Moisture Estimation of Transformer Pressboard by Micro-strip Ring Resonator at GHz Frequencies

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ABSTRACT

Increased moisture content (MC) is considered as one of the main factors for the failure of transformer insulation. This paper presents a method of estimating the MC of a transformer pressboard insulation based on the relative permittivity and loss tangent measurements performed at GHz using a multi-layer micro-strip ring resonator. It was fabricated on a material of known dielectric properties and the sample to be tested (i.e. pressboard) was placed on the ring structure. The dielectric properties, namely loss tangent and permittivity, of the sample were then estimated by measuring the S_{21} transmission characteristics of the ring structure using a vector network analyzer. The technique was validated using a test sample of known dielectric properties. Additionally the results were compared with traditional frequency domain dielectric spectroscopy (FDS) measurements conducted at 1 mHz -1 kHz.

The measurements were performed on oil impregnated and non-impregnated pressboard samples having different MCs conditioned by drying and/or wetting processes. The actual MC of the pressboard samples were obtained by weight measurements. It was found that the resonance frequency increased when the MC was reduced. Furthermore, a positive non-linear relation could be observed between the MC and both the relative permittivity and the loss tangent. It can be concluded that the proposed method could be used to estimate the MC of pressboards.

Index Terms - **Moisture Content, Transformer Pressboard, Ring Resonator, Permittivity, Loss tangent, High Frequencies, Microwave.**

1 INTRODUCTION

PERFORMANCE of power transformers plays an important role in power system reliability. The insulation found in power transformers are of two types: liquid insulation (oil) and solid insulation (paper and pressboard). It is well known that the dielectric properties of both of these types deteriorate with ageing. Excess moisture is one of the common cause of insulation failures [1-3]. Performance of the insulations can also degrade due to other factors such as the formation of substances like slug, acids, and gasses [1-3]. Long-term ageing may even result in transformer failure, severely affecting the power system reliability. As a result, condition monitoring of power transformers has become an important topic and a lot of research has been carried out in this field [1-5].

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The transformers with solid insulation are dried during the production process to reduce the moisture level to a value less than 0.5%. However the MC in the solid insulation increases with service time due to: (i) decomposition of cellulose of the solid insulation, (ii) direct moisture ingress from atmosphere, and (iii) residual water in other elements. The increased moisture resides within the solid insulation and eventually diffuses between the solid-liquid insulation and vice versa[4]. Thus, a quantitative value of the MC in a solid insulation at a specified temperature and equilibrium conditions is useful for condition assessment of transformers [5].

Condition assessment of transformers can be done using dielectric response measurement [6-8] or single point measurement techniques such as loss tangent and insulation resistance measurement. Out of these methods, dielectric response measurement is the most widely used technique at present. This is mainly because the dielectric loss effects can be clearly seen in the depolarization current in the time

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domain or in the complex permittivity in the frequency domain. However, the main drawback of this method is that the time domain measurements require long periods of observation and the frequency domain measurements demand equipment that can measure very low frequencies. For example, with a typical FDS measuring set-up that can measure down to 0.1 mHz, the testing time is usually around 12 hours [7]. The long testing time poses many issues, for instance, high interruption time and the variation of insulation temperature during the period of measurement. The temperature varies because the insulation will no longer be in an equilibrium state once the power supply is disconnected from the transformer. To overcome these issues, the attention is now directed towards the response measurements conducted at high frequencies to limit the testing time. Some recent studies reported measurement of insulation properties at THz frequencies [9]. The high frequency measurements can also be performed at GHz frequencies to estimate dielectric properties. These methods can be divided into three types: namely, reflectometric methods, transmission methods, and resonant methods [10].

The dielectric behavior of insulation in the frequency domain is characterized by its frequency dependent complex permittivity [11]. Usually,dielectric relaxations occur at low frequencies and the variations in the complex frequency can be observed only at low frequencies. However, the presence of moisture in a dielectric material may modify the complex permittivity with respect to its benchmark values. In resonant methods, the dielectric properties near resonant frequencies are measured, which can be effectively utilized to compare different moisture levels.

This paper presents the results of a dielectric property (permittivity and loss tangent) measurement of a transformer pressboard insulation at microwave frequencies from 500 MHz to 10 GHz. We use a microstrip ring resonator fabricated on a substrate of known dielectric properties and the sample to be tested is placed on the substrate as shown in Figure 1. The measurements were taken with and without the test sample and the dielectric properties of the test sample were estimated using the procedure described in Section 2.1 [12-17].

The method was used to estimate the MC of both non-aged impregnated and non-impregnated pressboard samples in real time during the processes of oven drying and wetting in a humidity chamber. These results are presented in Sections 3 and 4.

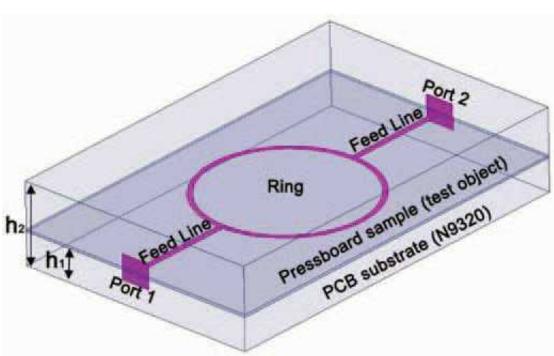

Figure 1. Geometry of the ring resonator.

