Nondestructive and Noncontact Dielectric Measurement Methods for Transformer Oil Using Free-space Microwave Measurement System in 19 – 25 GHz Frequency Range

A. M. Aziz[1], A. K. Ermeey[2], K. Jusoff[3]

Abstract – Nondestructive, noncontact and real time evaluation of dielectric properties of low-loss liquids are important for applications such as service-aged transformer oil, biomedical, remote sensing and design of radar absorbing material. Free-space methods were developed to measure dielectric properties of low-loss liquids at microwave frequencies. Metal-back method was developed for Free-space Microwave Measurement system (FSMM). The purpose of this research is to measure the dielectric properties of transformer oil by using free-space microwave measurement system between 18 – 26 GHz (K-band), to compare measured results with published results for transformer oil and to collect the variation values of dielectric properties in microwave frequency between 18GHz to 26GHz (k-band). FSMM system consists of spot focusing horn lens antennas, mode transitions, coaxial cables and vector network analyzer (VNA). Dielectric constants and loss factors were measured for new transformer oil and all results close agreed with published data. It is observed that metal-back method is suitable for dielectric measurement of transformer oil.

Keywords: Nondestructive, Noncontact, Metal back, Horn antennas, Coaxial, Microwave, Transformer oil.

I. Introduction

The increase use of microwave for industrial testing is generating a growing requirement for accurate permittivity measurement as a function of frequency [1]. Recent airborne and deep-space applications need broadband and real-time dielectric characterization for the health monitoring of man-made composites. The study of the electrical properties of liquids and powders is of great importance in applications like radar absorbing material (RAM) design and remote sensing. When discuss about power transmission systems almost of transformers in power engineering system around the world are filled with liquid, it is function as heat transfer agent or coolant. The sensitivity of transformer oil to temperature and impurities, the function as heat transfer agent or coolant will decrease, due to deterioration of dielectric properties of this oil. The aldehyde and acids compounds are the examples of impurities which can contribute to aging process of transformer oil [2]. The monitoring of moisture contain in transformer oil is highly concerned, because it will contribute to the existence of sludge in a tank, then the ability of transformer oil as insulator will gradually decrease. Dissolved gas analysis (DGA) is a certain method to diagnose incipient fault of transformers through the correlation between the content of gases dissolved in transformer oil and a particular malfunction [3]. There are many techniques, such as cavity resonant technique, coaxial line and waveguide employed to evaluate dielectric properties of liquids. However all these techniques are clearly destructive and requires contact with measuring equipment [1, 4]. In order to use waveguide and cavity techniques, the sample should be fitted exactly into the sample holder. A small misalignment can cause large measurement errors [1, 4]. The coaxial line technique, it is required that there is a perfect contact between the probe and the sample [1, 4]. A free-space microwave measurement system has been used to measure dielectric and magnetic properties of materials [5-6]. In this research, we present newly developed metal-back technique for liquid samples to achieve the objectives of this research, which are to measure the dielectric properties of transformer oil by using free-space microwave measurement system between 18GHz to 26GHz (K-band), to compare measured results with published results for transformer oil and to collect the variation values of dielectric properties in microwave frequency between 18GHz to 26GHz (k-band).

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II. Theory

In order to implement metal back method, complex permittivity ($\varepsilon_s *$) of the sample can be computed from measured reflection coefficient (S_{11}). Fig.1 shows the schematic diagram for metal back technique for liquid samples where d is the thickness of plexiglas layer and ℓ is thickness of sample. Reflection coefficient (S_{11}) is measured by inserting a metal plate behind of plexiglas container which is facing transmit antenna.

