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Condition Assessment of Power Transformers Using Loss Tangent Measurements

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Abstract: Mineral oil, cellulose paper and pressboard are the main insulation materials in a power transformer. During service, increase of moisture, as the by-products ageing and increases the risk of insulation failure. This paper presents the possibility to use loss tangent (or power factor) and capacitance (tanδ and C) measurements as an estimate of the 'wetness' of aged transformer insulation. Firstly oil, paper and pressboard samples were aged under laboratory conditions and their tanδ and dielectric constant (εr) values were measured. Applying the tanδ and εr obtained onto a transformer insulation model, the tanδ and C of transformer were calculated and the effects of insulation geometry, moisture content (MC) of pressboard, oil conductivity (σ_{oil}) and insulation temperature under test were established. It was found that tanδ and C values of a transformer strongly depended on its insulation geometry and the temperature. If the temperature is fixed, the change of tanδ value of a transformer can be a direct measure of moisture in pressboard for 'wet' and 'extremely wet' conditions. For a 'dry' transformer, the σ_{oil} oil value is needed as an additional known parameter in order to estimate accurately the moisture in pressboard.

Key words: Power transformer, ageing, moisture, loss factor, capacitance

1. Introduction

Power transformers are considered as one of the most vital and costly apparatus in power system networks. The usual 'design life' of a power transformer is expected to be 25-40 years. However, relying on condition assessment and residual life estimation, the utilities are keen on continuously operating the transformers over their designed lifetime without reliability and safety being compromised. Power transformers usually have insulation systems which consist of oil, paper and pressboard, and the deterioration of the insulation is one of the main factor to determine the lifespan of the transformer. Temperature, moisture and oxygen are the main ageing factors. Moisture in particular, is the main cause for weakening cellulose solid insulation and shortening the lifetime of transformer. It is suggested that the moisture content should be maintained below 2.0% in the paper insulation in order to provide good electrical and mechanical strength for a transformer to have a longer lifetime [1].

Tests are commonly used today [2-4] to assess the "wetness" condition of transformer insulation. As an example, oil samples are taken regularly to laboratory for measuring the moisture content in oil, and indirect estimation on moisture content in paper/pressboard insulation can then be achieved using moisture equilibrium curves [5,6]. In the field, electrical tests carried out during regular maintenance/ test period also provide information about the "wetness" of transformer insulation. Out of different electrical tests, attention has recently been paid on frequency domain spectroscopy (FDS) due to its noise effectiveness over the time domain measurements [7,8]. FDS measures tanδ or complex capacitance in the frequency range between 1mHz to 1kHz. Since the most prominent information about the moisture is mainly available at low frequencies, completion of one FDS measurement usually takes several hours out of the regular maintenance period of the transformer if the test is extended to below 1mHz. While the transformer is being tested in the field, it naturally cools down. The continuous temperature reduction could cause water diffusions as well as change of spectrum. These changes in transformer insulation affect on the FDS results due to long testing time.

On the other hand, the loss tangent and capacitance (tanδ and C) measurements at 50Hz,

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are commonly used by utilities as a diagnostic tool [9] and it is much less time consuming. Most importantly, some of the old transformers operating in the network normally do not have a complete set of tanδ and C test record since their very first factory test. Sometimes the details related to their geometry are also missing. However, estimation of moisture content (MC) in transformers can be achieved through a comparative approach once the relationship between the MC and tanδ is established. This work aims to use tanδ measurements as a MC assessment tool for transformer insulation. This is based on the understanding on how tanδ is affected by various parameters such as MC of paper/pressboard, geometry of the insulation, conductivity of oil, and the temperature inside the transformer. First, the basic relationships between MCs of individual oil, paper and pressboard with tanδ were established using laboratory tests. Second, the combined oil/paper/pressboard insulation was modelled using the obtained results from laboratory measurements in order to correlate tanδ with those affecting factors.

2. Power Transformer Insulation

A power transformer consists of main windings (LV and HV) and core. The windings are covered with paper insulation whereas the main insulation between LV and HV windings are oil and pressboard. Figure 1a shows a cross sectional view of a transformer. The oil/pressboard insulation consists of multiple oil ducts separated by cylindrical pressboard barriers and supported by spacers. The cross sectional view of Figure 1(a) for the main insulation is shown in Figure 1(b). Despite the windings are being cylindrical in shape the radius of LV winding is sufficiently large to assume the combined oil/paper/pressboard insulation as series/parallel plate capacitors. The same materials, pressboard, paper and oil ducts can be put together and the well known "X-Y model" for transformer insulation can be formed [10]. Here, when comparing oil and pressboard insulation, the current through oil has a considerable effect from its conductivity and negligible polarization effect compared to those in pressboard. Thus the current flow through series oil-pressboard barriers and axial pressboard spacers are nearly independent so that they can be treated separately. By lumping separately the distributed series oil-pressboard barriers and pressboard spacers together the insulation can be simplified to a composite model [10] as shown in Figure 1(c). By considering the width and the periphery of the insulation as unity, the parameters t, X and Y can be taken as

t = The ratio between the inter-turn paper thickness to the radial width of the main insulation

X = The ratio between the total thickness of pressboard barriers to the radial width of the main insulation

Y=The ratio between the total width of spacers to the average perimeter of the main insulation

X and Y parameters vary with the configuration and construction of the transformer. Between HV and LV windings, the typical values for X and Y are ~20% and ~25%. Between the LV winding and ground (core) the typical values for X= ~50% and Y= ~25%. Between HV winding and ground (tank) X is very small and Y is almost negligible [11].