2 PROPOSED METHODOLOGY

2.1 ESTIMATION OF RELATIVE PERMITTIVITY AND LOSS TANGENT

The method we used to find the dielectric properties of pressboards is published in [17]. However, we summarize the key steps in this Section, so that the methodology we followed to obtain various results can be easily explained. In a ring resonator, the resonances occur when the mean circumference of the ring is equal to an integer multiple of the guide wavelength. Thus, the resonant frequency is given by [12, 13],

$$f_{res} = \frac{nC}{2\pi r\sqrt{\varepsilon_{r\_eff}}} \tag{1}$$

where r is the mean radius, c is the speed of light, and ε_{r_eff} is the effective relative permittivity of the multi-layer stack. The n in equation (1) is an integer and different values of n lead to multiple resonance points. In this work, we measure the transmission characteristics, namely, S_{21} of the resonant circuit using a Vector Network Analyzer (VNA). The S_{21} response exhibits multiple peaks as the admittance of the circuit is minimal due to parallel resonance at the resonance points. The frequencies at the peaks (resonance frequencies) can then be substituted in equation (1) to find ε_{r_eff} values (at resonance points).

The relation between ε_{r_eff} and the relative permittivities of the PCB substrate and the pressboard is given by equation (2) [15].

$$\varepsilon_{r\_eff} = \varepsilon_{rSUB} q_1 + \varepsilon_{rPB} \frac{(1-q_1)^2}{\varepsilon_{rPB}(1-q_1-q_2)+q_2} \tag{2}$$

In equation (2), q_1 and q_2 are filling factors which depend on the line width (w) and the substrate thickness (h_1). The expressions for q_1 and q_2 can be found in [15] and we omit them to keep the content short. The ε_{rSUB} and ε_{rPB} are the relative permittivities of the PCB substrate and pressboard respectively**.** In our design,w is 1.85 mm and h_1 is 0.762 mm. In contrast to FDS measurements, the dielectric measurements are represented by the effective permittivity (ε_{eff}) and effective loss tangent ($\tan\delta_{eff}$) values which are functions of the dielectric properties of the PCB substrate material and the pressboard material. Therefore, if ε_{eff} and $\tan\delta_{eff}$ values are measured, the permittivity and the loss tangent of the pressboard sample can be calculated since those of the PCB substrate are known. As non-aged samples are used for this study, changes in the dielectric properties can be correlated with the moisture content. Such correlations can be used to estimate the MC from dielectric measurements.

Measurement of the loss tangent of the pressboard requires the unloaded quality factor, Q_u of the resonator [17]. Q_u can be obtained from equation (4) if the loaded Q factor, Q_L is known. Finding the loaded quality factor Q_L is not an issue since it is related to the -3dB bandwidth at resonance via equation (3). Since the value of S_{21} is available from the VNA measurements, equation (4) can be used to calculate Q_u.

$$Q_L = \frac{f_r}{BW_{-3dB}} \quad \text{Loaded Q} \tag{3}$$

$$Q_U = \frac{Q_L}{1-10^{\frac{S_{21}(f_0)}{20}}} \quad \text{Unloaded Q} \tag{4}$$

The loss in a micro-strip line has three components: the dielectric loss, the conductor loss, and the radiation loss [16]. The loss term in Q_u is the total of these three losses. If we define Q-factors considering individual losses, Q_u can be expressed as,

$$\frac{1}{Q_u} = \frac{1}{Q_c} + \frac{1}{Q_d} + \frac{1}{Q_r} \quad . \tag{5}$$

In equation (5), Q_d, Q_c, and Q_r are the quality factors defined considering the dielectric, conductor, and radiation losses respectively [16]. Since the effective loss tangent of the multi-layer stack, $\tan\delta_{eff}$ is related to Q_d by the equation,

$$\tan\delta_{eff} = 1/Q_d \tag{6}$$

The loss tangent of the pressboard, $\tan\delta_{PB}$ can be found if Q_d is known. This is because $\tan\delta_{PB}$ is related to $\tan\delta_{eff}$ via equation (8).

Calculation of Q_d is straight forward, if the values of Q_c and Q_r are known. However, reference [17] describes a method to find Q_d without using Q_c and Q_r values. In this method, two measurements are taken, one with the sample under test (pressboard) placed on the ring resonator and another without the sample (PCB substrate only). If it is assumed that the radiation and conductor losses in the two measurements are equal, the dielectric and the unloaded quality factors of the two cases are related by [17],

$$\frac{1}{Q_{d2}} - \frac{1}{Q_{d1}} = \frac{1}{Q_{u2}} - \frac{1}{Q_{u1}} \tag{7}$$

In equation (7), Q_{u1} and Q_{d1} are the dielectric and unloaded Q-factors of the case without any sample, i.e. with only one layer of dielectric material. Q_{u2} and Q_{d2} represent the same when there are two layers of dielectric material, i.e. when the test sample is placed on the substrate.

