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Research Paper



Degradation evaluation of high voltage insulating oils by terahertz spectroscopy

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Abstract

Background/Objectives: The stable electrical power supply is the most important issue for modern industrial society employing various electrical appliance. The power transformer is one of the most important component in the electrical power supply system.
Methods/Statistical analysis: The common diagnosis method of insulating oil of transformer is gas-chromatograph. The gas-chromatograph is performed to detect dissolved gas ininsulating oil of transformerduring the stop-period of transformer unit. In this research, the optical properties of insulating oils of transformer (unused new oil, used oil of normal operation, and waste oil of malfunction) are analyzed using a terahertz time-domain spectroscopy in the range of 0.1 ~ 3.0 THz.
Findings: The new insulating oil is colorless and transparent. The used insulating oil and waste insulating oil exhibit dark yellow and brown color. The THz sample pulses are delayed of phase and reduced of amplitude compare to passing through the free space. The reduce of amplitude is attributed to increasing of absorption due to aging effect of oils. The refractive index and absorption coefficient of insulating oils are calculated from measured THz pulses. The refractive index of 'new or used oil' exhibits a constant value of 1.455 and 1.463 in the full frequency range. But refractive index of 'waste oil' exhibits various values of 1.466 ~ 1.485 with the frequency, which is relatively high. The normalized amplitude of waste insulating oil is reduced. The absorption coefficient of waste insulating oil is increased linearly with the increase of frequency. The reducing of THz amplitude is attributed to increase of absorption due to aging effect of oils.
Improvements/Applications: The aging effect of insulating oils of transformer is characterized by the portable THz-TDS system. It can be applied to in situ monitoring of insulating oil conditions.

Keywords: *Terahertz Spectroscopy; Insulating Oil; Refractive Index; Dielectric Constant; Absorption Coefficient; Degradation.*

1. Introduction

The modern industrial society has been used various electrical appliance such as refrigerator, air conditioner, TV, computer etc. The stable electrical power supply is the most important issue for modern industrial society. The power transformer isone of the most important and cost-intensive component in the electrical power supply system. An unexpected outage results in substantial costs mainly caused by the outage of the power substation[1]. Therefore, a big interest and various methods for diagnosis of power transformer conditions are given [2-5]. The most common insulation system for power transformer is oil-board insulating system. Diagnostic methods of power transformer are broadly categorized such as chemical diagnostic methods, electrical diagnostic methods, optical/thermal diagnostic methods, and mechanical diagnostic methods. The most effective characterization method of insulating oil is the gas-chromatograph, thechemical methods which has high sensitive sensors, to detect internal gas (dissolved gas, gas-in-oil) of transformer. The maintain of electrical power quality is controlled by time based maintenance system. The electrical substations are equipped the parallel electrical power transformer units under time based maintenance system. The diagnosis of insulating oils of power transformer is performed by gas-chromatograph analysis in stop-period of power transformer unit [6-7]. The development of real time monitoring technique of insulating oil conditions is requested for effective condition based power maintenance system. Real time monitoring of insulating oil characteristics is possible with using an UV-visible spectroscopy, FT-IR spectroscopy, and Terahertz (THz) spectroscopy [8-10].
Terahertz wave is the part of electromagnetic spectrum between the microwave and far infrared bands (0.1 to 10 THz). THz-TDS (time-domain spectroscopy) has been employed to investigate a wide variety of materials, including liquids [11], graphene [12], paints [13-14], ceramics [15], and biomolecules [16].
In this paper, degradation evaluation of insulating oils of high voltage power transformer is characterized by THz-TDS for aging effect of insulating oils. The optical properties of insulating oils, such as the refractive index, absorption coefficient, dielectric constant, and tan delta are analyzed in the spectral range of 0.1 to 3.0 THz.

2. Experimental details

The THz-TDS system has conventional transmission geometry. In general, THz-TDS systems are consisted with bulk optical components which have beam alignment problems. But developed our portable THz-TDS system is beam alignment issues free due to the employing of single mode optical fibers. Optical pulses with pulse width of approximately 90 fs at 1560 nm are delivered from a mode-locked optical fiber laser at a repetition rate of 100 MHz. To generate THz pulse, the pumped beam is focused on the biased gap of a photoconductive antenna fabricated on a low-temperature-grown GaAs (LT-GaAs) layer. The THz pulse is measured in a phase sensitive detection circuit by lock-in amplifier (Stanford Research System, SR830). The THz waves are seriously affected by water vapor,

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thus the system is enclosed in a chamber which is purged with dry air to reduce THz absorption due to residual water vapor in the THz beam path. The measurements are carried out at room temperature and 1% of relative humidity.

