Breakdown Voltage Measurement of High Voltage Transformers Oils Using an Active Microwave Resonator Sensor

Ahmed A. Al-Mudhafar, Ali A. Abduljabar, Hayder Jawad Albattat

***Abstract*—**This work suggests a microwave resonator sensor (MRS) device for measuring the oil's breakdown voltage of high voltage transformers. A precise high-sensitivity sensor is designed and manufactured based on a microstrip split ring resonator (SRR). To improve the sensor sensitivity, a radio frequency (RF) amplifier of 30 dB gain is linked through a transmission line of 50Ω. The sensor operates at a microwave band (L) with a quality factor of 1.35×10^5 when it is loaded with an empty tube. In this work, the sensor has been tested with three samples of high voltage transformer oil of different ages (new, middle, and damaged) where the quality factor differs with each sample. A mathematical model was built to calculate the breakdown voltage of the transformer oils and the accuracy of the results was higher than 90%.

***Keywords*—**Active resonator sensor, oil breakdown voltage, transformers oils, quality factor.

I. Introduction

TRANSFORMERS are fundamental devices of significant presence within a power system. They, along with other equipment, are part of the elements that make up the electric power transmission and distribution systems that allow the supply of electric power to end users. For hundreds of years, oil-immersed transformers have primarily used petroleum-derived oils (mineral oil) for insulation and cooling.

Electrical insulating oils (EIO) are high quality petroleum products which are used in electrical equipment [1]. This oil has physical and electrical functions [2]. The first is summarized as heat dispersion and the second for insulating. When impurities and moisture (water content in transformer oil) are mixed with oil, the breakdown voltage (BV) is significantly reduced [3]-[5] and it is usually monitored by sampling during its life. In [6], the effect of moisture on BV was studied by a capacitive sensor which was affected by the amount of water molecules. Reference [7] used a photo sensor with the structure of a single mode-multimode-single mode (SMS) optical fiber. A central gap ring resonator (CGRR) with quality factor of $Q \approx 3000$ is used for identifying and sensing new or damaged oils [8].

In this work, we have employed the microwave resonant sensor to acquire a model for calculating the BV of the high-voltage transformer oil. The oil sample has as a consequence disturbance of the electric field generated in the microwave resonance sensor, which leads to remodeling its resonance properties such as frequency, losses, and quality factor [9]-[11]. Non-resonant methods depend on the general characteristics of the electromagnetic wave (impedance, wave velocity, reflection, etc.), which give less accurate results than resonant methods [9]-[13].

In this paper, we aim to design and fabricate a model that could help us to interpret the mechanics of the breakdown.

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II. Theory

Modeling microwave sensors uses perturbation theory to meet its approximate response formula. BV oil's age can be distinguished by designating a mathematician model based on the resonance properties (resonant frequency, input losses, and quality factor) of the sensor. The greatest electric field is concentrated at the edge of the ring gap, so inserting an oil-loaded tube into the ring gap will cause the liquid to become polarized and change the resonance properties of the sensor, and from that perturb, the complex permittivity of the liquid sample is measured via decreases in the resonant properties such as frequency, losses, and quality factors. These changes can be quantified as complex permittivity, which can be written as: $\varepsilon = \varepsilon_1 - j\,\varepsilon_2$ [9]-[13] where ε is complex permittivity, ε_1 is dielectric constant, and ε_2 is loss factor.

An SRR with a change of gap capacitance can subsequently change the resonant frequency changes according to the electrical permittivity (ε_1) of the oil sample in that gap [12], [13].