The connection between the effective loss tangent of a multi-layer stack and the loss tangents of constituent dielectric layers is given by equation (8) [14].

$$\tan\delta_{eff,2} = 1/Q_{d2} = P_{SUB,2}\tan\delta_{SUB} + P_{PB,2}\tan\delta_{PB} \tag{8}$$

where,

$$P_{SUB,2} = \frac{\varepsilon_{rSUB}}{\varepsilon_{r\_eff}} q_2 \tag{9}$$

and

$$P_{PB,2} = \frac{\varepsilon_{rPB} q_2 (1-q_1)^2}{\varepsilon_{r\_eff}(\varepsilon_{rPB}(1-q_1-q_2)+q_2)^2} \tag{10}$$

Similarly, for the single layer case (substrate only), we can write [14],

$$\tan\delta_{eff,1} = 1/Q_{d1} = P_{SUB,1}\tan\delta_{SUB} \tag{11}$$

where,

$$P_{SUB,1} = \frac{1}{1+\frac{F-1}{\varepsilon_{SUB}(F+1)}} \tag{12}$$

F In the above equation is given in [14],

$$F = (1+10h/w)^{1/2} \tag{13}$$

Combining equations (7), (8), and (11), following equation can be derived to calculate the loss tangent of the pressboard [17].

$$\tan\delta_{PB} = \frac{1}{P_{PB,2}}\left(\frac{1}{Q_{u2}} - \frac{1}{Q_{u1}}\right) + \left(\frac{P_{SUB,1} - P_{SUB,2}}{P_{PB,2}}\right)\tan\delta_{SUB} \tag{14}$$

2.2 TEST SET-UP AND MEASUREMENTS

The ring resonator fabricated for the measurements is shown in Figure 2. The circuit was fabricated for measurements from 500 MHz to 10 GHz. We selected NX9320 from Neltec, Inc., for the substrate, a material suitable to work in this frequency range. According to manufacturer supplied data, this material (NX9320) has a relative permittivity of 3.2 and a loss tangent of 0.0024 at 10 GHz. The particular substrate we selected is 30 mil (0.762 mm) thick and has a 0.5 oz.(0.018 mm) copper cladding. The inner and outer radius of the ring are 26.85 mm and 25 mm respectively. These radius set the line width of the ring to 1.85 mm which gives a characteristic impedance of 50 Ω. The gaps between the ring and the feeder lines are set to 0.4 mm each to ensure weak coupling. To be specific, we select the gap size so that it is in the -30 dB to -40 dB range. The design was simulated using a finite element electromagnetic simulator, HFSS version 10.1 from Ansoft Inc.

The Test sample was clamped to the microstrip ring resonator using drawing clips at each edge. This method of

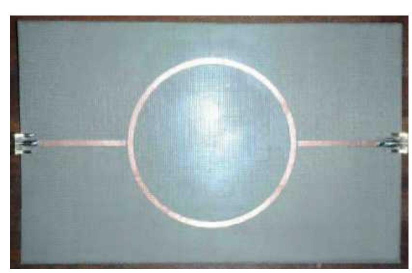

Figure 2. Fabricated circuit.

clamping was used to apply a certain amount of pressure to reduce the air gap between the sample and the resonator while maintaining the fixture as a microstrip setup. Applying a fixed uniform distribution of pressure using a weight was not possible as it transforms the fixture to a stripline system. The setup simulated at different air gaps displayed that the variation in S_{21} with air gap was negligible.

As it can be seen in Figure 2, we use edge mount SMA connectors to launch signals to the feeder lines. The measurements were carried out using an Agilent 8719ES vector network analyzer. The network analyzer was calibrated using a full two port calibration to minimize systematic errors. Figure 3 shows a comparison of the simulated results from Ansoft HFSS and the measured data from the network analyzer. The peaks in the figure are the resonance points and the valleys represent the region where the decaying curves from the adjacent resonance points meet. The lowest resonance frequency was observed at 1.1 GHz which complies with the value yielded by equation (1) when $n = 1$ and r is the mean radius. In addition, seven other resonance points can be observed within the measured spectrum at 1.1 GHz intervals. The simulated and experimental plots closely matched each other especially at the peaks.

We believe that slight mismatches are due to dispersion effects. This is because in the simulations, we assume that the dielectric properties to be independent from the frequency (i.e. non-dispersive), which is only approximately valid in practice. The difference between simulated and measured data is more prominent at valleys, at which the signal leaves are very low (around -50 dB). If the measured signal is weak, the measurement uncertainty dramatically increases.

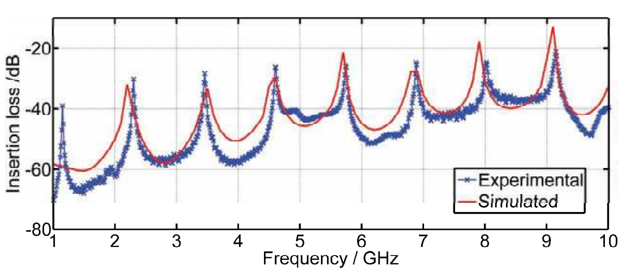

Figure 3. Experimental and simulated insertion loss of the designed ring resonator without any test samples placed.

