![Figure 9: Dielectric properties of electrical porcelain](d)

![Figure 9: Dielectric properties of silicone rubber (HTV)](e)

**FIGURE 9.** The results of dielectric properties on terahertz band of each material: (a) epoxy resin; (b) epoxy glass fiber; (c) polyethylene (XLPE); (d) electrical porcelain; (e) HTV Silicone rubber.

**B. SECOND NOVEL METHOD**

In the first basic method, all echo pulse is ignored in both the process of the theoretical modeling and data-processing. However, when the reflected echo pulse is significant, the second method can be applied. The second method proposed needs only the sample signal as the data source and the measurement of reference signal becomes unnecessary. The attempts are made by dividing the sample signal into main pulse and reflected echo pulse. After that, the FFT is performed to obtain the spectral signal of the main pulse $E_{1,m}(\omega)$ and the spectral signal of the reflected echo pulse $E_{2,m}(\omega)$. Then, the transfer function can be expressed as:

$$H(\omega) = \frac{E_{2,m}(\omega)}{E_{1,m}(\omega)} = M(\omega) - L(\omega)$$  \hspace{1cm} (13)

According to the definition, the transfer function can also be calculated by:

$$H(\omega) = \frac{E_{2}(\omega)}{E_{1}(\omega)} = \left[r_{21}p_{2}(\omega,d)\right]^2$$  \hspace{1cm} (14)

and could be further expressed by a function of $n_2(\omega)$:
Then, the optical parameters could be calculated by:

\[ n_z(\omega) = \tan^{-1} \left( \frac{c\alpha(\omega)}{2\omega} \right) \]  

(16)

\[ \alpha_z(\omega) = -\frac{\ln M(\omega)[1+n_z(\omega)]^2}{d} \]  

(17)

\[ k_z(\omega) = \frac{c\alpha_z(\omega)}{2\omega} \]  

(18)

and the dielectric properties could be obtained by (9)-(11).

Sample signal, the average refractive index value \( n \) can be given by:

\[ n = \frac{cM}{2d} \]  

(19)

The measured average refractive index values by (19) in the second method are almost the same as that by (12) in the first basic method because of the same theoretical background.

The electrical porcelain was selected as an example to demonstrate the method as its reflected echo pulse in sample signal is significant. Firstly, sample signal was divided into main pulse and reflected echo pulse, as shown in Fig. 10. Then, the dielectric properties of the electrical porcelain were calculated by (9)-(11) as is illustrated in Fig. 11.

**FIGURE 10. Signal separation of electrical porcelain in the second method: (a) The sample signal; (b) main pulse and reflected echo pulse after division.**

**FIGURE 11. Dielectric properties of electrical porcelain on terahertz band.**

**FIGURE 12. Comparison of dielectric constant of porcelain measured in the first and second methods.**

It can be observed that the valid frequency range of the spectrum is 0.2 THz-1.5 THz in the first method. For the second method the valid frequency range is between 0.2 THz and 1.2 THz.
and 1.0 THz as the dielectric loss tangent turns negative when the frequency is above 1 THz. In fact, the energies of the reference signal and sample signal in the transfer function of the first method are much higher than that of main pulse and echo pulse in the transfer function of the second method, respectively. This makes the SNR of the first method higher than that of the second method. Fig. 12 shows a comparison of dielectric constant of porcelain measured in the first and second methods. It can be seen from this figure that the values of dielectric constant in both methods are very close to the average value in Table II (the imaginary part of dielectric constant is much lower than the real part so the real part is close to the value of the modulus of complex dielectric constant).

It should be noted that for materials with high imaginary part of the dielectric constant, it is necessary to reduce the sample thickness to ensure enough terahertz energy if the second method is adopted.

IV. DIELECTRIC PROPERTIES ON 1 HZ - 1 MHz

The dielectric properties of each material were also measured by the Novocontrol BDS at frequency from 1 Hz to 1 MHz. The BDS, equipped with a liquid nitrogen cooling system (LNCS), was capable of controlling the temperature and humidity of the test environment. In the tests, the test environment was kept constant at 20°C and the relative humidity less than 10%. The measured dielectric properties of five kinds of materials in the frequency range of 1 Hz-1 MHz are shown in Fig. 13. Moreover, the dielectric constant and dielectric loss tangent of each material at power frequency (50 Hz) are listed in Table III.