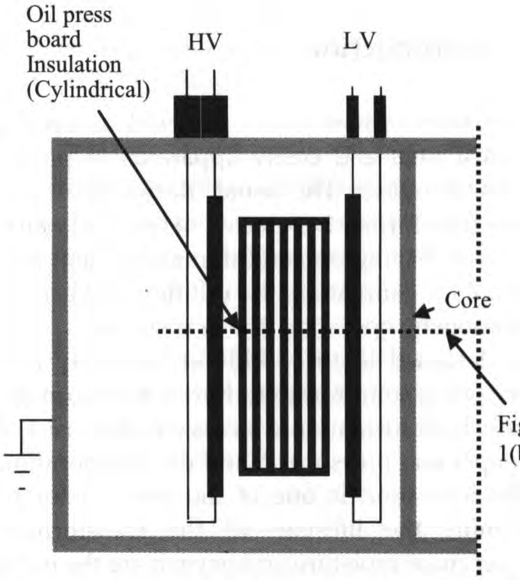

Figure 1(a) - Cross section view of transformer

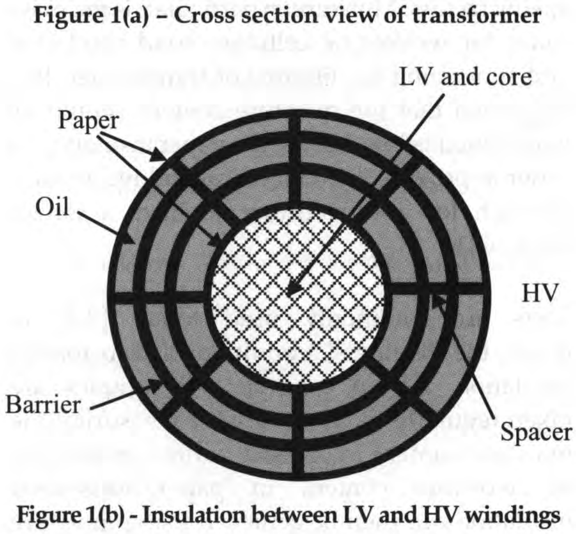

Figure 1(b) - Insulation between LV and HV windings

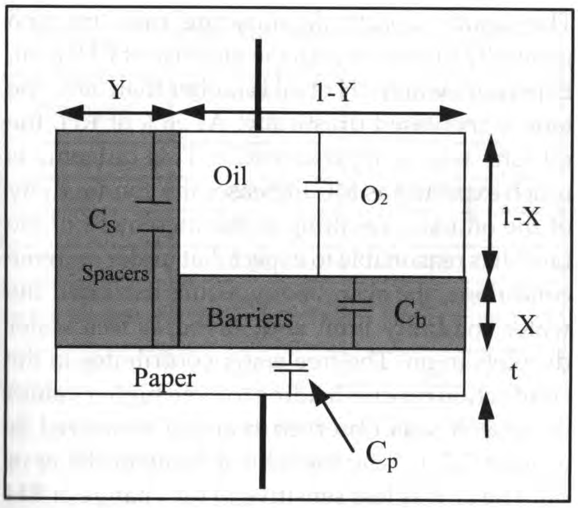

Figure 1(c) - Transformer paper/pressboard/oil insulation model between HV and LV windings as in X-Y Model [10]

3. Laboratory Measurements

3.1 Oil samples

Six oil samples (NYTRO-10-GBN insulating oil) were prepared for the study. Out of them four samples were used to check the moisture effect by varying the relative humidity (RH) condition. The rest of the samples were aged under laboratory conditions. In comparison a virgin oil sample was also used. The details of the samples are given below.

Sample 1	Virgin (700 ml)
Sample 2	Non-aged at RH 11.3% (700 ml)
Sample 3	Non-aged at RH 32.4% (700 ml)
Sample 4	Non-aged at RH 48.7% (700 ml)
Sample 5	Non-aged at RH 56.0% (700 ml)
Sample 6	Aged under sealed condition (1000 ml at 115^{0}C for 21 days)
Sample 7	Aged under unsealed condition (500 ml at 115^{0}C for 56 days)

For humidity treatment, the samples were conditioned in a desiccator at room temperature for about one week. The air RH of the desiccator was controlled by mixing different portions of glycerol and distilled water and the mixture was prepared and put in the dessicator for two hours beforehand to ensure it reached the equilibrium state before trays of mineral oil were put inside. The values of the RH were verified by a hygrometer inside the dessicator. The samples 6 and 7 were aged under sealed and unsealed condition in an air-circulating oven (inner size: 490x430x610 mm3). The two different methods i.e. sealed and unseal, were used in order to simulate hermetically sealed transformer and free breathing transformer during ageing process.