2.3 VALIDATION

The proposed method was validated by comparing the permittivity values of two known PCB substrate material samples. We used NX9320 from Neltec In., (ε_r= 3.2±0.4, tanδ = 0.0024 at 10GHz) and FR4 (ε_r= 4.3±0.2, tanδ= 0.0018 at 10 GHz) PCB substrates. Three measurements were taken with following materials as the upper material (i) air, i.e., without any samples placed, (ii) with NX9320, and (iii) with FR4. Figure 4 shows the comparison of the plots of measured insertion losses with these two materials. The permittivity and loss tangent values were calculated based on the resonance frequency and the -3dB bandwidth at resonance using the method described in Section 2.1. Table 1 shows the comparison of the permittivity and loss tangent values.

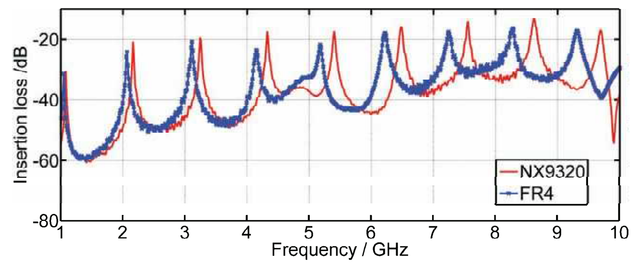

Figure 4. Measured variation of insertion loss for PCB materials with different relative permittivity.

Table 1. Measured ε_r and tanδ values of FR4 and NX9320 substrates.

FR4 (ε_r=4.3±0.2, tanδ=0.18%)			NX9320 (ε_r=3.2±0.4, tanδ=0.24%)		
Resonant Frequency (GHz)	ε_r	tanδ **(%)**	Resonant Frequency (GHz)	ε_r	tanδ **(%)**
2.07	4.2	0.51	2.16	3.1	0.38
3.11	4.0	0.26	3.24	3.1	0.54
4.16	4.0	0.59	4.32	3.1	0.35
5.18	4.1	0.39	5.40	3.1	0.24
6.22	4.1	0.60	6.49	3.1	0.55
7.25	4.1	0.29	7.57	3.1	0.35
8.28	4.2	0.39	8.62	3.3	0.45

In Figure 4, it can be observed that the resonance peaks corresponding to a particular value of n shifts to the left side as ε_r increases: a fact which is self-explanatory from equation (1). Since ε_r of NX9320 is less than that of FR4, the NX9320 sample shows higher resonance frequencies. The peak magnitudes of the insertion loss mainly depend on the dielectric loss. This is because the effects due to radiation and conduction losses are minimized in the method described in Section 2.1. Accordingly, the NX9320 substrate which has the lowest loss tangent shows highest peaks (see Figure 4).

The permittivity values estimated at 8.28 GHz are well within the range specified by the manufacturers for 10 GHz. Maximum variation among the values estimated at different frequencies is 0.2. Reason for such variation can be frequency dependency of the permittivity and measurement errors and accuracy limitations. However, the loss tangent values deviate from the actual values. One possible reason for this discrepancy is that, although the method described in [17] mitigates the radiation effects, it does not eliminate them. Another possibility is the accuracy limitation of the formulas presented in Section 2.

2.4 COMPARISON WITH FDS

This section compares the results obtained from the ring resonator method with conventional FDS measurements. The proposed method has several advantages over FDS measurements. FDS measurements are usually conducted from 0.1 mHz to 1 kHz so that testing time is considerably high (approximately 12 hrs). In contrast, the testing time of the resonator method is limited to only few minutes. Another issue in FDS based complex permittivity measurements, especially at low frequencies is the fact that the condition of the insulation is not the only factor which determines the measured value. Other factors such as temperature at which the measurements are made and electrode polarization [5, 8] also affect the readings. It is usually difficult to isolate the contribution due to the condition of the insulation from the contributions due to other factors.

Due to short measurement time, the ring resonator method is almost immune to the effects due to the other factors mentioned. In addition, in the proposed method, there is flexibility to select the frequency at which the measurements are made by designing a ring resonator of appropriate dimensions to produce resonant peaks at frequencies of interest.

We compare the results obtained using the ring resonator method and FDS using FR4 and NX9320 test samples. Each sample was first measured using the ring resonator method. FDS measurements were then taken from 1Hz to 1 kHz at rms voltage of 140 V using IDA 200. This gave geometric capacitances of 22.34 pF and 46.9 pF for the FR4 and NX9320 samples respectively. The temperature and relative humidity (for both measurements) were 25 °C and 81 % respectively during the measurement. Figures 5 and 6 show the comparison of relative permittivity and loss tangent values, respectively, measured from the IDA 200 (only for the frequency range of 1 Hz-1 kHz) and ring resonator.

