



Novel Planar Capacitive Interdigital Multifinger (IDCM) Sensor for the Detection of the Ageing of Electrical Transformer Oil

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Abstract: This work shows a planar interdigital sensor for rapid measurement of oils. The kit is characterised by the impedance meter, a Raspberry Pi3 and a sample port where the planar capacitive interdigital multifinger (IDCM) sensor is stored. For validation of this IDCM sensor, the data was compared with measurements performed by impedance spectroscopy (IS). The measurements show that the measured values of the new and used oils are very close, validating the IDCM sensor for fast oil measurements of oils in transformers and other devices.

Keywords: Planar Interdigital Capacitor, Permittivity, Transformer Oil

1. Introduction

Electricity industries currently require high safety precautions, especially in the maintenance of transformers, which demand time and high cost. In this context, it is important that a periodic analysis of the state of conservation of the oil contained in the transformer be held. For these analyses, refined techniques such as chromatography and UV-Vis spectroscopy are utilised that are expensive and time consuming. Moreover, new techniques are being developed for in-situ analysis with the same precision as other techniques.

In the literature some works with interdigital sensors, called planar capacitive interdigital multifinger (IDCM), present many applications in the most diverse areas such as chemical, biological, microelectromechanical, telecommunications, and piezoacoustic systems^[1-6]. New types of interdigital sensors having the most diverse configurations, with different numbers of electrodes, are being studied for various types of projects^[7-10]. The manufacturing process involves different types of substrates amongst which, FR4 can be cited for the cost-effectiveness and manufacturing quality of the circuit^[11]. The planar interdigital circuit is a parallel plate capacitor^[12] in which the electric field lines, generated by the sensors, pass through the material to be studied and directly influence the sensor impedance. The sensor follows the principle of a capacitor in which the reactive capacitance of the properties of the system, surrounding the sensor, can be measured and calculated^[8]. The permittivity of a material is the result between the relative permittivity (ϵ_r) and the permittivity in vacuum (ϵ_0), shown in Equation 1.

$$\epsilon = \epsilon_r \epsilon_0 \quad (1)$$

The relative permittivity of an insulating material, shown in Equation 2, can be calculated by the relationship between the capacitance of a capacitor (C), where the area between the electrodes is filled with an insulating material, and the capacitance in a vacuum (C_0).

$$\epsilon = \frac{C}{C_0} \quad (2)$$

According to Rahman et al.^[7], the term interdigital, in the acronym IDCM, refers to a digit-like, or finger-like, periodic pattern of parallel in-plane electrodes, used to build up the capacitance associated with the electric fields that penetrate into a sample material^[2], so that a voltage source can be applied between the positive terminal and the negative terminal^[8] and is a technique to measure the permittivity ϵ_r of fluids through the capacitance in systems with multiple capacitors^[3,7].

The characteristics of the studied material can be determined by the change in capacitance of the IDCM, filled with the fluids (oils for example) studied and is estimated by Equation 3^[13], where n is the number of parallel plates, A , the area of one side of each plate and d is the thickness of the dielectric^[3].

$$C = \frac{\epsilon_r \epsilon_0 (n-1) A}{d} \quad (3)$$

This work shows the fabrication and use of a 7-finger, where each pair of fingers corresponds to a flat capacitor of the IDCM sensor^[14,15] for fast measurements of the transformer oils and the lifting of a calibration curve referring to the quality of these oils. Each oil measurement is performed in a maximum of 2min and the result is sent to a company monitoring central, allowing in a few minutes, to suspend the use of the transformer, if the oil shows undesirable variations. For this measurement, a kit was developed that consists of a capacitance meter and a Raspberry PI3 for communication and transmission of the collected data. A study carried out by the software Comsol was extremely important, since the IDCM was built based on simulations that verified the effectiveness of the project, as shown in the results of this work.

2. Experimental Setup

The flat interdigital capacitor with parallel plates was built with copper sheets of thickness 0.2mm on a substrate of the FR4 epoxy ($\epsilon = 4.4$ and thickness 1.4mm). To identify the best thickness, length and distance between the fingers of the IDCM, the software COMSOL Multiphysics was used^[8], resulting in the dimensions shown in Figure 1(a).