After preparation of oil samples, the MCs levels were determined by Karl Fischer Titration method using Metrohm 684 Coulometer and 832 Thermoprep. Each sample was tested three times and the average value was obtained. Afterwards the tanδ and εr values were measured on samples using ELTEL ADTR-2K. Three measurements were taken for each sample inside an oil test cell which has the geometric capacitance value of ~70 pF and the test voltage was 2.0 kV. New virgin mineral oil was used to wash the test cell in between different measurements. The average value of the tanδ was used for the evaluation.

3.2 Paper samples

Two oil-free non-aged paper samples with the size of 150 mm x 160 mm and the thickness of 0.25 mm were used for the study. Each sample was separately impregnated under dry and wet conditions. The dry samples were first dried in the air-circulating oven at 1050C for 24 hours and were further dried in a vacuum oven at 1050C, 7.5 mbar for 24 hours. At the same time, mineral oil was put into the vacuum oven for degassing and dehydration. Finally, the samples were immersed into the pre-processed mineral oil for impregnation and kept for 48 hours. The wet samples were conditioned by exposing them to atmosphere at room temperature and RH of 50% for 48 hours and were immersed into pre-processed mineral oil for impregnation under vacuum for 72 hours.

The tanδ and εr measurements were taken on each paper samples using ADTR-2K at room temperature of 20^{0}C. The test sample was kept between upper and lower cylindrical electrodes of a three-terminal guarded solid test cell where the high voltage was supplied to the lower electrode. The diameters of the upper and lower electrodes were 100mm and 150mm respectively and the upper electrode was surrounded by a guarded ring of 10mm in thickness. The cell capacitance varied with the thickness of the samples and it was approximately 70 pF for a 1mm gap. The solid test cell was kept inside the desiccator under controlled humidity of 21% (approximately half of the air RH of the environment) using silica gel. The measurements were repeated for three times for each sample and the average value was taken. The MCs of the samples (before the test) were measured using Karl Fischer Titration method.

Additional tanδ measurements were taken on wet sample with different MC levels. First, the wet sample soaked in mineral oil were heated in the air circulating oven for two hours at 80°C to allow evaporating some of the moisture inside it in order to get different MC levels. Then the measurements of tanδ and MC were recorded two times at room temperature of 20⁰C.

3.3 Pressboard samples

Four oil-free non-aged pressboard samples with the size of 150 mm x 160 mm and the thicknesses of 1.5 mm and 3 mm for two each, were used for the study.

The four pressboard samples were divided into two sample sets of thickness 1.5 and 3 mm each. The samples were impregnated under dry and wet conditions similar to paper samples. The tanδ and εr measurements were taken on each pressboard samples. For wet pressboard samples, only one measurement was taken after the heat treatment.

4. Results of Laboratory Measurements

4.1 Conductivity Vs Loss Tangent for Oil Insulation

Table 1 shows the loss tangent and MCs of oil samples. For non-aged samples the RH values are included.

Table 1 - Results of relative humidity, MCs and loss tangents for oil samples

Sample No	Moisture content [ppm]	Relative humidity [%]	Loss tangent [%]
1	10.1		0.063
2	6.2	11.3	0.088
3	17.8	32.4	0.109
4	26.8	48.7	0.248
5	30.8	56.0	1.649
6		Sealed (7 days)	0.161
	34.5	(21 days)	0.687
7		Unsealed (7 ds)	0.151
		(21 days)	0.210
	27.9	(56 days)	0.355

The results clearly demonstrate that the tanδ generally increases with the increase of RH of oil. Especially when RH of oil is higher than 50%, the tanδ is increased drastically. At 56% of RH, the oil tanδ was as high as 1.65%. This outcome is much expected as MC increases the conductivity of the oil (σ_{oil}), resulting in the increment of the tanδ. It is reasonable to expect that under extreme conditions, the absorbed moisture exceeded the water solubility limit and stayed as free water droplets in oil. The free water contributes to the conduction process leading to even higher values of tanδ. It was observed that the measured εr around 2.2, i.e. the theoretical value of the εr of oil. The εr was less sensitive to the change of RH of the mineral oil. It is supposed that the amount of moisture containing in the oil is too small to influence the εr. Although the RH between each sample increased by at least 7%, yet from a different perspective, the MC is in the range of parts per million (ppm), and in these samples may differ by the most about 25 ppm, which is too little to make any influence to the εr.

During ageing the tanδ increased with ageing. It is clearly stated that the produced moisture and other ageing by-products increased the tanδ values for both sealed and unsealed conditions. The tanδ values for sealed and unsealed conditions with respect to time were similar up to 7 days and then later were significantly lower for unsealed samples than that of sealed samples. The ageing under unsealed conditions allowed free evaporating moisture and by-products from the oil samples so that the measured tanδ and MC values were lower. On the other hand, under sealed condition, with sufficient amount of free air inside the sealed container (about 500ml out of 1000 ml), the oxidization and hydrolysis actions took place increasing the losses and moisture.

Since the conductivity represents the effect of both moisture and other conductive by-products rather than MC, it was used for further investigations. The σ_{oil} can be calculated using measured loss tangents as

$$\sigma_{oil} = \omega \varepsilon_0 \varepsilon_r \tan\delta \quad (1)$$

At 50Hz, εr = 2.2, and $\varepsilon_0 = 8.85 \times 10^{-12}$. Table 2 shows the calculated conductivities (at 20⁰C). The measured loss tangent values are included for comparison.