Usually, the variations in dielectric properties can be clearly observed in the relative permittivity and loss tangent measurements at low frequencies [11]. Typically the ε_r, and tanδ values decrease as the frequency increases. This pattern could be observed in FDS measurements as shown in Figure 5a and 6a. The ε_r values at 1 kHz were 2.3 and 3.8 for NX9320 and for FR4 respectively. The loss tangent values at 1 kHz were 1.6 and 3.4 for NX9320 and for FR4 respectively. On the other hand, the observed ε_r and tanδ values in ring resonator method were nearly constant as expected, (see Figures 5b and 6b). The ε_r and tanδ values at 1 GHz were 3.1 and 50 for NX9320 respectively. Those values for FR4 were 3.7 and 29.63. The relative permittivity values seem to be in the same level for both FDS and ring resonator method. The tanδ values for ring resonator method were lower compared to those for FDS measurements.

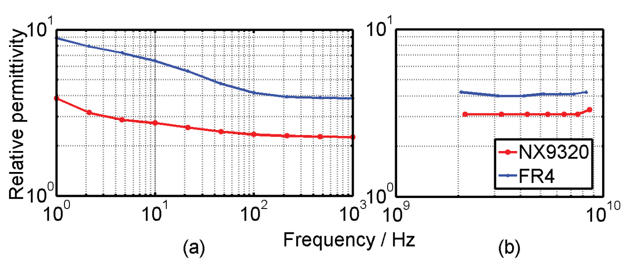

Figure 5. Variation of Relative permittivity values with respect to the frequency (a) from FDS, (b) from ring resonator.

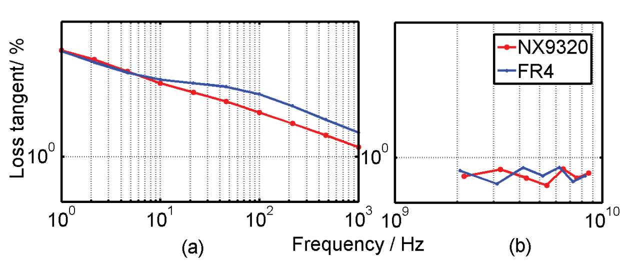

Figure 6. Variation of Loss tangent (%) values with respect to the frequency (a) from FDS, (b) from ring resonator.

3 DRIED SAMPLES

The multi-layer ring resonator was used to find ε_r and tanδ values of pressboard samples with different MC levels. Resonant frequencies were used to calculate ε_r and tanδ as described in Section 2.1. Two different levels of moisture variations were considered: (a) low level of MC variations achieved by drying samples in an oven and (b) broader levels of MC variations achieved by wetting samples in a humidity chamber. For each case both non-impregnated and oil impregnated pressboard samples were studied. This section covers the case of dried samples whereas Section 4 covers samples prepared by wetting.

3.1 SAMPLE PREPERATION

For non-impregnated pressboard samples, five sets of 11 cm x 11 cm pressboard samples (Class A type, thickness 2 mm) were selected. Their edges were sealed with epoxy resin to avoid the moisture absorption from edges during drying [18]. Then the samples were dried in an air circulation oven (74 cm x 67 cm x 90 cm) for 48 hrs at a temperature of 105 °C. According to [18], 48 hours is sufficient to remove moisture from the pressboard samples. The samples were fixed as the upper material in the ring resonator and S_{21} responses were measured using the VNA at different time intervals. The used drying times were 0, 3, 6, 24 and 48 hours. The MC values were estimated for each drying times by taking the average MC of the five samples.

For oil impregnated pressboard samples, five pressboard samples were prepared as in the case of the non-impregnated samples. The considered drying times were t=0, 3, 7, 24 and 48 hours. In parallel, mineral oil was also treated by drying in the oven at 105°C for 24 hours. Then the dried pressboard samples were impregnated with treated oil inside the oven. After cooling down to room temperature, the S_{21} responses were measured from the VNA.

3.2 RESULTS AND DISCUSSION

According to the weight measurements, the MC level for the pressboard samples without drying, were estimated as 10.8%. This is due to the natural wetting at a temperature and Relative Humidity (RH) of about 25°C and 75% respectively [4]. During the oven drying process at 105°C, it was very clear that moisture had evaporated from the samples. The evaporation rate usually follows a non-linear behavior i.e. initially a higher rate and then a lower rate with a tendency towards reaching a stable moisture level [19]. Thus, one would expect that a majority of the moisture might have evaporated from the pressboard sample due to 3 hrs of drying. Our results also confirmed this behavior and during the drying process from 3 hrs to 48 hours, slow moisture variation could be noted (about 0.2%). Figures 7 and 8 show the insertion loss for non-impregnated and oil impregnated samples. The samples prepared by 0 hrs of drying time (referred as 'Wet') and 48 hrs of drying time (referred as 'Dry') were considered for this analysis as they were the extreme cases.

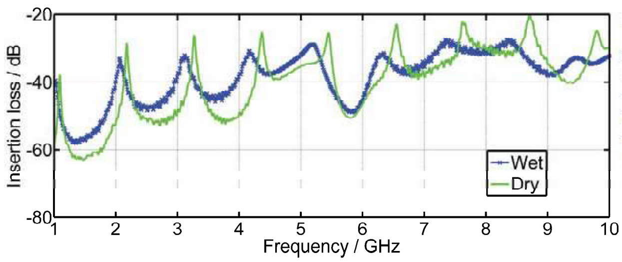

Figure 7. Variation of insertion loss of *oil*-impregnated wet and dry samples.

