A Noval Method for Moisture Content of Oil-paper Insulation Based on Non-destructive Testing Method

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Abstract-The detection for moisture content in oil-paper insulation has become a crucial a part of power transformer maintenance. However, the prevailing and widely used chemical titration method may be a quite destructive and time-consuming detection method. Therefore, it's of great significance to review non-destructive testing methods of oil-paper insulation moisture content. Moreover, because it are often applied to watch molecular-scale dynamic polarization phenomenon of water, terahertz (THz) dielectric relaxation spectroscopy could provide a valuable experimental window into the evaluation of moisture content in oil-paper insulation. Samples with different moisture content (0.4%-4.6%) were prepared by drying at different temperatures. The experimental results show that with the rising moisture content, the complex dielectric constant of oil-paper insulation in THz band increase, and these data are often fitted with relaxation-resonance model including two-Debye model and a damped resonance term, which might be wont to interpret possible micro-mechanism of polarization phenomenon caused by trace moisture in oil-paper insulation. supported the high frequency polarization characteristics of water in oil-paper insulation, this paper proposed a reliability and meaningful index for moisture detection from THz dielectric spectroscopy.

I. Introduction

The reliable and stable operation of oil-immersed power transformer is essential for electrical power system. In the oil-paper insulation of power transformer, the accumulation of moisture content from environment or insulation deterioration process would cause the increase of dielectric loss, which further leads to the decrease of breakdown voltage [1]. Therefore, monitoring the moisture content of oil-paper insulation is a necessary measure to ensure the safe operation of transformers. Karl Fischer titration (KFT) and frequency domain dielectric spectroscopy (FDS) [2, 3] are two main methods to measure the moisture content of oil-paper insulation, which have been widely used in power enterprises and research institutes. KFT is directly based on chemical method to measure moisture content of oil-paper with high accuracy, and has been used as a standard test method in the existing research on moisture content measurement of oil-paper insulation. But KFT method is not suitable for the field measurements, due to its operational complexity, time-consumption, and destructiveness. FDS based on dielectric polarization theory has a simple operation and can provide strong anti-interference capability. The dielectric characteristics obtained from FDS method have distinct information on the insulation status to assess and diagnose moisture and deterioration in the low-frequency range. However, long measurement time because of low-frequency oscillations is a mainly unavoidable disadvantage for FDS method [4].

To meet the requirements of field testing for oil-paper insulation, it is of great significance to study non-destructive and rapid testing methods of oil-paper insulation moisture content. Terahertz dielectric relaxation spectroscopy could provide a valuable experimental window into the evaluation of moisture content in oil-paper insulation because it can be applied to monitor molecular-scale dynamic polarization phenomenon of water [5, 6]. Water is highly absorptive in the THz range, while nonpolar medium such as paper and oil are reasonably transparent to THz wave. The higher permittivity of water compared to other materials in THz range enables a contrast mechanism for the detection and localization of moisture [7]. The THz spectroscopy has been applied for detection of water in leaf [8], wood [9], glass fiber reinforced polymers [10] and cells [11]. Meanwhile, the advantages of these water content measurement methods based on THz technology include simple operation, non-destructive testing and fast detection speed, as a result of the terahertz pulse emission time is in Pico second level.

Considering the high frequency polarization characteristics of water under the influence of oil-paper insulation remain to be explored, the aim of this paper is to find reliability and meaningful index for moisture detection of oil-paper insulation from THz dielectric spectroscopy. In this paper, oil-paper insulation samples with different moisture content were prepared, and the water content of each sample was calibrated by Karl Fischer titration method. Then the THz measurement for these samples was carried out, and the complex permittivity were further calculated. The validity of the THz dielectric response method has been experimentally verified. Finally, the relaxation and resonant motion of water molecules in oil-paper samples were analyzed.

II. Materials andMethod

A. Sample Preparation

Oil-paper insulation samples were prepared using 1 mm insulating paper board with an initial degree of polymerization of 1300 and 25 # naphthenic transformer oil. By drying the samples in vacuum for different time, we obtained 4 groups of samples with different moisture content and uniform moisture distribution, which were 0.452%, 0.895%, 2.156%, and 4.671%, respectively. The moisture content of these samples were determined by Karl Fischer titration method according to IEC 60814.

B. Experimental Setup

The transmission Terahertz time-domain spectroscopy (THz-TDS) system is consisted of femtosecond laser (Fs laser), THz radiation generator, time delay control system, THz detector, and signal conditioning module, as shown in Fig 1. The F spulse is split into a pump beam and a probe beam by the beam splitter. The pump beam is incident on the THz emitter through a delay line to generate terahertz pulses, which are focused on the samples by two sets of off-axis parabolic mirrors. The probe beam can gate the detector and measure the instantaneous terahertz electric field. Reference spectrum from probe beam and sample spectrum from pump beam can be obtained simultaneously in a single measurement. THz signals were registered with 5 times averaging for each sample at 25℃.