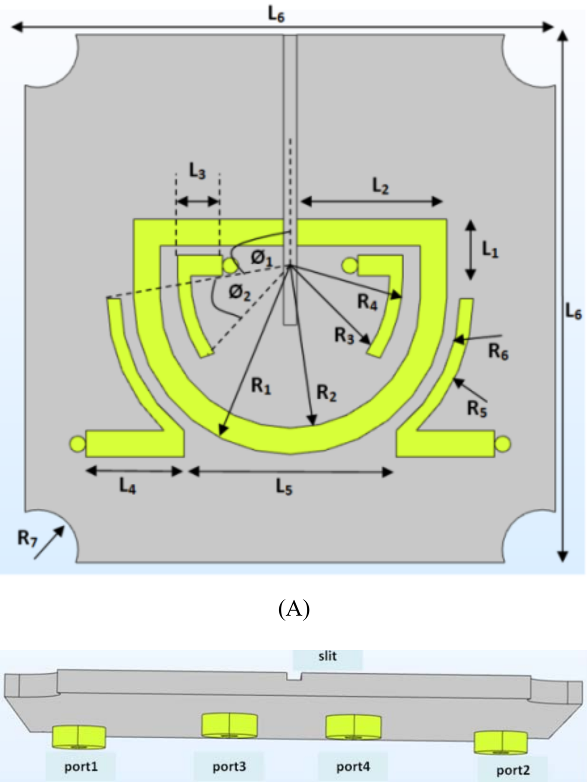
Under the action of the electric field on the oil at the sensor gap, collision and friction will occur between them and the quality factor will change [$Q \propto 1/\varepsilon_2$] [11], [13].

An obvious change was observed in the Q-factor of the sensor due to the effect on the dielectric loss (ε_2) when oil samples were used (old and new), however, a slight change was observed on the resonance frequency in the real part (ε_1) of the transformer oil [8], [9]. Consequently, the water content (Φ) influences the calculation of the dielectric loss (ε_2) significantly and decreases the BV of high voltage transformer oil, whereas water content was neglected in the calculation of the constant permittivity (ε_1) [3], [4], [8], [9].

III. Design and Fabrication

The MRS has been designed using the ADS-Software

(Advance Design System 2016.01) and fabricated on high conductivity copper plates 2.7 × 10^7 S/m, with two faces, each thickness of 35 µm, and between them is an insulating material that has minimal insulating losses of 0.0012 called Rogers (Rogers 5870), its thickness is 1.57 mm with a relative electrical permittivity of 2.33 ± 0.02. The sensor operates at the frequency 1.8 GHz and 62.5 mm physical transmission line and half wavelength electrical length. The dimension of this sensor is 1.64 × 3.5 × 3.5 mm. The annular resonator was inductively coupled (magnetically) with the feeder lines [10], [15]. Fig. 1 shows the sensor geometry and its dimensions are shown in Table I. Fig. 2 shows the general schematic of active MRS which draw power from the S-parameters block through two 50 Ω feed lines (port 1 and port 2), and port 3 and port 4 of the resonator are connected to an RF amplifier, the resonator becomes active (otherwise it is called passive). Fig. 3 illustrates the clear change of the peak single bandpass curve (S_{21}) with resonance frequency (freq) for bare active and passive MRS (unloaded tube).



(A)

(B)

Fig. 1 (A) Dimensions of the resonator; (B) Location of the slit, and a view from the bottom of the resonator to clarify the input and output (SMA) ports

The suggested sensor was fabricated by utilizing a chemical etching procedure after the ideal dimensions were selected and numerically evaluated and a slot width of 1 mm and a height of 0.5 mm was made on the top surface of the resonator along the length of the sensor to its center through the gap in order to place the test tube in it.

TABLE I
SENSOR DIMENSIONS (IN MM)

Index	R	L	Ø
1	11.8	4	108°
2	9.8	11.3	19°
3	7.4	3.4	/
4	8.4	7.4	/
5	12.8	12	/
6	13.8	35	/
7	4	/	/