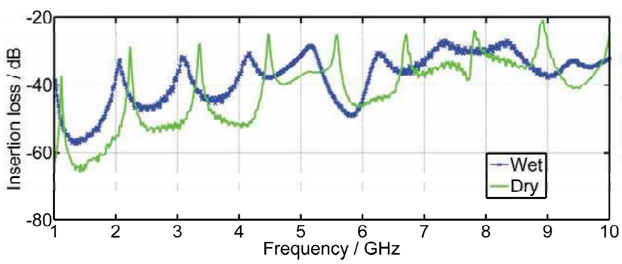

Figure 8. Variation of insertion loss of non-impregnated wet and dry sample.

From Figures 7 and 8, a clear shifting of resonant peaks could be observed among wet and dry samples. In addition, the loss peak levels were smaller for the wet case compared to the dry one. These observations were similar for both non-impregnated and oil impregnated samples. Accordingly, the frequencies of the resonant peaks for wet samples were comparatively lower than those for the dry samples. For example in the oil impregnated case, 2nd peak of the wet samples were at 2.05 GHz and for dry it was at 2.17 GHz. These observations could be explained as follows.

The resonant frequency and effective ε_r have inverse correlations. In the presence of moisture, ε_r usually increases (ε_r of water is 70). Thus wet samples showed a lower resonance frequency with respect to dried ones. On the other hand, wet samples having high MC levels lead to high loss peaks compared to dried samples.

In order to investigate variations of ε_r and tanδ at low levels of MC, the results of the samples dried from 3 hrs - 48 hrs were analyzed. Figures 9 and 10 show enlargements of four different resonant peaks (second, third, fourth and fifth) for impregnated and non-impregnated samples respectively.

Although variation of MC level among these samples i.e. (ΔMC) were comparatively lower i.e. 0.2% variation, clear shifts in resonant frequencies could be noted. It is interesting to note that the frequency changes (Δf) are clearly visible towards the higher harmonic frequencies. When comparing non-impregnated and impregnated samples, impregnated samples gave more accurate results. Because of impregnation and testing, MC levels in the impregnated samples might not have changed compared to the non-impregnated ones. Based

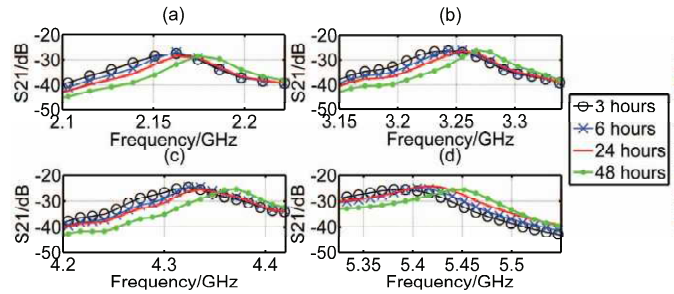

Figure 9. Variation of S_{21} of impregnated samples in different resonant. (a) Second, (b) Third, (c) Fourth and (d) Fifth.

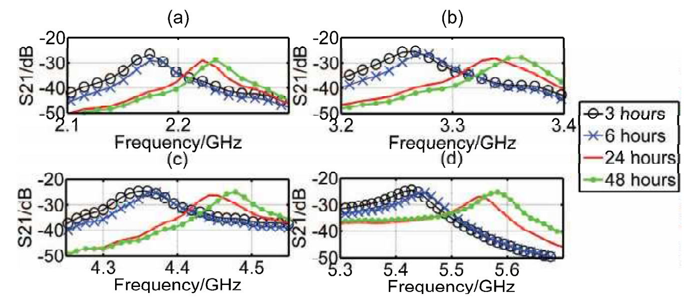

Figure 10. Variation of S_{21} of non-impregnated samples at different resonant peaks. (a) Second, (b) Third, (c) Fourth and (d) Fifth.

on the peaks, the average values of ε_r and tanδ% were calculated. Table 2 shows the ε_r and tanδ values for wet and dried samples (i.e. t=0 hrs and t=48 hrs). It is very interesting to note that the difference between both ε_r and tanδ values for the dry and wet samples were significant at GHz frequencies. The latter parameter i.e. tanδ variations in wet samples were very high and about 400-500% with respect to the dried samples.

Figure 11 shows the calculated ε_r and tanδ values of impregnated pressboard samples at low levels of MC variation i.e. 3 hrs to 48 hrs. Since the MC level variations were small, changes of MC i.e. ΔMC% and normalized ε_r and tanδ values against the dry samples were used for

Table 2. Estimated relative permittivity and loss tangent results of impregnated and **n**on-impregnated pressboard samples for dried and wet cases.