C. Data acquisition

The complex permittivity ε^* can well describe the interaction between the sample and the incident electromagnetic wave. Therefore, the experimental data are processed according to the optical parameter extraction model [12] to obtain the complex permittivity of the oil-paper sample in terahertz band. The refraction index $n(\omega)$, and the extinction coefficient $\kappa(\omega)$ can be directly obtained by Fourier transform. The calculation formulas are as follows:

$$n(\omega)=\frac{\varphi(\omega)c}{\omega d}+1 \quad (1)$$

$$\kappa(\omega)=\ln\{\frac{4n(\omega)}{\rho(\omega)[1+n(\omega)]^2}\}\frac{c}{\omega d} \quad (2)$$

where ω is the angular frequency, c is the light velocity, d is the thickness of the sample, $\varphi(\omega)$ is the phase difference between the reference spectrum and the sample spectrum, and $\rho(\omega)$ is the amplitude ratio of the reference spectrum to the sample spectrum. Knowledge of the extinction coefficient and refraction index [13] allow us to compute its complex dielectric response by

$$\varepsilon'=[n(\omega)]^2-[\kappa(\omega)]^2 \quad (3)$$

$$\varepsilon''=2n(\omega)\kappa(\omega) \quad (4)$$

where ε' is the real part of dielectric constant and ε'' is the imaginary part of dielectric constant.

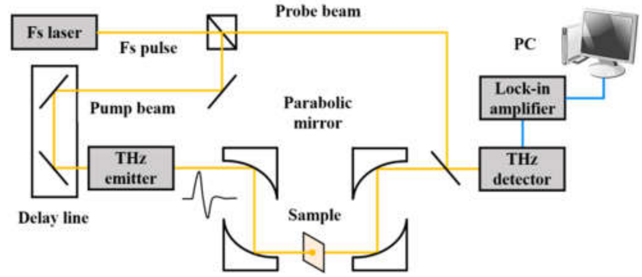

Fig. 1. THz-TDS system

III. RESULTS ANDDISCUSSION

The terahertz transmission time-domain energy spectrum of each experimental sample as shown in Fig. 2. Obviously, with the increase of water content, the terahertz signal amplitude decreases and the phase delay increases. This is due to the absorption and scattering of THz pulse signal through oil-paper samples. The slight change of water content has a significant impact on the experimental results, which indicates that THz wave is sensitive to water, but hasa good penetration characteristics for non-polarized materials. By vacuuming the sample, the influence of air in the mixed medium of oil-paper insulation was eliminated. Therefore, we believe that the difference between the experimental results is mainly due to the change of moisture content.

It is necessary to reveal the physical significance of THz spectrum of oil-paper insulation with different moisture content. In this paper, the dielectric properties of oil-paper insulation in terahertz band are further studied. According to (1)-(4), the dielectric constant of oil-paper insulation samples with different moisture content is presented in Fig. 3 and Fig. 4. The real part ε' and the imaginary part ε'' of dielectric constant of the oil-paper sample increases as a result of the rising moisture content. In oil-paper insulation, water molecule will play a leading role in the polarization of oil-paper in the electric field as the most important polar molecule.

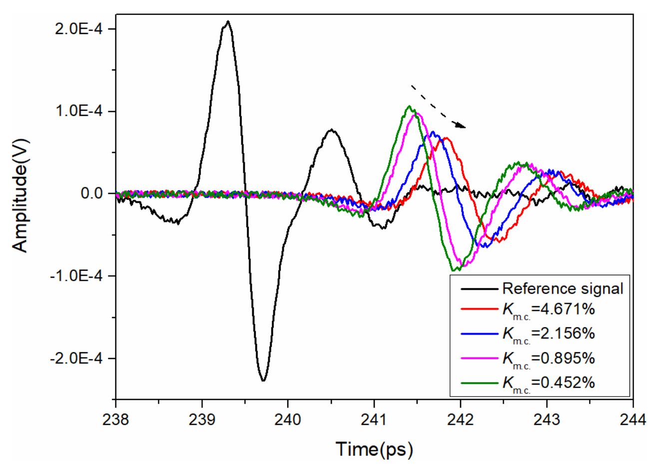

Fig. 2. THz transmission time-domain energy spectrum of oil-paper insulation samples with different moisture content ($K_{m.c.}$)