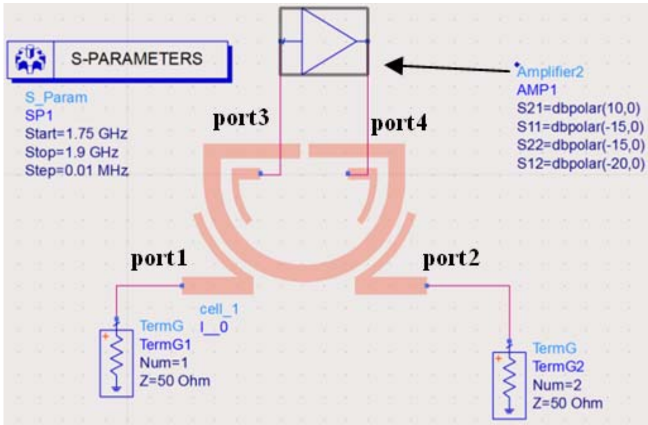


Fig. 2 ADS schematic view of active MRS

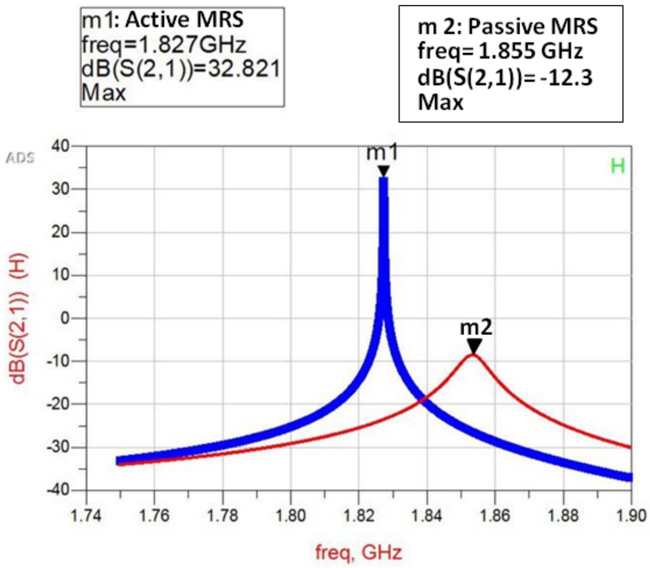


Fig. 3 Numerical simulation S_{21} for both active and passive sensor (without tube)

The sensor was installed at the bottom of the aluminum container box (45 × 45 × 45 mm) as shown in Fig. 4, and a capillary tube is inserted through one side of the box wall such that the tube tip is oriented exactly to pass through the split gap. The tube is made of quartz with 0.5 and 1 mm inner and outer diameters, respectively. The resonator's ports (3 and 4) are assigned to feed the RF amplifier with a rage of 0.1-2000 MHz, and constant DC voltage regulated with 30 dB gain, as depicted in Fig. 5.