Sample type	Drying time / hours	Impregnated samples		Non-impregnated samples	
		ε_r	tanδ %	ε_r	tanδ %
Dry	48	2.05	0.55	1.44	0.58
Wet	0	3.5	2.85	3.7	2.58

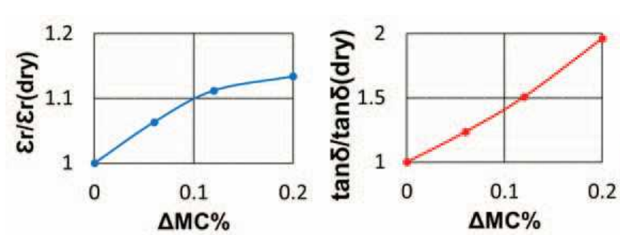

Figure 11. Normalized relative permittivity and loss tangent variation with ΔMC% in impregnated pressboard samples.

analysis. Despite the limited variations in MC levels (i.e. 0.2 %), a clear dependency of both ε_r and tanδ could be noted. This behavior is the same for non-impregnated samples too. This results indicate that the proposed ring resonator method can be used as a diagnostic tool to monitor variations in dielectric parameters due to even slight variations of MC levels This method also can be employed for the verification of the transformer drying process in a factory environment.

4 WETTED SAMPLES

4.1 SAMPLE PREPERATION

Five sets of 11 cm x 11 cm pressboard samples (Class A type, thickness 2 mm) were selected. Their edges were sealed with epoxy resin. The first pressboard samples were dried in the air circulation oven at 105°C for 24 hours (similar to the drying case). Then the samples were further dried in a vacuum oven at 35°C temperature and a pressure of 0.1-0.15 kPa for 24 hours. Samples were kept in the humidity chamber (with a size of 40 cm x 48 cm x 36 cm) for 30 hours under a controlled humidity level. The humidity was controlled by placing different salt solutions in the humidity chamber. The humidity chamber was kept in an air-conditioned room at a temperature of 20°C and RH of 70%. Three different humidity levels were maintained by using three salts namely: (i) NaOH (ii) $CaCl_2$ and (iii) NaCl, according to ASTM E14-02 standard [20, 21]. Then the S_{21} responses were measured using the VNA initially and after 30 hours in the chamber. According to [19] 30 hrs is sufficient to for the pressboard samples to absorb moisture and reach a saturated level. The measurements were repeated for all three humidity levels as well. In parallel, weight measurements were taken to estimate the MC levels before and after moisture absorption. Five other sets of the samples were impregnated with dried mineral oil and the S_{21} response measurements were repeated for those samples as well.

4.2 RESULTS AND DISCUSSION

When wet non-impregnated samples are dried in the oven and then in the vacuum oven, the moisture in the samples evaporates. In the humidity chamber, the dried pressboard samples are exposed to controlled air/moisture in the chamber so that within the chamber, the moisture starts diffusing to the pressboard samples from the surrounding air. MC levels of the pressboard samples usually stabilize after 30 hrs of exposure to the saturated MC level characterized by the humidity of the chamber[19]. The respective humidity levels are (i) 5.5% (NaOH), (ii) RH 32.5% ($CaCl_2$), and (iii) RH 76% (NaCl).

Figures 12 and 13 show the enlargement of the insertion loss (S_{21}) at the second, third, fourth and fifth resonant peaks for impregnated and non-impregnated samples respectively. Clear frequency shifts could be visible with the change of saturated humidity levels i.e. different MC levels in the pressboard samples. Samples kept at high RH showed lower resonant frequencies compared to ones kept at low RH in agreement with the theory part and section 3. Similarly, loss peaks also showed reductions towards wet samples indicating high MC levels. The observations were similar for both

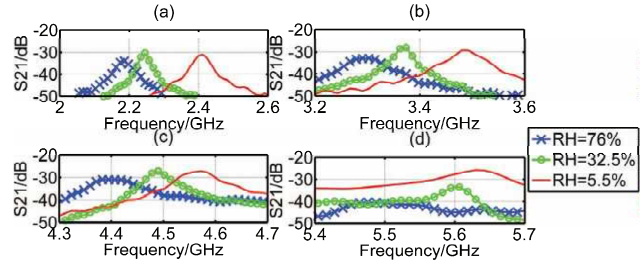

Figure 12 Variation of S_{21} of impregnated samples at different resonant peaks. (a) Second, (b) Third, (c) Fourth and (d) Fifth.

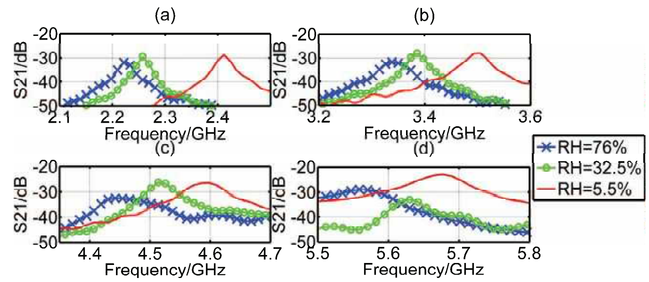

Figure 13. Variation of S21 of non-impregnated samples at different resonant peaks. (a) Second, (b) Third, (c) Fourth and (d) Fifth.

impregnated and non-impregnated samples. The saturated MC levels were estimated for each humidity level and tabulated in Tables 3 and 4 together with details about the resonant peaks. The corresponding ε_r and tanδ values were calculated as explained in Section 2. Figures 14 and 15 show the variation of ε_r and tanδ with MC level for impregnated and non-impregnated samples respectively. In both the graphs, the curves corresponding to the average and the error bar represent the variation due to the resonance frequency. It is worth to mention that this methodology can be used with the measurements at even a single resonance frequency.