Table 2 - Conductivity values for oil samples

Sample	Loss tangent [%]	Conductivity [pS/m]
1	0.063	3.86
2	0.088	5.38
3	0.109	6.67
4	0.248	15.17
5	1.649	100.86
6	0.687	42.02
7	0.355	21.71

4.2 MC Vs Loss Tangent for Paper and Pressboard Insulation

Table 3 shows the variation of tanδ values for paper and pressboard samples with different treatments. Figure 2 shows the variations of tanδ and εr values for paper and pressboard samples with different MC levels. The trend lines for the scattering of data points are also included.

It could be clearly observed that the tanδ and εr values increase with MC values. In the former case, the variation of tanδ is significant as exponential whereas for the latter case the εr values double for wet pressboard samples. Water is much more polar as compared with cellulose, and therefore MC increases conductivity of paper and pressboard and subsequently increases the tanδ. Similarly, higher εr of moisture than that of cellulose contributes towards the increase of εr value of the wetted samples.

Table 3 - MCs and loss tangent values for paper and pressboard samples

Treatment	MC [%]	tanδ [%]
Paper samples [0.25 mm]		
Dry	0.718	2.4
Wet	1.426	33.8
2 hrs heating	0.949	19.9
4 hrs heating	0.737	7.5
Pressboard samples [1.5 mm]		
Dry	1.091	0.663
Wet	5.455	57.0
2 hrs heating	3.595	48.6
Pressboard samples [3 mm]		
Dry	1.518	0.70
Wet	6.511	70.0
2 hrs heating	5.254	57.0

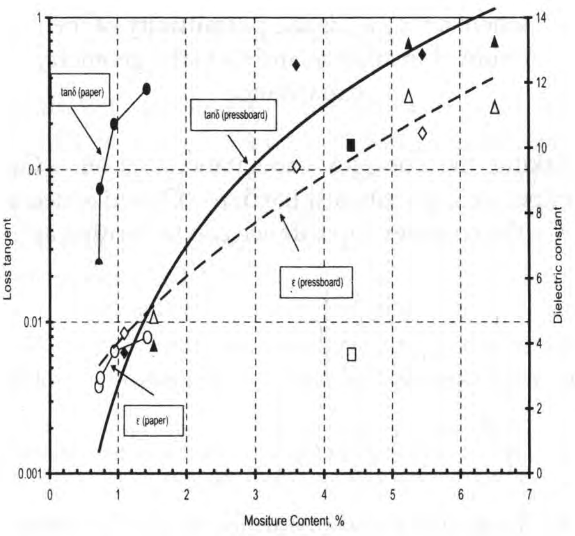

Figure 2 - Loss tangent and dielectric constant of paper (0.25 mm) and pressboard (1.5mm & 3.0 mm) samples as a function of the MC.
◆ tanδ for 1.5, ◇ εr for 1.5, ▲ tanδ for 3.0,
△ εr for 3.0, ● tanδ for 0.25, O εr for 0.25,

The tanδ value is expected to be geometry independent. However, higher levels of tanδ values could be seen for paper than pressboard samples at the same level of MC. This is due to the structural difference between paper and pressboard. The oil/cellulose volume ratio in paper almost doubles that in pressboard, and therefore the same level of MC in paper would means a higher percentage of moist cellulose in paper than in pressboard and the tanδ of paper with the same level of MC is therefore much higher.

5. Modelling of Transformer Insulation

The information on tanδ versus MC/σ of individual oil, paper and pressboard insulations were used to model the combined oil/paper/pressboard insulation of a transformer. According to Figure 1(c), the oil and pressboard barriers act as series capacitors. Since the total width of oil ducts is much thicker than that of pressboard, the oil capacitance is much smaller and therefore is dominating. The combined oil/barrier and spacer/barrier act as parallel capacitors and both contribute significantly towards the measured capacitance of transformer. The complex capacitance of the combined oil/paper/pressboard transformer insulation can be written as

$$C^* = C_0\left[\varepsilon' - j\varepsilon''\right] \quad \text{...(2)}$$

where $\varepsilon = \varepsilon' - \varepsilon''$, is the permittivity of the combined insulation and C_0 is the geometry capacitance.

Taking the complex capacitances of oil - C_o, paper - C_p, pressboard barriers - C_b and spacers -C_s, the complex capacitance can be written as

$$C^* = \frac{\left[C_s^* + \frac{C_o^* C_b^*}{C_o^* + C_b^*}\right] C_p^*}{\left[C_s^* + C_p^* + \frac{C_o^* C_b^*}{C_o^* + C_b^*}\right]} \qquad (3)$$

By assuming the transformer height as unity, the individual complex capacitances of oil (C_o), paper (C_p), pressboard barriers (C_b) and spacers (C_s) can be written as (4)-(7).