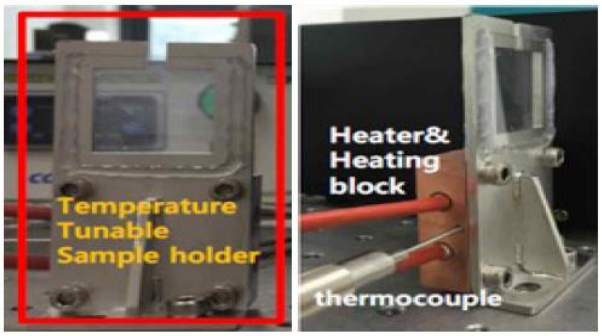


Fig. 1: Digital Photos of Thz Liquid Sample Holder and Liquidsample Cell.

The liquid sample holder is fabricated with the aluminum plate and polypropylene (PP) plates which are THz window, and has 2 mm thickness as shown in Figure 1. The sample cell shape is a rectangular slab with 5 mm interspace thickness. The sample holder is assembled on heating block of copper.The heater and thermocouple are embedded into heating block. The heating block is controlled with 1ºC accuracy.The Korean Electric Power Corporation (KEPCO) is offered insulating oils to analyze the aging effect of insulating oils. The 'waste insulating oil' was extracted from the malfunction transformer. The 'used insulating oil' was extracted from the normal operation transformer. The last 'new insulating oil' is a fresh insulating oil which is an unused oil. The KEPCO has several kinds of insulating oils. But the offered insulating oils are same types in this analysis. Figure 2 is a digital photograph of insulating oils. The new insulating oil is colorless and transparent. The used insulating oil and waste insulating oil exhibitdark yellow color and brown color.



Fig. 2: Digital Photos of Insulating Oils which are Characterized by Thz-TDS (Unused New Oil, Used Oil of Normal Operation, and Waste Oil of Malfunction).

3. Results and discussion

The measured THz pulses and normalized amplitude spectra are shown in Figure 3. The black solid line is a THz reference pulse passing through the empty cell of PP window. The sample pulses transmitted though the same cell filled with the liquid insulating oils were obtained in the time domain. The THz sample pulses of transmitted or reflected are reduced of amplitude, and delayed of phase compare to passing through the free space. In general, strong reducing of amplitude indicates strong absorption, and large delay of phase indicates large refractive index. The normalized amplitude spectra of insulating oils, which are obtained by Fast Fourier Transform (FFT) of the measured THz pulses, are shown in Figure 3 (b).It shows that reducing of amplitude is attributed to increase of absorption due to aging effect.

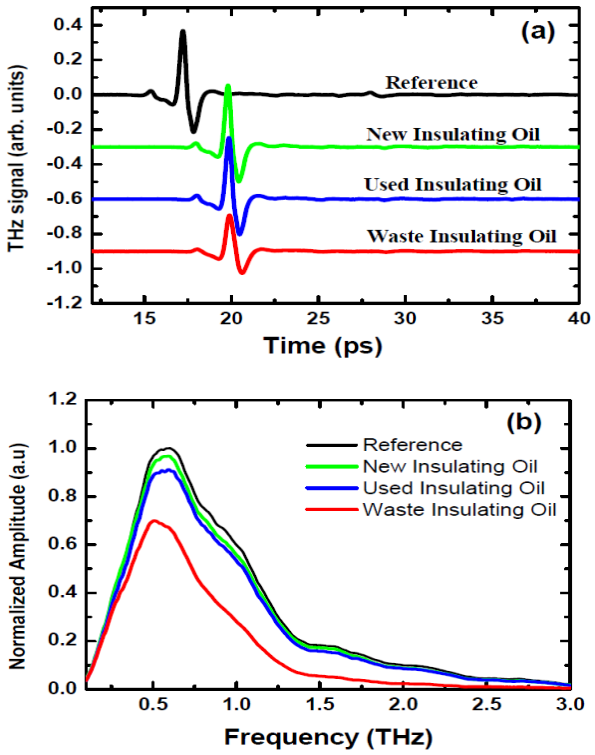
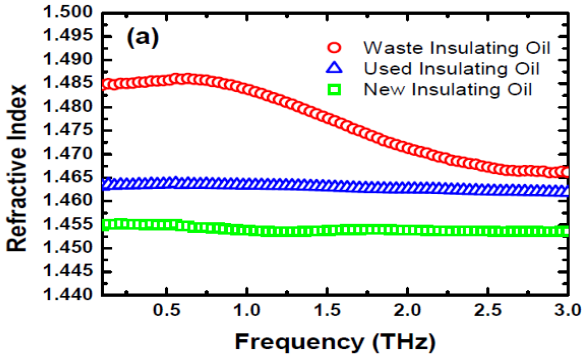


Fig. 3: (A) Measured Thz Pulses. Black Line Is the Reference Pulse Passing Through The Empty Sample Cell. (B) Normalized Amplitude Spectra which are obtained by Fast Fourier Transform (FFT) of the Measured Thz Pulses.