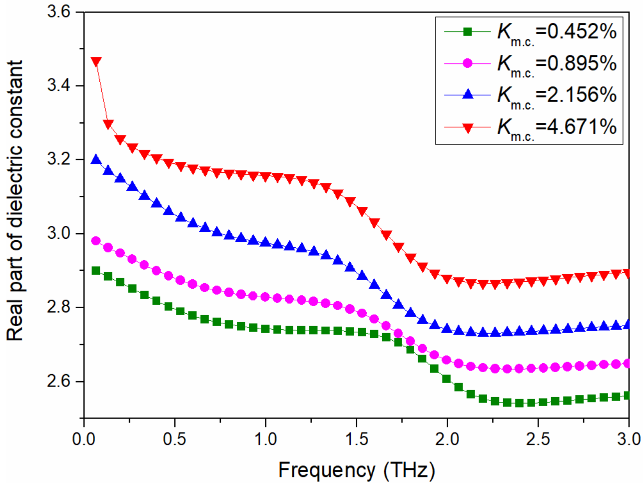

Fig. 3. The real part ε' of dielectric constant of the oil-paper sample

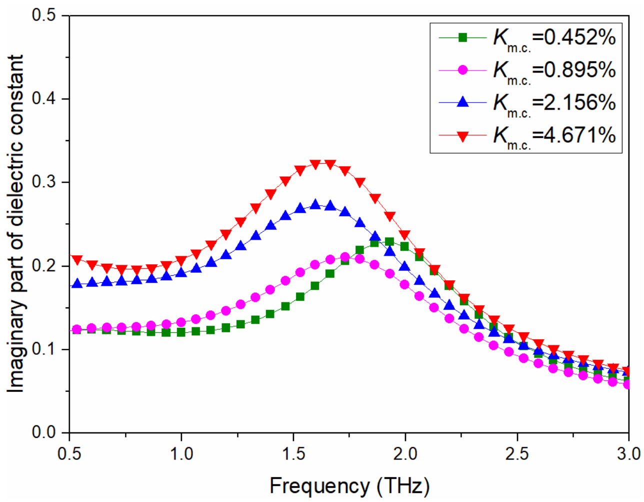

Fig. 4. The imaginary part ε'' of dielectric constant of the oil-paper sample

Considerable research has been done on the dynamic polarization of water molecules in terahertz band. Previous reports argue that two Debye relaxation processes with different relaxation times that dominates the dielectric relaxation of water below 1 THz [5, 6, 14]. Besides, at higher frequencies, the resonance polarization caused by the intermolecular stretching and libration cannot be neglected [15]. Therefore, we decomposed the complex dielectric constants into the relaxation-resonance integrated model by Levenberg-Marquardt method [16] fitted to the following equation:

$$\varepsilon^*(f)=\varepsilon_\infty+\frac{\Delta\varepsilon_1}{1+i2\pi f\tau_1}+\frac{\Delta\varepsilon_2}{1+i2\pi f\tau_2}+\frac{A_{OSC}/(2\pi)^2}{f_{OSC}-f^2+i(k_{OSC}/2\pi)f} \quad (5)$$

where ε_∞ is the dielectric constant in the high frequency limit, $\Delta\varepsilon_1$ and $\Delta\varepsilon_2$ are the relaxation strengths of the two Debye relaxation modes with τ_1 and τ_2 relaxation times, respectively. A_{OSC} are the amplitude, f_{OSC} are the frequency, and k_{OSC} are the damping constants of the resonant polarization term, respectively.

Using this approach, the real and imaginary parts of the complex permittivity of oil-paper insulation samples were determined over the 0.1THz to 3 THz with different moisture content, as shown in Fig. 5 and Fig. 6. The fitting calculation was performed for the spectrum decomposition procedure until the chi-square χ^2 could reach 10^{-5}. The fitting data are in good agreement with the experimental data, which indicates that the relaxation-resonance integrated model can effectively reveal the polarization behavior of oil-paper insulation in terahertz band. The best-fit values of the two Debye relaxation times $\tau_1 = 7.96 \pm 0.32$ and $\tau_2 = 0.37 \pm 0.09$, which is consistent with the calculation results of existing studies [7, 8, 14, 15]. The relaxation polarization characteristic of trace moisture is independent of other dielectrics in oil-paper insulation. This might be due to the observed frequency band we specially selected is insensitive to the relaxation time of insulating oil and cellulose insulating paper.

The amplitude of the resonant polarization term A_{OSC} as shown in Fig. 7. This intermolecular stretching polarization mode is known to be delocalized over the proximal water molecules, reflecting the structural and dynamical characteristics of the water hydrogen bond network. In oil-paper insulation, there are two main hydrogen bonds formed by water molecules: water-water hydrogen bond and water-cellulose hydrogen bond. With the increase of water content, the number and strength of two types of hydrogen bonds formed by water molecule increase in different degrees. It should be pointed out that the change of hydrogen bond network inside the cellulose will not be observed in this frequency band (0.1 THz - 3 THz). More detailed inspection of the data in Fig. 7 suggests that A_{OSC} is positively correlated with the moisture content, and thus can be used as a characteristic parameter to detect the moisture content of oil-paper insulation.