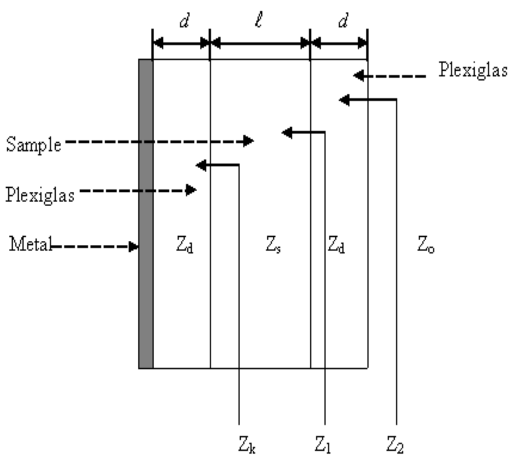

Fig. 1. Schematic diagram for metal back methods.

Where Z_s is characteristic impedance for sample which is defined as:

$$Z_s = \frac{Z_o}{\sqrt{\varepsilon_s *}} \quad (1)$$

The characteristic impedance for Plexiglas can be defined as:

$$Z_d = \frac{Z_o}{\sqrt{\varepsilon_d *}} \quad (2)$$

Where Z_o is characteristic impedance for free-space:

$$Z_o = \sqrt{\frac{\mu_o}{\varepsilon_o}} = 377.0 \text{ Ohms} \quad (3)$$

Complex phase constant for sample and Plexiglas define as

$$\beta_s = \frac{2\pi}{\lambda_o}\sqrt{\varepsilon_s *} \quad (4)$$

$$\beta_d = \frac{2\pi}{\lambda_o}\sqrt{\varepsilon_d *} \quad (5)$$

Referring to Figure 1, input impedance for the second layer (Plexiglas) can be defined as

$$Z_k = jZ_d \tan(\beta_d d) \quad (6)$$

After that, let define $X_d = \tan(\beta_d d)$ to simplify the equation 6, then

$$Z_k = jX_d Z_d \quad (7)$$

Based on transmission line theory, Z_1 in Figure 1 can be expressed as:

$$Z_1 = Z_S\left[\frac{Z_k + jZ_S \tan(\beta_s \ell)}{Z_S + jZ_k \tan(\beta_s \ell)}\right] \quad (8)$$

Equation (8) can be simplified by defining $\tan(\beta_s \ell) = X_s$ Then,

$$Z_1 = Z_S\left[\frac{Z_k + jZ_S X_S}{Z_S + jX_S Z_k}\right] \quad (9)$$

After substituting Z_k, we get

$$Z_1 = Z_S\left[\frac{jX_d Z_d + jZ_S X_S}{Z_S + jX_S(jX_d Z_d)}\right] \quad (10)$$

Next Z_2 as shown in Figure 1 is the input impedance of the metal-Plexiglas-Sample-Plexiglas assembly. The relation of Z_2 and Z_1 based on transmission line theory, it can be expressed as:

$$Z_2 = Z_d\left[\frac{Z_1 + jZ_d \tan(\beta_d d)}{Z_d + jZ_1 \tan(\beta_d d)}\right] \quad (11)$$

Then, the calculated value of S_{11} is given by

$$S_{11}^{cc} = \left[\frac{Z_2 - Z_o}{Z_2 + Z_o}\right] \quad (12)$$

However, sample permittivity ε_S cannot be expressed explicitly in terms of S_{11}^{cc}. So, it is necessary to find it iteratively by assuming a guess value for the complex permittivity of the sample. This is done by using a zero finding technique which finds the zeros of the error function. The error function is defined as:

$$E = |S_{11}^{mc} - S_{11}^{cc}| \quad (13)$$

where S_{11}^{mc} is the measured reflection coefficient of Plexiglas container terminated by metal plate, this value of

S_{11}^{mc} is obtained from FSSM. The Muller method with deflation is used for calculation of zeros of the error function [7] which gives ε_S.

III. Materials

The measurement setup Free-space Microwave Measurement system (FSMM) is presented in Fig. 2. Transmit and receive antennas which are spot-focusing horn lens antennas were mounted on a large table (1.83 m by 1.83 m). The spot-focusing horn lens antenna consists of two equal plano-convex dielectric lenses mounted back to back in a conical horn antenna. The spot-focusing antennas were connected to the two ports of S-parameter test set by using circular-to-rectangular waveguide adaptors, rectangular waveguide to coaxial line adaptors, and precision coaxial cables. S-parameter measurements in free-space were measured by Wiltron 37269B vector network analyzer system.