Assuming the normal incidence of THz pulse and non-scattering surface of sample surface, THz-TDS measurement can describe with the Fresnel equation. The refractive index, absorption coefficient, and dielectric constant of insulating oils can be calculated from measured THz pulse in time domain and phase components which are obtained from FFT of THz pulse in frequency domain. Figure 4 shows the refractive index and absorption coefficient of insulating oils. The refractive index of 'new insulating oil' and 'used insulating oil' exhibit constant values of 1.455 and 1.463 in the full frequency range. But the refractive index of 'waste insulating oil' exhibits various values of 1.466 ~ 1.485 with the frequency, which is relatively high. It shows that high refractive index and changing of refractive index value with the frequency are attributed to aging effect of insulating oils. The absorption coefficient of 'new insulating oil' and 'used insulating oil' exhibit constant values of 0 ~ 1 cm^{-1} and 0.8 ~ 1.8 cm^{-1} in the full frequency range. But the absorption coefficient of 'waste insulating oil' is changed 1 ~ 17 cm^{-1} with the increase linearly of frequency. It is also aging effect of insulating oils.



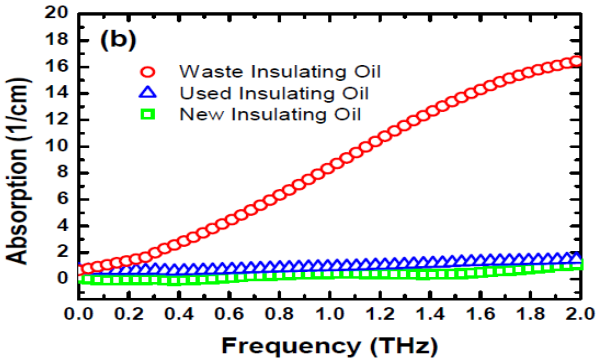


Fig. 4: The Thz Characteristics of Insulating Oils. (A) Refractive Index, and (B) Absorption Coefficient.

The complex dielectric constant($\epsilon(\omega) = (n_r + n_i)^2$) of insulating oils can be calculated from refractive index and absorption coefficient($\alpha = 2n_i\omega/c$) of insulating oils. The real part and imaginary part of dielectric constant are calculated by $\epsilon_r = n_r^2 - n_i^2, \epsilon_i = \alpha n_r c/\omega$. It is shown in Figure 5. The real dielectric constant of 'new insulating oil' and 'used insulating oil' exhibit constant values of 2.12 and 2.14. But real dielectric constant of 'waste insulating oil' exhibits relative high of 2.15 ~ 2.21. It is also aging effect of insulating oils.

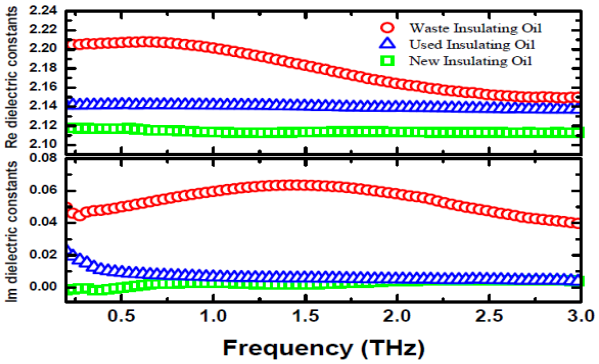


Fig. 5: Dielectric Constants of Insulating Oils Characterized as Functions of Thz Frequency.

The loss coefficient tanδof power loss can be calculated from $\tan\delta = \epsilon_i(\omega)/\epsilon_r(\omega)$. The loss coefficient is shown in Figure 6. The loss coefficient of 'new insulating oil' is nearly zero, which means zero power loss. But the loss coefficient of 'waste insulating oil' exhibits relatively highof 2.0 ~ 3.0.

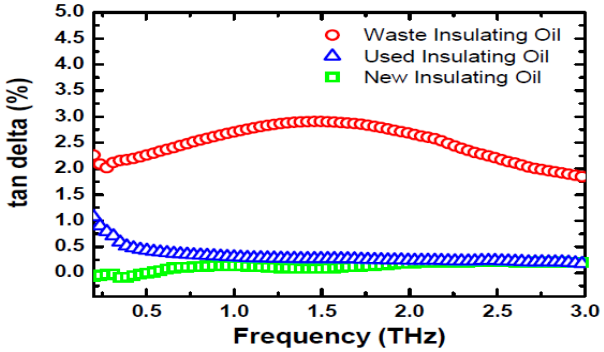


Fig. 6: The Tan Delta of Insulating Oils, which are Indicated Dielectric Power Loss Obtained from Complex Dielectric Constants of Insulating Oils.

4. Conclusion

The aging effect of insulating oils of high voltage transformer is characterized by the portable THz-TDS system. The absorption coefficient and power loss coefficient of 'new oil and normal operation oil' exhibit low constant value in the range of 0.1 ~ 3.0 THz frequency. But absorption coefficient of 'waste oil of malfunction' exhibits linearly increase with the increase of frequency. The power loss coefficient of 'waste oil' exhibit relatively high. The portable THz-TDS system is a compact and beam alignment free system. Thus the portable THz-TDS system can be applied to in situ monitoring of transformer in substation. The in situ monitoring of transformer in substation is key play of stable electrical power supply with the low cost.

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