$$C_o^* = \frac{\varepsilon_0 (1-Y)}{(1-X)} \left(\varepsilon_o' - j\varepsilon_o''\right) \qquad (4)$$

$$C_p^* = \frac{\varepsilon_0}{t} \left(\varepsilon_p' - j\varepsilon_p''\right) \qquad (5)$$

$$C_b^* = \frac{\varepsilon_0 (1-Y)}{X} \left(\varepsilon_b' - j\varepsilon_b''\right) \qquad (6)$$

$$C_s^* = \varepsilon_0 Y \left(\varepsilon_s' - j\varepsilon_s''\right) \qquad (7)$$

The real part of permittivity (ε') represents the relative permittivity, ε_r of the material whereas the imaginary part (ε'') provides the information about the losses in each insulation. The measurable tanδ of the combined transformer insulation can be calculated by (2) as

$$\tan\delta = \frac{\varepsilon''}{\varepsilon'} \qquad (8)$$

The measurable capacitance of the combined transformer insulation is $C_0\varepsilon'$ where geometric capacitance C_0 is considered as unity. In order to model the tanδ and capacitance the information on individual material, oil (4), paper (5) and pressboard (6&7) were extracted from laboratory measurements described in section 4.

In order to model the transformer insulation, the relationships among MC, tanδ and εr values for paper and pressboard samples were extracted from laboratory results. The selected MC levels were 0.5%, 1%, 2%, 3%, 4% and 5% which covered dry (0-2%), wet (2-4%) and extremely wet (>4.5%) insulation conditions according to [1]. The extracted results are shown in Table 4. The tanδ and capacitance of combined insulation was estimated using equations (2)-(8) and different effects due to insulation geometry, moisture, σ_{oil} and the temperature were separately studied.

Table 4 - Estimated tanδ and εr values for paper and pressboard samples

Moisture content [%]	Pressboard Tanδ	Pressboard ε_r	Paper Tanδ	Paper ε_r
0.5	0.0005	4.3		
1.0	0.004	4.3	0.024	2.7
2.0	0.03	6.0		
3.0	0.11	7.7	0.34	4.2
4.0	0.24	9.1		
5.0	0.50	10.4	0.34	4.2

5.1 Effect of Insulation Geometry

Four different insulation geometry cases were considered to represent different practical X and values between LV and HV windings. They were (i) X=20%, =25%, (2) X=20%, =15%, (3) X=30%, =25%, and (4) X=30%, Y=15%. The paper thickness was taken as 2%. Figures 3a and 3b show the normalized capacitance and tanδ versus pressboard MC under different X, values.

It is clear that tanδ and capacitance increase with the increase of , as an example, the capacitance of transformer increases 21% at extremely wet conditions (MC=5%) when Y changed from 15% to 25%. However, if the transformer is under dry insulation condition the difference due to the change of insulation geometry is very low. On the other hand, variation of capacitance due to increase of X seems to be constant with the change of pressboard MC. Similar results could be observed for tanδ results.

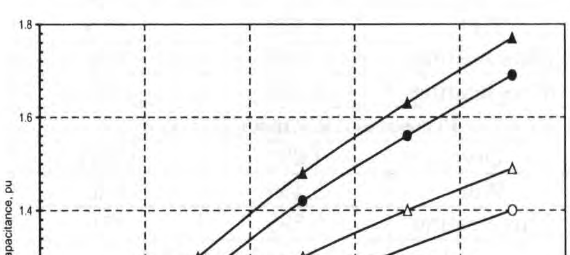

Figure 3(a) - Normalized capacitance of combined insulation as a function of pressboard MC and different insulation geometry

O X= 20%, Y= 15% △ X= 30%, Y= 15%
● X= 20%, Y= 25% ▲ X= 30%, Y= 25%

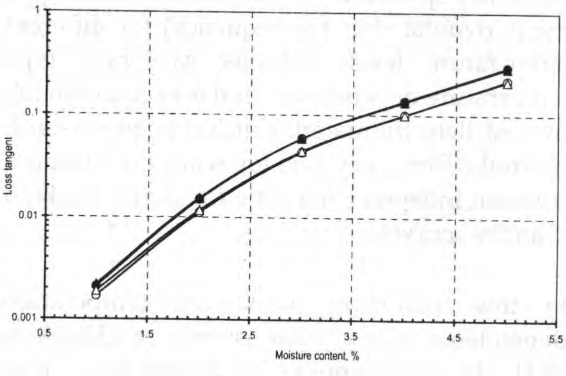

Figure 3(b) - Loss tangent of combined insulation as a function of pressboard MC and different insulation geometry

O X= 20%, Y= 15% △ X= 30%, Y= 15%
● X= 20%, Y= 25% ▲ X= 30%, Y= 25%

This geometry dependence can be explained as follows. According to Figure 1c, the oil and pressboard barriers act as series capacitors where the oil equivalent capacitance is much smaller than that of pressboard and therefore is dominating. Since εr of oil is almost constant with moisture, variation of resultant capacitance is not significant. The oil/barrier and spacer/barrier act as parallel capacitors and both contribute significantly towards the measured capacitance of transformer. Since the ε_r of spacers increases with MC, see Figure 2, the final measured capacitance change significantly with the change of spacer ratio Y. In the following study, the geometry was assumed to be fixed and was restricted to case 1, i.e. X=20%, Y=25%.