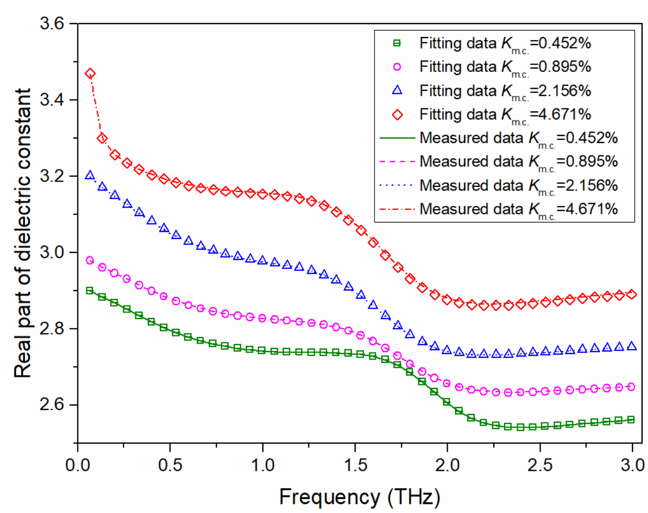

Fig. 5. The fitting data of the real part ε' of dielectric constant

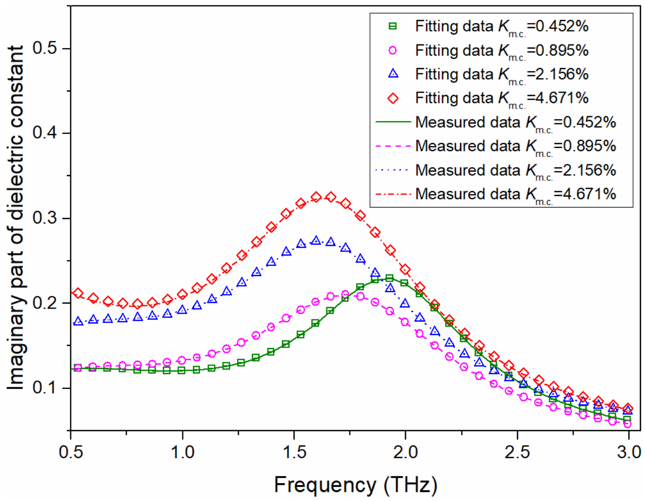

Fig. 6. The fitting data of the imaginary part ε'' of dielectric constant

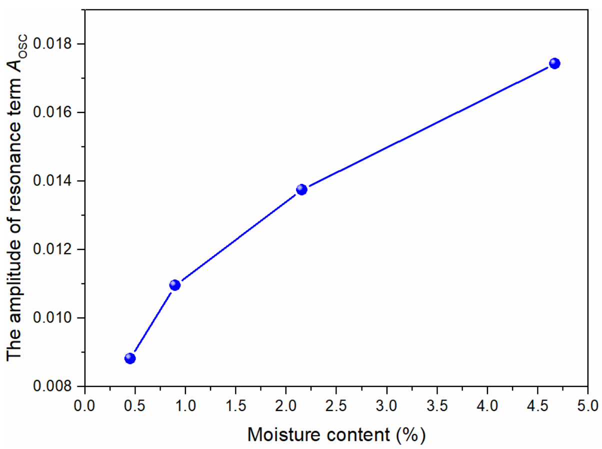

Fig. 7. The amplitude of the resonant polarization term A_{OSC} is positively correlated with the moisture content

IV. CONCLUSIONS

THz nondestructive testing method can effectively and rapidly detect moisture content in oil-paper insulation. The experimental results indicate that the polarization of oil-paper insulation increases with rising water content, so the THz dielectric response of oil-paper insulation samples with different moisture content shows significant difference. In terahertz band, water molecules in oil-paper insulation are affected by relaxation polarization and harmonic polarization. The fitting results show that the THz dielectric properties of oil-paper insulation samples basically conform to the relaxation-resonance integrated model. The amplitude of resonance term A_{OSC} in the model is related to the vibration of hydrogen bonds between water molecules and cellulose in THz frequency range. Moreover, A_{OSC} is positively correlated with the moisture content, and thus can be used as a characteristic parameter to detect the moisture content of oil-paper insulation.

It is expected that the proposed method can be further developed for on-line monitoring the moisture distribution of oil-paper insulation. The quantitative relationship between the A_{OSC} and water content in different environments can be determined by further molecular simulation studies. The imaging of the non-uniform distribution of moisture content in oil-paper insulation using THz method are currently underway.

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