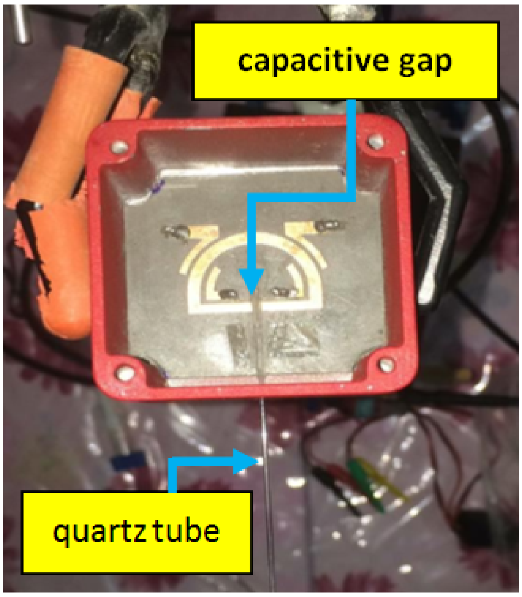


Fig. 4 Top view of MRS and the quartz tube inside the red box

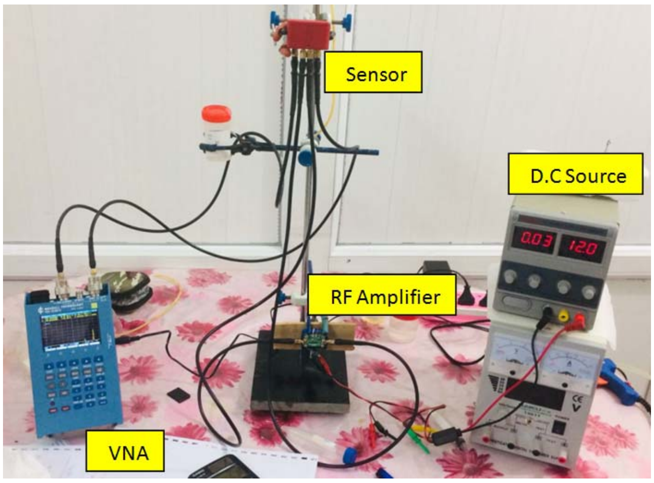


Fig. 5 Experimental configuration

IV. Results and Discussion

As shown in Fig. 6, three samples of (mineral) high-voltage transformer oil were created, each with distinct ages (new, medium, and damaged), where the Megger-OTS80PB device was used to measure the BV for each sample. The transmission coefficient (S_{21}) was measured at the frequency resonator at 25° for both passive MRS (0 VCC) and presenting the amplifier (+12 VCC). Q-factors are computed based on the resonant frequency (fr) ratio to the 3 dB bandwidth of S_{21} curve. Fig. 7 illustrates the relation between S_{21} and frequency for four testing cases, where an empty tube was tested with active (with amplification) and passive (no amplifier) resonator, and the tests were repeated for a tube filled with oil.

A significant change is observed in the value of the Q-factor, which represents a measure of the sensor's efficiency and an inverse measure of the physical losses resulting from surface impedance of copper, conductive losses, losses resulting from insulating material (Rogers5870), and electromagnetic emission losses of the MRS where the value of the Q-factor changed from 126.4 to 135298.2. The results are summarized in Table II.

TABLE II
Measurements of the Physical Properties of the Sensor When It Was Loaded with an Empty Tube (Air)

Case	f_r(GHz)	S_{21}(dB)	Q-factor
Empty-passive	1.7860323	-22.5769	146.4
Empty-active	1.7859339	31.90171	135298.2

TABLE III
Measurements of the Physical Properties of the Sensor When It Was Loaded with Oil Samples

Case	BV (kV)	f_r (GHz)	S_{21}(dB)	Q-factor
New-oil	65.8	1.785907	32.49055	76190.55
Middle-oil	41.9	1.785887	31.44411	74723.28
Old (damaged)-oil	25.8	1.785865	30.24713	71750.31

Because the sensor increases its sensitivity and accuracy with increasing the quality factor, being a measure of efficiency [14], [16]-[18], the network analyzer (VNA-KC901V) has been tuned to plot the sensor losses curve (S_{21}) within the frequency range 1.785-1.786 GHz when its gap is occupied by the quartz tube. It is loaded with transformer oil (New, Middle, and Old) as shown in Fig. 8, where a new tube was used for each sample, taking into account the absence of air bubbles between the oil fluid in order to avoid errors; and from these results are extracted the resonant characteristic of the sensor recorded in Table III, with the value of each is its BV. In order to build a mathematical model to find the BV of the oil for different ages based on the resonance results of the sensor when loading the tube with the new oil sample and the damaged (old) oil sample as they represent the first point and the second point, the curves in Fig. 9 show the fitted linear equation for two variables (x & z) between the BV with resonant frequency and quality factor: $y = a_0x+a_1z+a_2$ where y represents the value of BV, x is the value of fr with coefficient a_0, z is the value of quality factor with slope a_1, and a_2 represents the sum factors affecting the resonance properties of the sensor such as temperature, humidity, and pressure applied to the oil, etc.

The Q-factor of the active sensor is a good indicator for sensing different age oil as it reduces from 135298 to 71750 when the quartz tube was empty and filled with damaged (old) oil, respectively. The shift resonant frequency between samples less than 50 kHz. In [8], it was shown that with oil change the resonance frequency does not change significantly; and hence, the frequency value (fr (GHz)) can be ignored and the resulted equation becomes:

$$BV = a_1 \times Q + a_2 \quad (1)$$

The value of the slope (a_1) of (1) can be found by defining at least two points, such as (Q_1, $B.V_1$) and (Q_2, $B.V_2$).

From substituting a_1 and Q_1, $B.V_1$ in (1) to find the unknown coefficient (a_2) of the liner equation, we obtained the mathematical model in (2):

$$B.V = 9 \times Q \times 10^{-3} - 620.56 \quad (2)$$

To verify the validity of (2), the results of the third sample (medium-life oil (middle)) were used, where the calculated value of its BV was 51.9 kV and its difference from the value calculated by the Megger device by 10 kV. This value suggests that the accuracy of the results of the mathematical model is higher than 90%.