5.2 Effect of Moisture in Paper

Out of paper and pressboard, the paper insulation can be easily deteriorated as high temperature in windings cause thermal degradation faster and the contaminated oil diffuses moisture quicker. The effect of paper MC was separately analysed by changing the MC level up to 3% using extrapolation of curves in Figure 2. However it was found that the influence of paper MC on tanδ and capacitance of combined insulation was negligible. As far as the dimensions of a transformer is concerned, the thickness of the paper (t) is negligible (high capacitance) compared to pressboard insulation so that the tanδ and capacitance value of transformer mainly reflects the MC in pressboard.

5.3 Effect of Oil Conductivity

Different σ_{oil} levels were selected from the results in Table 2. Figure 4 shows the calculated tanδ and capacitance values for combined insulation at room temperature for different MCs of pressboard. The trend line of tanδ for pressboard insulation is also included for comparison. The dependence of capacitance vs MC in pressboard on σ_{oil} was found as very small and one conductivity level has been included.

Since the tanδ of the combined insulation is a function of both pressboard MC and σ_{oil} it is convenient to discuss the results in three different 'wetness' levels.

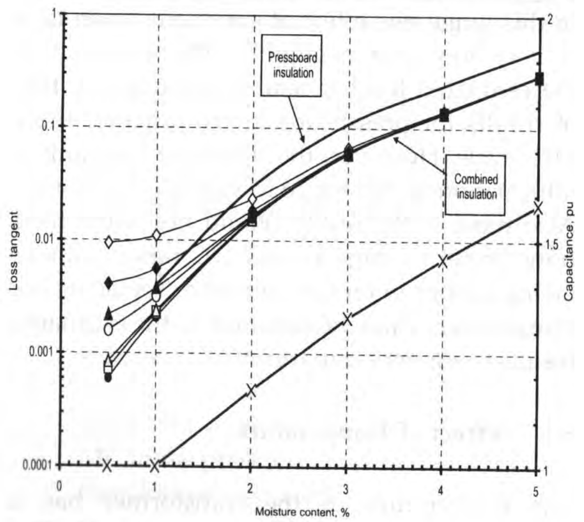

Figure 4 - tanδ and normalized capacitance of combined transformer insulation as a function of pressboard MC and oil conductivity

● Sample 1, □ Sample 2, △ Sample 3, O Sample 4, ◇ Sample 5, ◆ Sample 6, ▲ Sample 7, X Capacitance

Dry insulation (MC <2%):
According to Figure 4, the σ_{oil} brings uncertainty of estimating MC of pressboard from the measured transformer tanδ value. At 0.5% of MC level i.e. very dry insulation, extremely wetted oil has contributed more than 10 times to the overall tanδ value. So, the estimation is unreliable unless the information about the σ_{oil} is precisely known. However, one could argue that since the dry transformers are in good condition in the range the exact values of MC of pressboard is not very important. So, tanδ measurements can still be useable for rough estimation on pressboard 'wetness' in this range of MC levels.

Wet insulation (2 % < MC <4 %):
The region of MC level is highly concerned by the utility. According to Figure 4, it can be clearly seen that the σ_{oil} has limited contribution towards the measured transformer tanδ value. The 'wetness' of the pressboard dominates the tanδ value and the behaviour is dominant when coming closer to the upper limit of MC. The trend line between tanδ and MC for pure pressboard validates these findings. Therefore one could make a judgment on the 'wetness' of the insulation by tanδ measurements. If the history of the tanδ values of the transformer is known the reliability of estimation increases further.

Extremely wet insulation (MC > 4.5 %):
In this range, the effect of conductivity on tanδ is very low and negligible. The accuracy of the estimated level is mainly followed by that of results for pressboard in the range of these MC levels. However, the literature has limited information in this range to validate the results. Also most of the utility would not allow their transformer running in this MC range without taking actions of on-line drying or replacing the transformer. Thus the accuracy of the estimated results is not very important.

5.4 Effect of Temperature

The temperature of the transformer has a significant effect on tanδ values [6, 8]. The temperature of windings may increase up to even 70-90^{0}C depending on loading conditions. When a transformer is switched off for its regular maintenance/tests, the temperature drops with the time initially at a higher rate. Thus the modelling work was extended to see the effect of temperature on tanδ measurements. With the change of temperature, both the σ_{oil} and tanδ of pressboard vary significantly. The temperature dependence of σ_{oil} is given by Arrhenius equation as in Equation (9).

$$\sigma = \sigma_0 e^{\left(-\frac{E_{dc}}{KT}\right)} \quad \text{(9)}$$

The E_{dc}, T, K, and σ_0 are activation energy, absolute temperature, the Boltzmann constant and pre-exponential factor respectively.The calculation of temperature dependence of tanδ of pressboard is not straightforward as that of oil, but one could use master curve technique [12] applied to dielectric measurements (complex capacitance, i.e. $C_0(\varepsilon'+j\varepsilon'')$) over a wider frequency spectrum. In master curve technique, the horizontal shift (in frequency) for different temperature levels exhibits Arrhenius type temperature dependence similar to equation (9). In most dielectric materials including pressboard, when the frequency is in log scale, this shift is a constant independent of the frequency for both ε' and ε" curves.