When compared Fig. 13 with Fig. 11, it can be seen that, for each material, the dielectric constant at terahertz frequencies is lower than that at the frequency range of 1 Hz-1 MHz for all five specimens and the dielectric loss tangent is generally higher than that at power frequency except epoxy resin. To explain this phenomenon, electrical porcelain is taken as an example. Electrical porcelain (aluminum oxide or Al₂O₃) is an excellent electrical insulator and one of the most widely used advanced ceramic material. As an ionic crystal, electrical porcelain has a low dielectric constant value. The dielectric constant of electrical porcelain in a relatively low frequency band can be derived.

The intensity of polarization $P$ can be expressed as:

$$ P = \varepsilon_0 (\varepsilon_r - 1)E $$  \hspace{1cm} (20)$$

where $\varepsilon_r$ is the relative dielectric constant which then can be calculated by:

$$ \varepsilon_r = 1 + \frac{N(\alpha_1 + \alpha_2 + \alpha_a)}{\varepsilon_0} $$  \hspace{1cm} (21)$$

where $N$ is the number of particles per unit volume; $\alpha_1$, $\alpha_2$, and $\alpha_a$ are the electron polarizability of positive ions, the electron polarizability of negative ions, and the displacement polarizability of ions, respectively.

According to Maxwell theory,

$$ \varepsilon_\infty = n^2 = 1 + \frac{N(\alpha_1 + \alpha_2)}{\varepsilon_0} $$  \hspace{1cm} (22)$$

where $\varepsilon_\infty$ is the dielectric constant on optical frequency band and $n$ is the refractive index.

Thus, the dielectric constant $\varepsilon_r$ can be expressed by:

$$ \varepsilon_r = n^2 + \frac{n}{\varepsilon_0} $$  \hspace{1cm} (23)$$

The dielectric properties of epoxy resin

<table>
<thead>
<tr>
<th>Material</th>
<th>Dielectric Constant ($\varepsilon_r$)</th>
<th>Dielectric Loss Tangent (tan$\delta$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epoxy resin</td>
<td>9.02</td>
<td>1.0202×10^{-3}</td>
</tr>
<tr>
<td>Epoxy glass fiber</td>
<td>7.50</td>
<td>9.38×10^{-3}</td>
</tr>
<tr>
<td>Polyethylene (XLPE)</td>
<td>3.96</td>
<td>2.27×10^{-4}</td>
</tr>
<tr>
<td>Electrical porcelain</td>
<td>11.54</td>
<td>6.15×10^{-3}</td>
</tr>
<tr>
<td>HTV silicone rubber</td>
<td>5.80</td>
<td>4.42×10^{-2}</td>
</tr>
</tbody>
</table>

The dielectric constant and dielectric loss tangent of five materials at power frequency (50 Hz)

TABLE III

The intensity of polarization $P$ can be expressed as:
FIGURE 13. The measured dielectric properties of five materials in the frequency range of 1 Hz-1 MHz: (a) epoxy resin; (b) epoxy glass fiber; (c) polyethylene (XLPE); (d) electrical porcelain; (e) HTV Silicone rubber.

FIGURE 14. Types of polarization and dielectric constant in the long range of frequency band.

It can be concluded from Eq. (21) to Eq. (23) that the difference between the polarization of dielectrics on a low frequency band (1Hz-1MHz) and on terahertz band (close to optical frequency band) depended on the polarization type. On the broad frequency band near power frequency, the process of most types of polarizations could be completed. Thus, the intensity of the polarization and the corresponding dielectric constant are high. However, on a rather high frequency band, there are many time consuming polarization processes failed to be completed such as relaxation polarization, steering polarization, interlayer polarization, and ion displacement polarization, etc. Fig. 14 shows the corresponding frequency band in which the process of each type of polarization occurs. Among the types of polarization, the effective frequency band for electron displace polarization is the widest while the effective frequency band for interlayer polarization is the narrowest.

FIGURE 15. Relationship between $\varepsilon_r$, $\tan\delta$, loss power $P$, and frequency.