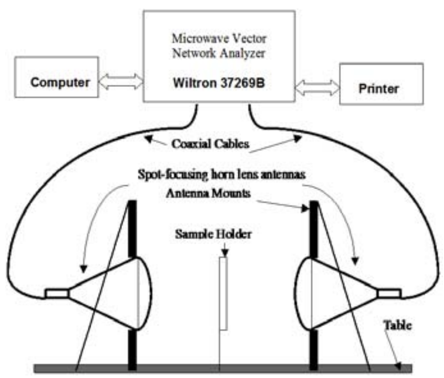

Fig. 2. Schematic diagram of free-space microwave measurement system

Error in free-space measurement of S-parameters due to multiple reflections between the spot-focusing horn lens antennas and the mode transitions were eliminated by implementing LRL (Line, Reflect, Line) calibration techniques in free space [5-6]. Post calibration errors are minimized by using time-domain gating which is a feature of VNA.

After LRL calibration, for verification purposes, dielectric properties of Teflon™ and Plexiglas materials were measured at 22 GHz with consider the center of frequency. Measured values of dielectric constants for Plexiglas and Teflon™ samples were 2.65 and 2.1, respectively. In the literature [8], Plexiglas and Teflon™ values were reported as 2.59 and 2.08, respectively. There is a good match in dielectric constant values. However, loss factor values for these materials cannot be measured accurately because they have loss tangent values less than 0.025.

Fig. 3 and Fig. 4 shows the process of measurement preparation. Plexiglas has chosen as a container because transparent and easy to cleaned.

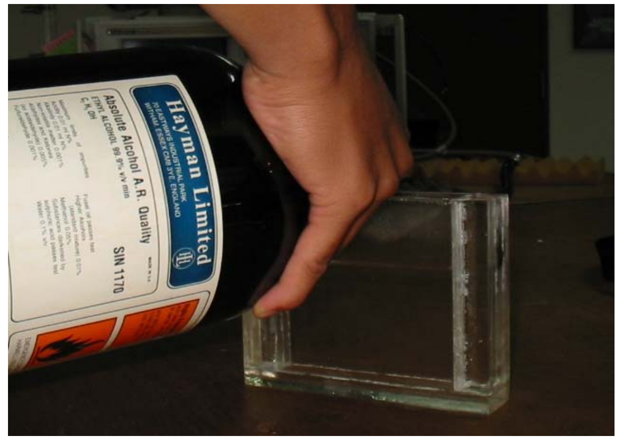

Fig. 3. Sample poured into container

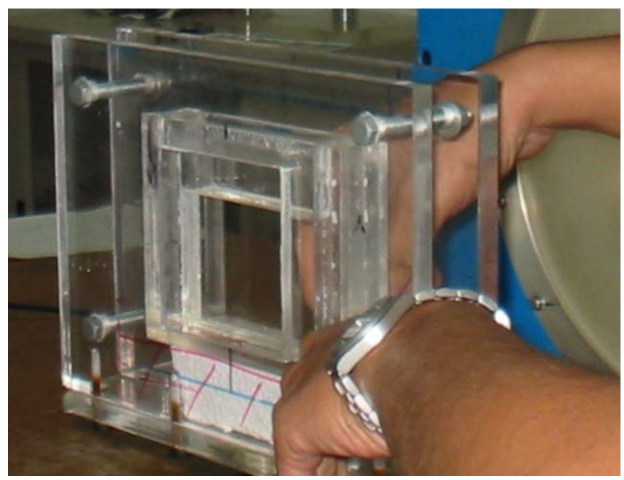

Fig.4. Container sandwiched on the sample holder

IV. Results and discussion

All measurements are done at 20°C. Fig.5 and Fig.6 show the measured dielectric constants and dielectric loss tangent of new transformer oil. The measured dielectric constant for transformer oil is 2.2 as reported [9] at 50 Hz. Based on these data our measured values are close to published data. The results are also compared to reference [10] at 8 to 12 GHz. Values of dielectric constant and loss tangent in the range of 0.00 to 0.1. It should be noted that this method have poor accuracy for measurement of loss tangent values less than 0.025. The inaccuracy in loss tangent measurement is due to simultaneous determinations of ε_S^* which resulted in higher sensitivity to measurement errors. Thus ε_S^* cannot be measured accurately.