In this modelling work, the temperature dependence of εr (ε') was assumed negligible at 50 Hz. Then the temperature dependence of tanδ which is only described by the effect of ε", can be calculated by using the horizontal shift of tanδ vs frequency curves at different temperatures according to equation (10).

$$\Delta \tan\delta \approx m\frac{E_a}{K}\left(\frac{1}{T_2}-\frac{1}{T_1}\right) \quad \text{(10)}$$

The m is the approximate gradient of tanδ vs frequency curves around 50 Hz.

In this work, the temperature dependent tanδ values were estimated for different temperature levels of 30^{0}C, 40^{0}C and 50^{0}C by considering 20^{0}C as the base values. The approximate gradient values were extracted from the results of frequency and temperature dependent complex capacitance graphs in [13]. Ekanayake in [13], has presented the frequency dependent (from 1 kHz to 0.1 mHz) complex capacitance (ε' and ε") curves for pressboard samples having different MC levels (1%-4%) at different temperature levels (20^{0}C, 50^{0}C and 80^{0}C). By using those curves, the gradient, m values were estimated for different MC levels (1%-4%) and different temperatures levels (30^{0}C, 40^{0}C and 50^{0}C). The results are shown in Table 5.

Table 5 - Estimated gradient values for equation (10) according to [13]

Temperature [°C]	Moisture content of pressboard [%]			
	1.0	2.0	3.0	4.0
30	0.1	0.15	0.1	0.25
40	0.15	0.3	0.2	0.5
50	0.25	0.5	0.3	0.8

The temperature dependent tanδ of combined transformer insulation was obtained by considering the effects of oil and pressboard. Two conductivity levels were used to cover the extreme ends of virgin oil (3.86 pS/m) and non-aged wetted oil (100.86 pS/m). The obtained results are shown in Figure 5. The comparative trend line of tanδ Vs MC for pressboard is also included by scaling down its trend for clear comparison.

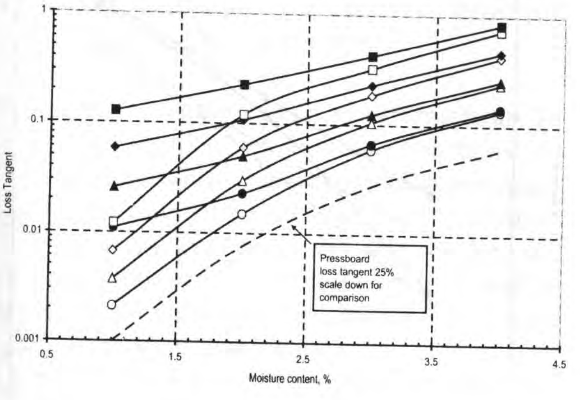

Figure 5 - tanδ of combined transformer insulation as a function of pressboard MC, oil σ and T.

○ At 20⁰C (virgin)	● At 20⁰C (wetted)
△ At 30⁰C (virgin)	▲ At 30⁰C (wetted)
◇ At 40⁰C (virgin)	◆ At 40⁰C (wetted)
□ At 50⁰C (virgin)	■ At 50⁰C (wetted)

The tanδ of combined insulation always increases with elevated temperature due to the fact that the σ_{oil} and MC of pressboard raise the losses of the insulation with temperature. The behaviour follows the trend line for virgin oil. From the results it is clear that the oil temperature is an essential parameter to determine the MC of pressboard.

6. Practical considerations

The above modelled results on tanδ measurements are mainly valid if the moisture diffusion is in equilibrium state between oil and pressboard. However, when a transformer is naturally cooled, the moisture starts to diffuse from oil to pressboard, but in most cases of field tests, the diffusion may only start and is far from reaching to the equilibrium condition because of the temperature reduction. For example for 1 mm thick pressboard, the time taken to reach the equilibrium state will be up to two weeks at 20⁰C [5]. In addition, the elevated temperature along the height of the transformer from bottom to top also affects different levels of moisture distribution between pressboard and oil. These two factors, the most probable effective non-equilibrium conditions appearing during natural cooling, may influence the accuracy of using tanδ measurements to estimate the moisture level.

As a case study, the effect of non-equilibrium state and temperature variation has been superimposed to the analysed data in part 5. The following assumptions are made on the analysis:

-Initially the transformer operates for a long time. Despite the daily changing operating cycles, it is in the equilibrium state for moisture diffusion. The temperature variation along the height of the insulation is 40⁰C -70⁰C where the middle temperature is 55⁰C.

- The MC of pressboard varies along the height and obeys Oommen equilibrium curves [5].
- Since the oil circulates continuously, its MC value is constant.
- Now, the transformer is switched off and the temperature of the insulation drops to 20⁰C-30⁰C, where the middle temperature drops to 25⁰C.
- The time is insufficient for moisture to diffuse from oil to pressboard during continuous temperature reduction to reach the equilibrium state, so that the MC in the pressboard is same as when the transformer operates.

The height of the transformer was divided into seven parts. The tanδ of each part was estimated and the overall tanδ was estimated by treating them as seven capacitors connected in parallel. In the equilibrium state, the temperature varied in each part as 40ºC, 45ºC, 50ºC, 55ºC, 60ºC, 65ºC and 70⁰C. Three levels of MCs in pressboard were used as 1%, 2% and 3% which appeared in the middle height of the insulation. The MC values in the other six parts (except the middle) were calculated using equilibrium curves [5].

