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Research paper

Simple capacitor dielectric sensors for determination of water content in transformer oil

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Abstract

In this paper, two electrode dielectric sensors for evaluation of water content in transformer oil are presented. Several setup and design were investigated. Parallel plate electrode was the most optimum design. The first sensor could be used for lab testing of transformer oil while the second sensor designed to be used for online and in-situ testing. Validation and calibration standard procedures were developed for both electrode dielectric sensors. The calibration and validation standard were performed to improve the accuracy of the sensors for measuring dielectric properties of the transformer oil. The results of the dielectric constant and loss factor of transformer oil containing different amount of water content were evaluated. The results of dielectric properties also evaluated and measured in the frequency range from one kHz to one MHz. The results of complex permittivity of transformer oil show that the real and imaginary part (dielectric constant ε' and loss factor ε'') of transformer oil raise with increasing oil water content while both real and imaginary parts decline with increasing operating frequency. The dielectric sensor shows its capability to determine the water content in transformer oil and could be used for quality control of oil.

Keywords: *Capacitor; Dielectric properties; Sensor; Transformer oil; Water content.*

1. Introduction

Transformer oil is characterized as oil with high electrical insulation properties and is considered high stable characteristic even at very high temperatures. Transformer oil is used in some engineering applications in general and in many applications of electrical and electronic engineering in particular. These applications include high voltage capacitors and circuit breakers. Other uses of transformer oil include transformers filled with oil and fluorescent lamp brakes[1]. The principal and vital function of transformer oil is to cool and isolate electrical transformers to prevent electrical short circuit that can lead to fire and explosion, especially in electrical power plants. Several main characteristics determine the quality of the oil to use as transformer oil for insulation. One of the most important characteristics is that the oil has strong electrical insulation and be stable chemically and resist the process of decomposition to a high degree and for an extended time. In addition to these characteristics must have suitable thermal conductivity and does not contain a very low water content or that the proportion of water pollution is nil[2].

Mineral transformer oil is the most used oil and is produced by distillation and treatment of heavy crude oil. The most important types of mineral transformer oil are naphtha-based and paraffin based. Industrialized esters and estratetol tetra-fatty acid are also among the mineral transformer oil types which have been used intensively in recent years. These oils possess a lower pour point and low water content and very stable at elevated temperature. Another expensive transformer oil called silicone and fluorocarbon oils were also used. These types are more fire resistance compared to other oils. Some investigation tries to used vegetable such as coconut oil and olive oil. Few researchers claimed that these oils are unsuitable for use but very limited results are available to conclude [3].

Water is found in transformer oil in several forms. These forms include free water, which is the most water type that reduces the quality of oil followed by dissolved water associated with hydrogen and its effect on the quality of oils is a little [4].

The water content in transformer oil is a critical issue and undesirable because it increases the dielectric properties of oil significantly which lead to absorb more energy result in the fire of power plant. Also, the water content in oil may affect the quality and function of paper used as an insulator in power plants because it is hygroscopic and absorb any excess water in the transformer oil. This results in reducing the service life of the paper insulator [5]. This is another factor limiting the amount of water in transformer oil [1].

Determine the quality of the transformer oil to continue using or changing it is a critical issue. Therefore, periodic and often daily samples of the oil are taken and the quality tests, especially the content of the water in the oil are carried out and compared to international standards [6]. This process is economically costly and requires considerable time and effort [7]. These methods are accurate, but it is tedious, high-cost, time-consuming and required a relatively long time to perform. The development of sensors that do this work continuously is a significant challenge. This paper explores the development of an electromagnetic probe that can perform this task at a low cost and continuously.

The rapid development of electronic devices and telecommunication systems in the last two decades reduces the cost of electromagnetic sensors. This leads to increase the uses of electromagnetic sensors in many sensing fields including advanced material characterization. Several electromagnetic sensing techniques and methods were investigated and developed for quality control and material characterization. These techniques may including ground penetration radar (GPR) and time domain reflectometer (TDR) [8],-non contact electromagnetic method known as free-space [9], transmission line methods using coaxial probe [10], terminated transmission called open-ended circular and rectangular wave-guide [11], electromagnetic cavity called resonator [12] and electrode methods using parallel plates to form a rectangular cell operating in low radio wave frequency [13]. Parallel plate electrode capacitor is used in many application because it uses an AC current makes it simple, low cost, and very suitable for characterization of liquids and particulate material. This method is easy to test any shape.