Table 3. Correlation of resonant frequencies with MC Values for impregnated pressboard samples.

Salt/Base solution	RH % At 20°C	MC% after 30 hours	Resonant frequency in n^{th} harmonic / GHz			
			n=2	n=3	n=4	n=5
NaOH	76	6.7	2.19	3.3	4.42	5.48
$CaCl_2$	32.5	2.5	2.25	3.37	4.49	5.6
NoCl	5.5	1.3	2.41	3.48	4.57	5.64

Table 4. Correlation of resonant frequencies with MC Values for non-impregnated pressboard samples.

Salt /Base solution	RH % at 20°C	MC% after 30 hours	Resonant frequency in n^{th} harmonic / GHz			
			n=2	n=3	n=4	n=5
NaOH	76	6.9	2.22	3.35	4.48	5.57
$CaCl_2$	32.5	2.4	2.26	3.39	4.53	5.64
NoCl	5.5	1.3	2.41	3.5	4.6	5.68

The MC levels varied from 1.3 to 6.7 in impregnated samples and 1.3 to 6.9 in non-impregnated samples when the humidity was controlled from 5.5% to 76%, showing a broader moisture variation. The obtained ε_r and tanδ values also showed significant variation. For example, when MC

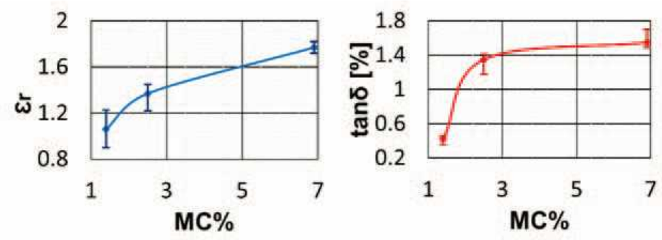

Figure 14. Relative permittivity and loss tangent variation with MC% in impregnated pressboard samples.

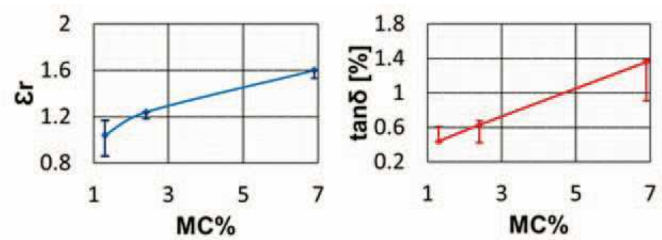

Figure 15. Relative permittivity and loss tangent variation with MC% in non-impregnated pressboard samples.

levels increased from 1.4 to 6.9, the ε_r values increased from 1.06 to 1.77 and from 1.04 to 1.6 respectively for impregnated and non-impregnated samples. In addition, the tanδ values increased from 0.44 to 1.55 and from 0.44 to 1.36 respectively for impregnated and non-impregnated samples. Both results provide promising outcomes to use ring resonator as a good diagnostic tool for estimating MC in pressboard for high variation of MC due to wetting conditions.

5 CONCLUSIONS

The multi-layer micro-strip ring resonator used in this work displays resonant peaks at fundamental and harmonic frequencies in the GHz range. The resonant peaks correlate well with the effective relative permittivity and the effective loss tangent of the substrate and test sample composite. Thus, the relative permittivity and the loss tangent of the transformer pressboard can be estimated by using the pressboard as the top layer of the dielectric composite.

The simulated and measured insertion loss of the ring resonator agreed well, which demonstrates the accuracy of microwave measurements. The measured relative permittivity of the PCB substrate material is in a range similar to the supplied data by the manufacturer. The results are also in agreement with frequency dielectric spectroscopy measurements at low frequencies, thus, confirming the validity of the ring resonator method to measure relative permittivity and loss tangent.

During the oven drying process, moisture content in the pressboard samples reduce due to evaporation. As a result, the relative permittivity and the loss tangent values also reduce. Accordingly, the resonant frequency increases during drying. In agreement with this, both loss tangent and the relative permittivity estimated from insertion loss measurements increase with the MC. Despite the limited variations in MC levels during drying (i.e. 0.2 %), a clear dependency on both the relative permittivity and loss tangent could be noted. This behavior is same for non-impregnated samples as well.

During wetting at controlled humidity conditions, the pressboard samples absorb moisture and reach saturation. As a result the relative permittivity and loss tangent values increase. Accordingly, the resonant frequency decreases during wetting. Samples wetted to relative humidities of 5.5% to 76% resulted in a broader moisture variation reaching up to 6.9% (moisture content). The estimated relative permittivity and loss tangent values also show significant variations and indicate positive non-linear correlations with the moisture content.

Considering all the tested cases, it can be concluded that the proposed micro-strip ring resonator method can be used to estimate the moisture content of impregnated pressboard samples by measuring the loss tangent and/or the relative permittivity. The method is applicable for large and small moisture content variations. We believe that with further investigations of practical aspects, the proposed method can be improved to a fast on-line monitoring tool.

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