When the temperature drops to 20-30ºC, the tanδ of pressboard in each segment was calculated using Figure 5. The tanδ of oil was estimated using the temperature dependent conductivity (eqv (1) and (9)). Two cases were considered as non-aged and aged oil to represent the extreme ends of oil conductivity. Then the resultant tanδ values were estimated for the combined insulation at different MC levels of the pressboard i.e. the average value appearing in the middle of the transformer.

Figure 6 shows the variation of estimated tanδ values. The corresponding tanδ results for equilibrium state are used for the comparison. As expected, the tanδ values at non-equilibrium state are lower than that of equilibrium state confirming the moisture appears mainly in oil. Further the relationship between measurable tanδ values (non-equilibrium) and modelled results (equilibrium) was established and it has been found that the relationship can be approximated to a linear behaviour. So, the approximate tanδ value at equilibrium state can be determined by increasing about 60% to that of non-equilibrium state. This relationship is nearly valid for both aged and non-aged oils.

As a summery, by using the above established relationships, the following general guidelines can be given to estimate MC of the insulation from the measurement of loss tangent across LV and HV windings of the transformer.

The marginal level of MC in the pressboard insulation is 2% and periodic measurements (at least annually for transformers with longer service period) will help to see the tendency of moisture development.

If a transformer is allowed to cool naturally for a sufficient period to achieve the equilibrium condition i.e. couple of days, and if the tanδ measurement is done at room temperature, the effect of temperature and non-equilibrium conditions can be eliminated. Thus rough estimation of MC level of insulation can be obtained from the results established in Figure 4. For lower MC levels additional tanδ measurement is required from an oil sample collected from the same transformer at room temperature.

During regular maintenance period, if the duration lasts only several hours, still rough estimation of MC level can be achieved by taking the measurements when temperature reaches closer to the room temperature. Since this situation is under non-equilibrium state, calibration is necessary to predict for that under equilibrium condition. i.e. see Figure 6.

One of the challenges that utility facing is the lack of information on the geometry of old transformers. The figures are given for typical power transformer i.e. X=20% and Y=25%. Since Y is the dominant part affecting the tanδ value and at the same time, analysis were done at the upper limit of Y, for other cases, the estimated MC values may be slightly above the actual values, see the Figure 3. On the other hand, the X value has a limited effect on the estimated results of MC.

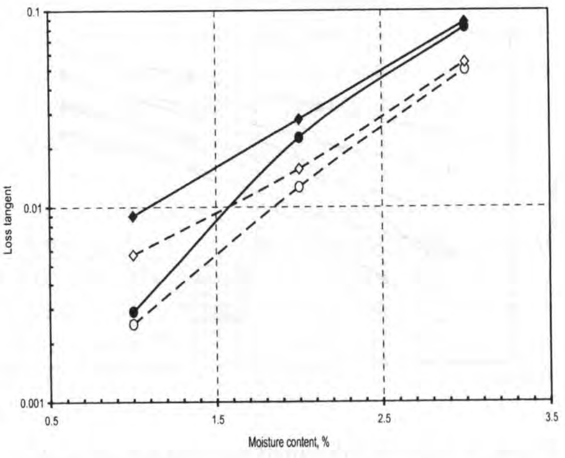

Figure 6 - tanδ as a function of pressboard MC under equilibrium and non-equilibrium conditions

- O Non-equilibrium state for non-aged oil
- ● Equilibrium state for non-aged oil
- ◇ Non-equilibrium state for aged oil
- ◆ Equilibrium state for aged oil

7. Conclusions

The moisture content in the paper and pressboard increases as the result of insulation ageing in a power transformer. For an in-service transformer which gradually approaches its end of designed life, the measured loss tangent of the transformer can be used as a diagnostic tool to indicate the 'wetness' of the insulation. However, the other factors such as insulation geometry, oil conductivity, insulation temperature and state of moisture equilibrium between oil and pressboard are also contributed towards the loss tangent result and a necessity arises to rectify these effects:

- Out of paper and pressboard, the moisture in pressboard is the dominating part contributing to the increase of loss tangent measurement which directly expresses the 'wetness' of the insulation.
- The amount of pressboard spacers strongly affects the rate of the increase of loss tangent and capacitance with moisture content, whereas the amount of pressboard barriers has a constant increment.

- The oil conductivity affects the loss tangent when the transformer is in dry condition whereas under wet and extremely wet conditions, pressboard moisture dominates the result.

- The insulation temperature generally increases the loss tangent.

- The naturally cooled transformers are in non-equilibrium condition for moisture between oil and pressboard, the measured loss tangent value can be considerably low as compared to that under the equilibrium condition, and therefore needs calibration to indicate the correct wetness of pressboard.

It can be concluded that for a transformer with the insulation geometry fixed to X=20% and Y=25%, at the room temperature and under equilibrium condition, the measured loss tangent value of 2% and above indicate that the transformer is wet. If any of the fixed factors deviates, one can still use the measured loss tangent as a diagnostic tool if proper calibration is carried out according to the established relationships.

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