Recent years witnessed an increasing use of electromagnetic electrode based on parallel plate capacitor theory in many interdisciplinary, multi-disciplinary and cross-disciplinary engineering applications such as soil contamination and pollution control [14], material thermal assessment and analysis [15], sensing material humidity and water content [16], degree of hydration cement and concrete material [17], evaluation of fiber dispersion, orientation and content in composite and concrete [18] and monitoring the sitting process and time of composite materials [19]. Despite that, the simplicity and low cost of advanced characterization of liquid such as transformer oil and other various material employing electrode dielectric parallel plate sensor relied on the measured impedance and the calculated complex permittivity. These measured impedances and dielectric properties are highly depended on the success of modeling the circuits in order to remove several other impedances associated with the setup of the electrode system. These associated impedances in the measured impedance includes fringing impedance, electrode impedance, and stray impedance.

This paper aims to develop two dielectric sensors for quality control of transformer oil which can be used for laboratory and in-situ application. The sensor will be used to evaluate the water content of the transformer oil because the water content is the main and critical quality parameter of transformer oil.

2. Electromagnetic dielectric theory

Electromagnetic AC current signal is composed of an electric field signal and magnetic field signal. The interaction between the AC signal and material such as transformer oil and water is control by two important electromagnetic properties of the material. The first property is the complex permittivity (ε*) which represents the interaction between the electric field and oil transformer material. The second properties are the complex permeability (μ*) of material control the interaction between the magnetic field and oil transformer. Transformer oil and water are a nonmagnetic material which limits the discussion to the complex permittivity. Dielectric constant (ε') of material is the real part of complex permittivity and it is a measure of the amount of energy absorber from electric field as polarization. The loss factor (ε'') is the imaginary part of complex permittivity represents the conductance of the material called dissipation loss from the electric field. Both real and imaginary part of complex permittivity is given by:

$$\varepsilon^{*} = \varepsilon^{'} - j\varepsilon^{''} \quad (1)$$

The impedance (Z) of an electrical circuit is a complex quantity represents the resistance of the circuit to AC current and its real part (Z') known as resistance while the imaginary part (Z'') called conductance. The reciprocal of the impedance (1/Z) is call admittance (Y). The admittance also composed of the real part (Y') and imaginary part (Y''). The real part of the admittance is called conductance (G), and the imaginary part known as susceptance (B). The material under testing such as transformer oil when contact with the electrode, it forms a component of an electric circuit. The impedance or admittance of transformer oil could be determined from the measured admittance of the whole circuit using a proper model circuit for removing unwanted impedances such as stray, electrode and fringing impedances. Both parts of complex permittivity of oil (dielectric constant ε' and loss factor ε'') could be determined using the following equations.

$$\varepsilon^{'} = \frac{Y^{''}}{\omega C_o} \quad (2)$$

$$\tan\delta = \frac{Y^{''}}{Y^{'}} \quad (3)$$

$$\varepsilon^{''} = \varepsilon^{'}\tan\delta \quad (4)$$

3. Electrode dielectric sensor

Two types of electrode dielectric sensor were designed and developed. The first sensor for lab testing of transformer oil and other liquids and particle materials and the second electrode dielectric sensor for online and in situ testing of transformer oil.

3.1. Lab dielectric sensor

The setup and design of the lab electrode parallel plate dielectric sensor for quality control of transformer oil is shown in Figure 1. The sensor consists of LCR meter used as a source of AC signal and measured the impedance or admittance of the whole circuit. LCR meter connecting through coaxial cables and fixture to two electrode parallel plates forming a rectangular cell. The cell will be filled with transformer oil. The unwanted impedances were removed using the model circuit and the impedance of transformer oil will be determined. Dielectric properties of the transformer oil and liquid material could be determined using equations 1 through 4 listed in section 2. Further details are given in previous work [20]. This design of the sensor allows accurate, rapid, and precise measurements of the impedance and dielectric properties of oil transformer in a large radio wave frequency which could be ranged from one kHz to thirty MHz.