Fig. 6 Oil samples

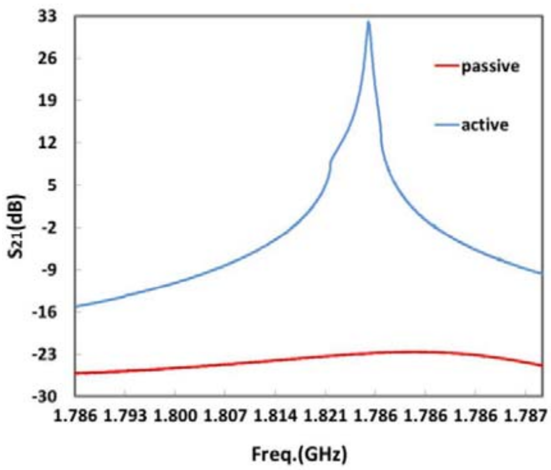


Fig. 7 Measured S_{21} for both active and passive sensor (with empty tube)

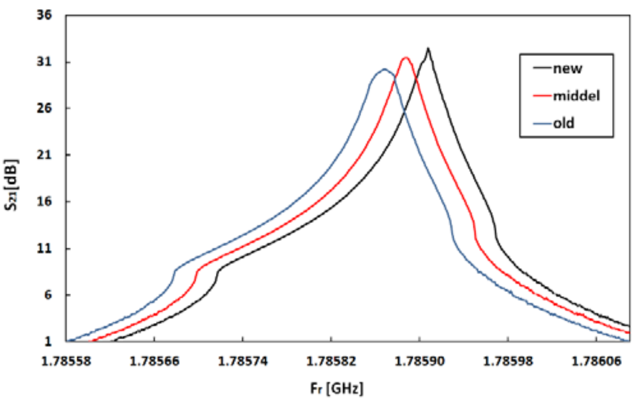


Fig. 8 Measured S_{21} of the sensor when the tube was loaded with different oil ages

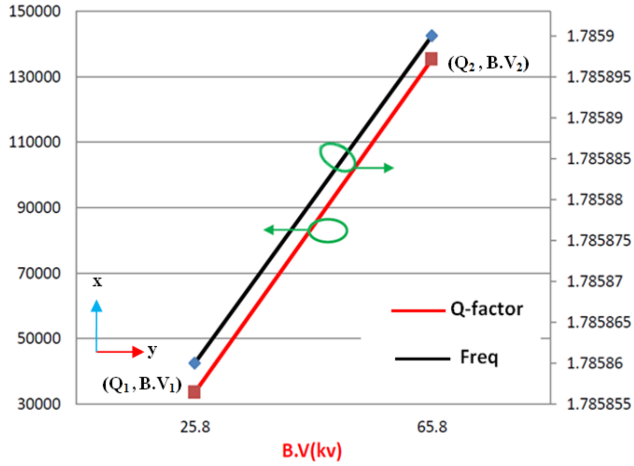


Fig. 9 The linear relationship between BV, resonance frequency, and quality factor when the sensor was loaded with samples of oil (Old and new)

V. Conclusion

The quality factor of the active sensor ($Q > 1.35x10^5$) means high sensitivity for distinction for each of the samples of oils and also high sensor efficiency due to the use of an optimal coupling between the ring and the amplifier. The Q-factor of the active sensor is a good indicator for sensing different age oil as it reduces from 135298 to 71750 when the quartz tube was empty and filled with damaged oil, respectively. The shift resonant frequency between samples was slight (< 50 kHz) so it is neglected in measuring the BV of a transformer's oil. Equation (2) calculated BV with an efficiency more than of 90% as the equation is easy to use and quick to give results in a standard time, less than the time spent by other measuring devices. Based on the aforementioned results, the proposed sensor is effectively capable of measuring the BV transformer's oil despite the small volume inside the tube (≈0.4 μL) which is an efficient approach to avoid wasting large quantities of oil when compared to Megger which requires at least 0.5 L of oil.

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Competing Interests

The author(s) declare none.

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