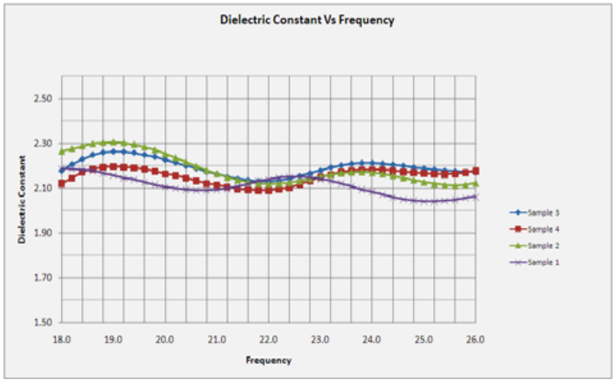

Fig. 5. Value of dielectric constant

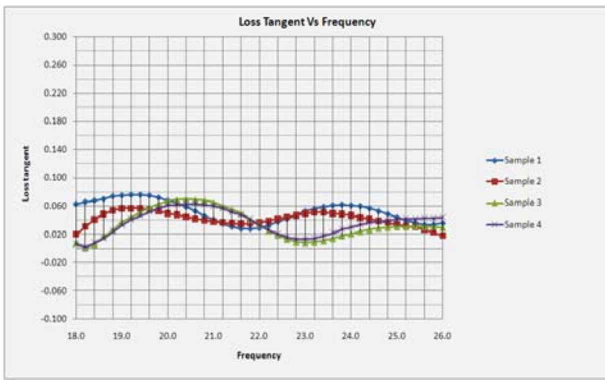

Fig.5. Value of loss tangent

V. Conclusion

The variation of dielectric constant new transformer oil in the range of frequency is close to the expected values as published by others. The metal back method using Free-space Microwave Measurement system can be applied to measure the electrical properties of transformer oil. Metal back Free-space Microwave Measurement system if feasible promises an option to measure the deterioration of transformer oil on site. In order to accommodate the high demand for fast and real time data determination, this technique has an advantage as noncontact method requires no sample preparation in laboratory experimentation.

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Authors' information

[1]**A. M. Aziz** was born in Semporna Sabah. He is a lecturer at Faculty of Electrical Engineering, Universiti Teknologi MARA Terengganu. He received his Bachelor in Electrical Engineering 2000from Universiti Teknologi MARA Shah Alam Malaysia and received his Masters in Electrical Engineering 2005 from same.

A. M. Aziz is a member of The Institute of Electrical and Electronics Engineers (IEEE) in Microwave Theory and Technique Society and Antenna and Propagation Society. E-mail: mohda474@tganu.uitm.edu.my

[2]**K. A. Ermeey** was born in Sentul Kuala Lumpur. Malaysia. He is a lecturer at Faculty of Electrical Engineering, Universiti Teknologi MARA Terengganu. He received his Bachelor in Electrical Engineering 2000from Universiti Teknologi MARA Shah Alam Malaysia and received his Masters in Electrical Engineering 2005 from same.

K. A. Ermeey is a member of The Institute of Electrical and Electronics Engineers (IEEE). E-mail: ermee461@tganu.uitm.edu.my

[3]**Hj. Kamaruzaman Jusoff (Corresponding Author)** received his PhD in 1992 in Forest Engineering Survey/Applied Remote Sensing from Cranfield University, England, UK. He has been a Professor with UPM since 1999. He was a Visiting Professor with Yale's Center for Earth Observation, Environmental Science Center, Yale University, New Haven CT, USA and rescently, with Harvard University. E-mail: kjusoff@yahoo.com

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