3.2. In-situ dielectric sensor

Several probes for the dielectric sensor were designed and prepared. These designs include a pin electrode, the coaxial electrode, and the parallel plate electrode. The parallel plate was the most straightforward method, and more accurate results were obtained. Figures 1 and 2 represents both proposed probes for lab and in-situ which were developed in this study.

3.3. Calibration and validation

Prior to the use of the two electrode dielectric sensors proposed in this study, calibration, and validation of the sensors were performed. Two standard calibration techniques and methods were used. These calibration techniques were open circuit calibration and short circuit calibration proposed and provided by HP. These two standard calibration techniques were installed and integrated with the LCR meter [21]. To validate the accuracy of the sensor in measuring the impedance and dielectric properties of the liquid material such as transformer oil and water, standard material possesses definite dielectric properties were used. The standard material used is Teflon. The Teflon dielectric constant is equal to 2.1 while its loss factor is very low and equal to 0.003. The two sensors were used to determine the dielectric properties of Teflon. The measured dielectric properties of Teflon is very close to the actual dielectric properties. The error in the measured dielectric constant is less than 2% at all frequency in the range of one kHz to one thousand kHz and it is very close to the reported values [22]. The model circuits developed for both dielectric sensor along with the calibration standard and validation procedures performed to enhance the accuracy of the sensor was superior in removing the unwanted impedances such as fringing and electrode impedance and make a concise measurement of dielectric properties of liquids and transformer oil.

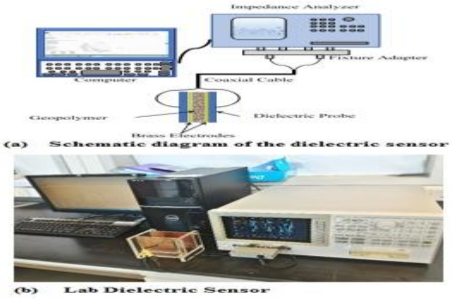

Fig. 1: Lab Electrode Dielectric Sensor.

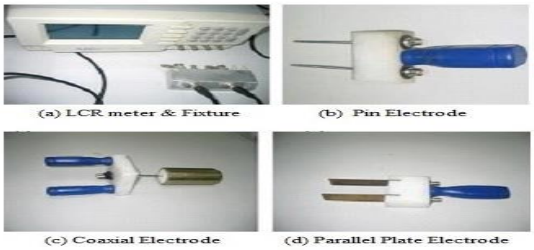

Fig. 2: In-Site Electrode Dielectric Sensors.

4. Result and discussion

Dielectric constant ε' and loss factor ε" of deionized water, transformer oil, and several natural vegetable oils were measured using the proposed capacitive electrode dielectric sensors. The results are presented in the following subsections. To evaluate water content a transformer oil were contaminated by deionized water at 6 level by volume such as 0%, 0.01%, 0.02%, 0.03%, 0.04% and 0.05%. The complex permittivity of all oils was evaluated at each water content. The impedance, dielectric constant and loss factor of water, transformer oil and natural oil were measured at a different frequency ranging from 1 kHz to 1000 kHz. Statistical and regression analysis were performed using SPSS packages and correlation coefficients were determined to determine the quality of regression models.

4.1. Effect of frequency

The impedance of deionized water was measured using the proposed sensor. These results are given in Table 1. Using the model circuit introduced and designed to eliminate unwanted impedance including in the measured one, the impedance of deionized water were determined and presented in Table 1. Dielectric constant ε' and loss factor ε" of deionized water were determined from the calculated impedances using the equations given in Section 2.

Table 1: Measured impedance and corrected water impedance of deionized water using the proposed dielectric sensor at a different frequency.

Frequency (kHz)	Measured Impedance		Water Impedance	
	R (ohm)	X (ohm)	R (ohm)	X (ohm)
300	518.27	-76.19	514.76	-78.20
600	522.34	-146.41	514.78	-144.43
900	505.81	-165.23	496.89	-159.14

Table 2: Measured dielectric constant and loss factor of deionized water using the proposed dielectric sensor at a different frequency.