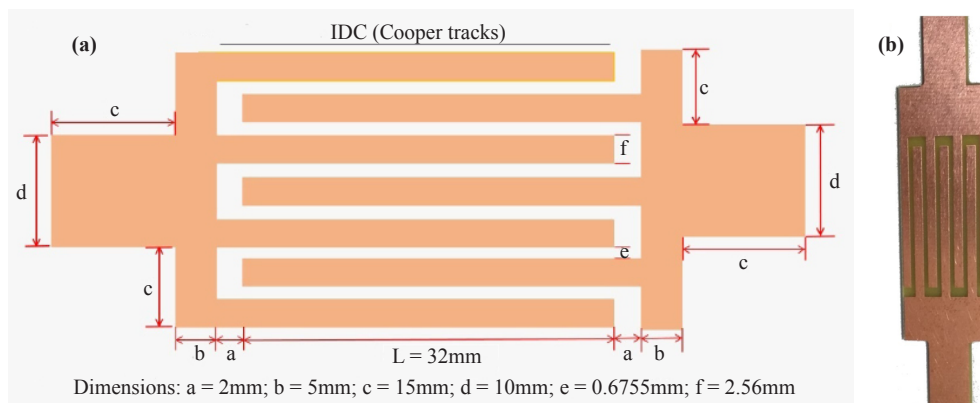


Figure 1. Interdigital capacitor. (a) Projected dimensions of IDCM, (b) IDCM produced

Figure 1(b), presents the designed and manufactured IDCM, which will be used for the measurements of the oils. To control the amount of oil in all measurements, a support for the IDCM was designed and built and this model is shown in Figure 2.

After the capacitance measurement, the numerical value is sent to the developed software and installed in the raspberry PI3, where, through the measured capacitance, the relative permittivity was calculated thus estimating the relative permittivity value of all the measured oils. These were compared with the oils that were measured by impedance spectroscopy (IS) on a Solartron 1260 model in the frequency range of 1 Hz to 1 MHz.

Table 1. Oils analysed

Oil	ϵ_r	Oil	ϵ_r	Oil	ϵ_r	Oil	ϵ_r	Oil	ϵ_r
New (IDCM)	2.401								
101	2.442	111	2.411	121	2.383	131	2.379	141	2.445
102	2.371	112	2.371	122	2.399	132	2.304	142	2.409
103	2.388	113	2.353	123	2.369	133	2.363	143	2.418
104	2.387	114	2.323	124	2.331	134	2.432	144	2.409
105	2.372	115	2.427	125	2.144	135	2.445	145	2.395
106	2.442	116	2.358	126	2.285	136	2.442	146	2.441
107	2.420	117	2.420	127	2.414	137	2.391	147	2.451
108	2.424	118	2.398	128	2.361	138	2.372	148	2.421
109	2.467	119	2.372	129	2.377	139	2.378	149	2.407
110	2.353	120	2.462	130	2.397	140	2.446	150	2.374

The support for the IDCM guarantees the amount of oil to be measured and can be used from 1 ml up to 10ml. The oils volume control is made through a Pasteur pipette. In the measurements made with p to 10ml. The oils volume control is made through a Pasteur pipette. In the measurements made with the new and used oils, an amount of 2ml of oil was used to calculate the capacitance and permittivity. After the oil is deposited on the holder, the reading is performed through a capacitance meter, Minipa MX -1050, as shown in Figure 3, where the frequency ranges from 100Hz to 100kHz.