Fig. 15 shows how the dielectric loss tangent and dielectric loss power change with frequency. 1) at low frequencies, the process of various polarizations can be completed, thus the relaxation polarization loss is approximately zero and the conductance loss is also low. However, the reactive current is extremely low, so $\omega \to 0$, $\tan\delta \to \infty$; 2) with the increase of frequency, the relaxation polarization cannot keep up with the change of the external electric field. Therefore, $\tan\delta$ increases with the frequency gradually; 3) in the high frequency region, since the dipole steering polarization can
hardly be started, $\tan \delta$ decreases with the increase of frequency but it is still higher than that at some lower frequencies.

V. CONCLUSION

In this paper, two methods using the terahertz wave technique were proposed to investigate the dielectric properties of five electric insulation materials which were commonly used in the power system. In the first method, the system echo pulse and the reflected echo pulse were excluded in both the reference signal and the sample signal. This method can be applied to all five insulation materials. For materials with low absorption and high reflection index such as electrical porcelain, the second method can be adopted. In the second method, sample signal was divided into main pulse and reflected echo pulse, making the measurement of reference signal unnecessary.

From the tests, it was found that the first method had a better signal-noise ratio and a wider effective frequency band of spectrums. It was also found that, for all specimens, the dielectric constant at terahertz frequencies was much lower than that measured by broadband dielectric spectrometer which used a relative lower frequency band (1Hz-1MHz). For most materials, the dielectric loss tangent at terahertz frequencies was generally higher than that at power frequencies.

As insulation material ages, its dielectric properties change over time. Therefore, the aging state can be evaluated by measuring the dielectric properties at different times and analyzing its variation. As a non-destructive method, terahertz technique has wide prospects in the applications such as aging testing and defect detection of insulation materials and could find useful applications by those who are actually working at THz frequencies.

REFERENCES


Hongwei Mei (M’11) was born in Changzhou, Jiangsu Province, China, in 1979. He received the B.S. and M.S. degrees in power system and its automation from the Department of Electrical Engineering, Harbin Institute of Technology, Harbin, P.R. China, in 2002 and 2004, respectively. He received the Ph.D. degree in electrical engineering from the Department of Electrical Engineering, Tsinghua University, Beijing, P.R. China, in 2011. He is now a lecturer in Graduate School at Shenzhen, Tsinghua University. His major research fields are high voltage insulation and electrical discharge.

Lanxi Li was born in Qujing, Yunnan Province, China, in 1996. He received the B.S. degree in Electrical Engineering from the Department of Electrical Engineering, Tsinghua University, Beijing, P.R. China, in 2018. He is now pursuing his master’s degree in Graduate school at Shenzhen, Tsinghua University. His major research fields are high voltage technology and testing of insulation materials.
Fanghui Yin (M’16) was born in Jiangxi Province, China, in May 1983. He received the B.Sc. and M.Sc. degrees at Chongqing University, Chongqing, China, in 2004 and 2008, respectively. After that, he obtained his Ph.D. degree at Université du Québec à Chicoutimi (UQAC), Canada, in collaboration with Chongqing University, China. He is now a postdoc at Graduate School at Shenzhen, Tsinghua University. His main research interests include high voltage technology, external insulation and transmission line’s icing.

Wei Hu was born in Hubei province, China, in 1979. He received the master degree in power electronics and power drives from Wuhan University (WHU), Wuhan, China, in 2006. Currently, He is working as a senior engineer in State Key Laboratory of Power Grid Environmental Protection of China Electric Power Research Institute. His research interests include UHV external insulation technology and high-tension bushing technology.

Jianben Liu was born in Hubei province, China, in 1985. He received the B.Eng. degree and the Ph.D degree in electrical engineering from Huazhong University of Science and technology (HUST), Wuhan, China, in 2007 and 2013, respectively. He is now working as a senior engineer in State Key Laboratory of Power Grid Environmental Protection of China Electric Power Research Institute. His research interests include power electronics, power system electromagnetic compatibility, harmonic suppression and reactive power compensation.

Liming Wang (M’10-SM’18) was born in Shaoxing, Zhejiang Province, China, on 30 November 1963, and received the B.S., M.S., and Ph.D. degrees in high voltage engineering from the Department of Electrical Engineering, Tsinghua University, Beijing, P.R. China, in 1987, 1990, and 1993, respectively. He has worked at Tsinghua University since 1993. His major research fields are high voltage insulation and electrical discharge, flashover mechanism on contaminated insulators, and application of pulsed electric fields.