Frequency	Dielectric Properties of mineral oil (transformer oil)	
(kHz)	Dielectric constant	Loss factor
	ε'	ε"
300	81.09	405.46
600	80.02	289.02
900	79.14	256.33

The results of all electromagnetic properties of deionized water such as impedance, dielectric constant ε' and loss factor ε" decline with increasing alternative current frequency. These results may refer to the reduction of current conductance at a higher frequency. The results of dielectric constant ε' and loss factor ε" of both transformer oil and olive oil are given in Table 2. The results indicate that both dielectric constant ε' and loss factor ε" declines with increasing frequency for both oils. The value of dielectric constant of both transformer oil and natural olive oil is in a good match with the values published by other researchers [23]. The dielectric properties of transformer oil and natural oils are very close which indicate that natural oil could be used as alternative transformer oil.

Table 3: Dielectric properties of transformer oil and olive oil using the dielectric sensor

Frequency	Mineral oil (transformer oil)		Natural oil (olive oil)	
(kHz)	Dielectric constant ε'	Loss factor ε"	Dielectric constant ε'	Loss factor ε"
300	2.35	0.015	2.53	0.044
600	2.31	0.013	2.51	0.041
900	2.30	0.012	2.50	0.039

4.2. Effect of water content

The result of the dielectric constant and loss factor of both transformer oil and olive oil at different water content are given in Figures 3 and 4. The dielectric constant and loss factors of both oils increase with increasing water content. This trend could be attributed mainly to the increase in dipole polarization as a result of an increase in the oil conductivity due to the increase in the amount of free water. The relationship between dielectric constant ε' and oil water content could be modeled as a simple mathematical linear regression model. The model fit was measured using correlation coefficients R^2. The correlation coefficients were 0.9837 for transformer oil and 0.9997 for olive oil. The similar linear model was also the best fit between oil water content and loss factor.

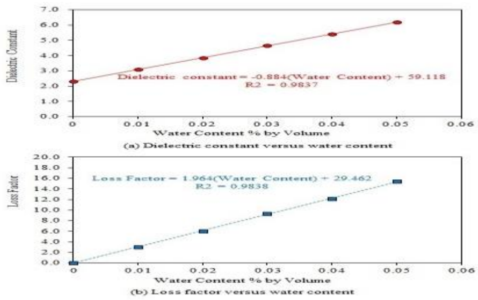

Fig. 3: The dielectric properties of transformer oil versus water content at 600kHz.

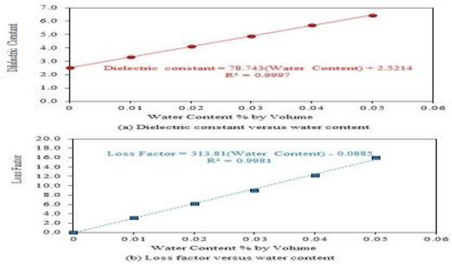

Fig. 4: The dielectric properties of olive oil versus water content at 600kHz.

4.3. Dielectric properties of oils

Dielectric constant ε' and loss factor ε" of several Vegetable-Based oils were measured using the proposed capacitive dielectric sensor. The results are given in Table 3. The results are in good very close and in a good match with the values reported by another researcher [23].

Table 4: Dielectric properties of some natural oils at frequency 600 kHz

Vegetable-Based Oil	Dielectric Properties of mineral oil (transformer oil)	
	Dielectric constant ε'	Loss factor ε"
Olive oil	20.5	55.17
Soya bean oil	2.16	0.29
Coconut oil	2.16	0.29
Palm tree oil	2.16	0.29
Sunflower oil	2.95	5.13

5. Conclusion

This paper presents the development of two electromagnetic electrode sensors one for lab and the other for in site quality control of transformer oil. The two sensors were designed and appropriate model circuits were developed to quantify the associated and unwanted impedances including in the measured one. This leads to determine the accurate impedance of transformer oil then the dielectric properties of several transformer oils were calculated. The two proposed sensors were calibrated and validated using standard procedures and methods. The following conclusions could be drawn from the results of the measured impedances, dielectric constant ε' and loss factor ε" of transformer oil:

(1) Dielectric properties of transformer oil decrease with increasing frequency,
(2) Dielectric properties of oil increase with increasing oil water content, and
(3) The water content of transformer oil could be determined accurately using a simple linear regression between the dielectric properties of oil and its water content.
(4) Dielectric properties of several vegetable oils were determined

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