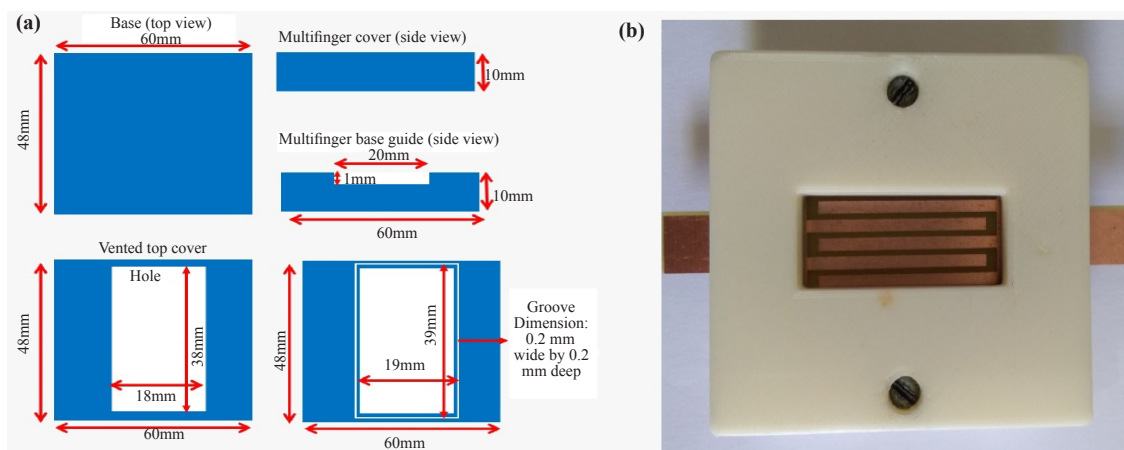


Figure 2. Interdigital capacitor. (a) Projected dimensions for IDCM, (b) Support for the oil control over IDCM

The multifinger kit makes quick oil measurements, so do does not take moisture into account. The measurements only certify whether the oils are working within a pattern or not. For more accuracy measurements involving other parameters that should be studied other techniques will be indicated. In this study, it was used as a measurement standard to validate the results obtained in the multifinger, the solartron 1260. In the solartron 1260, the error expressed by measurement is on the order of 10^{-3} , while in the impedancimeter is on the order of 10^{-1} , which is an acceptable price for this type of measure, as the Impedance deviation is given by the Equation 4, where D is the measured percentage deviation, DC is the main parameter of the measured elements, DREF is nominal value, shown on the impedance meter display.

$$D\% = \frac{D_c * D_{REF}}{D_{REF}} * 100 \quad (4)$$

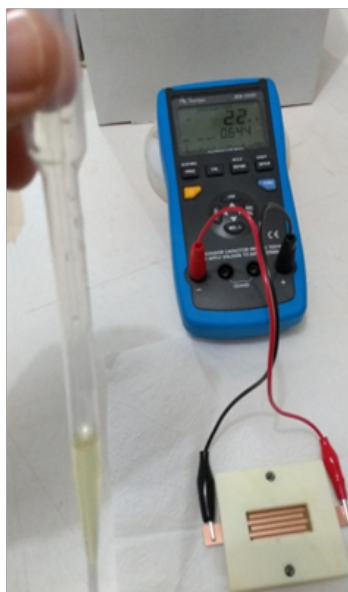


Figure 3. Mounted system for the measurement of oil capacitance

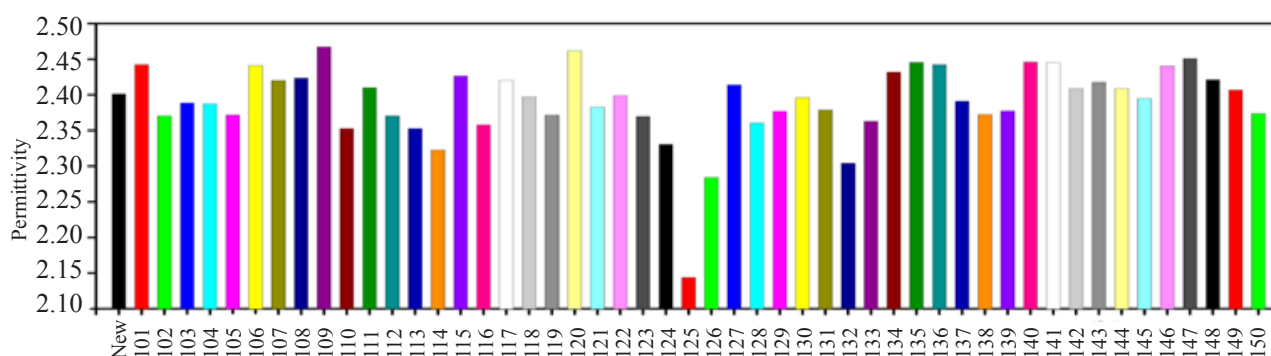


Figure 4. Values of the 51 analysed oil

3. Experimental Results and Discussions

For comparing and validating the method, initially water and isopropyl alcohol were measured with the IDCM, where their respective permittivity was 80 and 18 for a frequency of 100KHz. The IDCM measured empty presents a capacitance value of the 10.69pF, at 100KHz.

