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Quality Monitoring of Mineral and Synthetic Oils Using a High Q-Factor Single-Mode Resonance Cavity and Kajfez' Algorithm at 2.45 GHz

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Summary

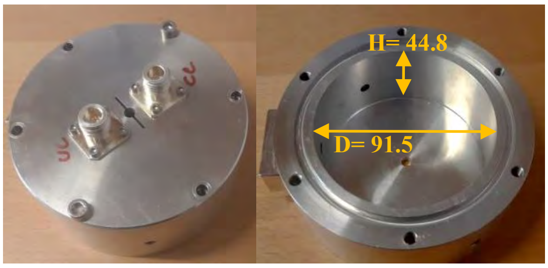
The permittivity of oils can be used as a key indicator for monitoring the quality of oils in many industrial equipments such as transformers. In this work, the complex permittivity of several kinds of industrial mineral and synthetic oil samples are calculated using a high Q-factor single-mode resonance cavity at 2.45 GHz and a developed Kajfez' algorithm in python.

1. Introduction

The complex permittivity of mineral or synthetic oils is used to monitor their quality and performance in industrial equipments, particularly transformers. Measuring the permittivity of oil samples can help to identify contaminants or impurities that maybe present, and can be used to ensure that the oil meets specific quality standards [1]. Many microwave-based techniques are developed to measure the exact complex permittivity at specific frequencies for non-destructive test [1]–[4]. In this work, measurement results of different types of mineral and synthetic oil samples are presented using a high Q-factor TM010 single-mode resonance cavity at 2.45 GHz for transformer applications.

2. Theory, measurement setup, and oil samples

Resonant cavities are microwave devices which resonance at the desired frequency with high Q- factor that are used to measure the exact value of the complex permittivity ($\varepsilon = \varepsilon' - j\varepsilon''$) of the materials. The single mode resonance cavity provides this matter in the dominant resonance mode [5]. A single mode TM010 resonance cavity at 2.45GHz is used to measure the accurate complex permittivity of oils (Figure 1.a) using presented test setup in Figure 1.b.



(a)

(b)

Figure 1. (a) TM010 single mode cavity (b) Test setup to measure oil's complex permittivity

The algorithm developed by Kajfez estimates the complex permittivity of a sample by a resonance cavity and use of the reflection coefficient (S11) measurement method [6]. In this method, the resonance frequency (f_l) and Q-factor (Q_0) of the cavity with and without sample will be measured. Then the dielectric constant (ε') and dielectric loss (ε'') calculated by (1) and (2) [7]. Where, V_C and V_S are is the volume of the cavity and sample, f_0 , and f_s are the resonance frequency of the cavity with and without sample, and Q_{LS}, and Q_{L0} are the Q-factor of the empty and loaded cavity that calculated by Kajfez's algorithm.

$$\varepsilon' = 1 + 0.539\frac{V_c(f_0 - f_s)}{V_s f_0} \quad (1)$$

$$\varepsilon'' = 0.269 \times \frac{V_c}{V_s} \times \left(\frac{1}{Q_{LS}} - \frac{1}{Q_{L0}}\right) \quad (2)$$

Using above literature, to improve accuracy of complex permittivity measurement, Kajfez's algorithm is developed in Python in this work. The developed algorithm could be used for calculating Q-factor using lower points and narrower resonance band. With the development of environmental standards, new alternative oils like synthetic oils, natural esters have received more attention compared to the mineral oils. Therefore, in this work, the complex permittivity value of several commonly used oil samples like Palm Fatty Acid Ester (PFAE), Nytro 10X, Envirotemp 360, Midel 7131, Diala S5, Diala S4 natural, and Diala S4 zx14 are measured and reported.

3. Measurement results

Based on presented setup for measurement in Figure 1.b, S11 of each sample are measured, Figure 2. Then based on the measured S11 and utilizing the developed Kajfez's algorithm in Python, the complex permittivity of oil samples are extracted which are shown in Table 1. Also, in Table. 1, the loss tangent ($tan\delta = \varepsilon''/\varepsilon'$) are calculated for each sample.

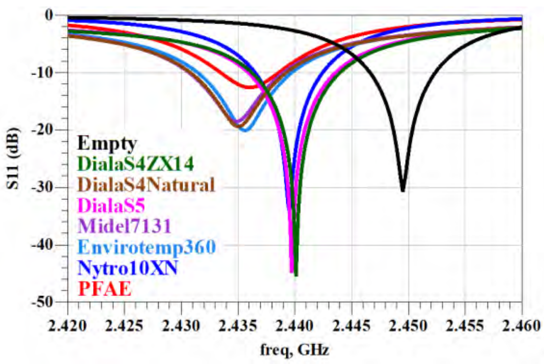


Figure 2. Measured S11 and resonance frequency for each sample

Table 1. Calculated complex permittivity of oil samples using the developed technique

Oil samples	ε'	ε''	$tan\delta$
PFAE	**3.151283**	**0.607961**	**0.192925**
Nytro 10XN	**2.596730**	**0.154032**	**0.059318**
Envirotemp360	**3.238928**	**0.138506**	**0.042763**
Midel 7131	**3.358444**	**0.150602**	**0.044843**
Diala S5	**2.582388**	**0.055986**	**0.021680**
Diala S4 Natural	**3.323864**	**0.144957**	**0.043611**
Diala S4 zx14	**2.527252**	**0.055892**	**0.022116**

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