Knowing the capacitance when there is only air in the sample port, the capacitance of the studied oil is measured by calculating the oil permittivity through Equation 2. From the literature, it is known that the permittivity of new transformer oils is around $\epsilon \approx 2.40^{[16-18]}$, with oils that fall outside this value being oils that have been used or damaged. The oils analysed in this work vary from new oil to others in different states of conservation and use. The dielectric measurements of these samples, performed through the IDCM, are shown in Table 1.

As can be seen in Table 1, the values of the new oils measured by the IDCM are compatible with oils studied in the literature, where the dielectric constant values are measured according other techniques, showing the efficiency ^[14,19]. Note that the impedance meter measurement is a very fast measurement not taking into account air humidity, the measurement error is negligible since the are compatible with the solatron results and quality of the measurements by the IDCM. Table 1 shows a comparison between the oils measured in the IDCM, and by IS, at a specific frequency of 100KHz, showing the proximity between the values.

The values that are different from the range of values considered normal (new oil) can confirm that in this case the oils may have either lost their chemical properties, or that there was a contamination or a change in the chemical composition of the oil. For example, water with a permittivity around 80 is consider a contaminant for oil. Figure 4 shows 51 oils and it can be seen that the permittivity of all the oils present close values, thus creating a standard to establish a pattern curve for the IDCM, since through this curve a quick measurement of the oils can be made.

A 2ml oil sample is placed inside the IDCM and the data obtained must be compared to the system database for the oil quality information to be obtained. A value is quickly presented within the established calibration curve, with the measurement presenting a tolerance factor of 2%, which was established by experimental measurements and by more detailed observations of Figure 4.

Many oils were measured, and their permittivity was calculated for comparison with respect to the new oil. A tolerance factor of 2% was determined to estimate the physical quality of the oil. If the permittivity of the oil is within one per cent, relative to the permittivity of the new oil, this means that the oil still retains its properties and can be used for some time. If the difference in permittivity of the new oils is between one percent and two percent, this means that attention must be paid to the oil and its properties analysed for its suitability for use. If the difference is greater than two percent, this means that the oil should be changed immediately, where we can highlight that oil 125 needs to be changed immediately, as it presents a 10.7% percentage change in relation to new oil, representing a risk to the transformer. Of the analysed samples, oil 126 presents degree of impurities around 4.83%, also representing a risk of use. The tolerance value was established by the measurement of many oils: new, burned, and used oils.

The kit consisting of the impedance meter, sample holder and the IDCM, has been validated and has become another effective method for the rapid measurement of transformer oils, and other types of uses in the commercial area, since it is easy to handle, has low cost and is very efficient. The studies showed that through the capacitance, the permittivity is obtained, which represents a set of properties of the oil, and from this value it is possible to classify the oil as NEW oil (in perfect state), deserves ATTENTION (make a new check in half of the forecast time, that is, 6 months reviewing in 3 months) and DANGER (a more detailed analysis of the oil needs to be done).

4. Conclusion

In view of the studies carried out, it can be concluded that the IDCM presents itself as an optimum option for verifying the quality of the oils used in transformers, being able to estimate their quality quickly and efficiently. The validation of the measurements of the IDCM were carried out comparing the measurements made by impedance spectroscopy and the values were found to be comparable. Therefore, the IDCM in conjunction with an impedance meter, a Raspberry Pi3 and a sample port, where the IDCM sensor is placed, are a kit for rapid measurement of fully functioning oils and can be a powerful tool in the analysis of transformer oils in hydroelectric plants and other industrial devices.

Acknowledgments

The authors are grateful to CNPq (402045/2013-0), the US Air Force Office of Scientific Research (AFOSR) (FA9550-16-1-0127), CNPq (Process: 402561/2007-4, Edital MCT/CNPq nº 10/2007) for providing financial support and Foundation for Research Support of the State of Mato Grosso (FAPEMAT). Acre Electricity Company (ENERGISA).

On behalf of all authors, the corresponding author states that there is no conflict of interest.

Conflict of interest

The authors declare no competing financial interest.

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