DIAGNOSTIC TESTING OF POWER TRANSFORMER INSULATION BY RESPONSE MEASUREMENTS IN FREQUENCY DOMAIN

K. MULARACHCHI* and M. FERNANDO
Ceylon Electricity Board, Mahaweli complex, Kandy,
University of Peradeniya, Faculty of Engineering, Peradeniya

ABSTRACT

This paper presents results of frequency domain response measurements on field–aged power transformer insulation comprising oil and cellulose material (paper, pressboard, etc.). Different types of oil-paper insulated power transformers were selected from the hydropower stations in Sri Lanka. The loss tangent of the transformer insulation was measured over a broad frequency range. It is shown that the variation of loss tangent over frequency provides an easy classification of new and aged transformers.

INTRODUCTION

Power transformers are the main apparatus in transmission and distribution of electrical energy. Power transformers are very expensive so that, they are expected to operate at least thirty years in healthy condition. Majority of power transformers is of type oil-paper insulated. However, power transformer insulation deteriorates with aging due to the influence of electrical, thermal, mechanical and environmental stresses. These stresses influence the properties of insulation, such as the conduction & polarization of the material, consequently accelerating the deterioration. In general, a high percentage of all the supply failures in electrical industry is caused by insulation failures. Therefore, condition monitoring of power transformer insulation is crucial to maintain the reliability of power supply at an acceptable level.

Reliable methods and suitable equipment for condition monitoring of insulating systems of power transformers are still very much subjected to discussion among maintenance engineers and researchers in the world. Over the past 50 years, different types of test methods, classified as destructive and non-destructive, have been used to analyze the condition of electrical insulation of power transformers. Usually, destructive tests are not used in condition monitoring of power transformer insulation. Some of the non-destructive methods are:

i. insulation resistance
ii. polarization index
iii. dielectric dissipation factor ($\tan(\delta)$) and capacitance at power frequency
iv. partial discharges
v. quality of transformer oil (conductivity, breakdown voltage etc.)
vi. generated gas analysis
vii. degree of polymerization of the paper insulation, and
viii. chromatographic analyses.

The first four test methods above, describe the condition of the composite oil and paper insulation as a unit; the drawbacks of these methods are deterioration of the insulating material after the test, and difficulty in interpretation of the results. The last four test methods above, describe oil and paper insulation as separate units. However, most of these tests need precise instruments therefore, they could not be performed in Sri Lanka. Presently, the Sri Lankan power utility, Ceylon Electricity Board (CEB), performs some of the above mentioned tests i.e. insulation resistance, polarization index, and oil breakdown voltage, on their periodical investigation of power transformers. The data related to these measurements were collected from hydro-power stations belonging to CEB. The obtained test results do not provide a clear picture of the insulation condition. Thus these methods could not be used for a reliable interpretation.

Therefore, in this study, special attention is given for the diagnostic of insulation by response measurements that provide the full characteristic of insulation. The dielectric response measurement techniques have been widely used in the last decade (Helgeson 1997, Lapworth and Heywood 2000, Neimanis 1997, Course Materials 2000). This was mainly due to the advent of new instruments with high precision. There exist two different strategies for response measurements. One is the time domain and the other is the frequency domain.

Time domain dielectric response measurements include:

(i) relaxation currents (polarization & de-polarization current), and
(ii) return voltage and derived polarization spectrum.

In these measurements, a voltage step is applied across the insulation and the charging and discharging currents (polarization & de-polarization currents) are measured. Afterward the circuit is opened and the 'recovery voltage' that built up across the insulation is measured. Main advantages of time domain measurements are easy to detect conduction current, and availability of cheaper measuring instruments. However, it is difficult to reach higher frequencies above 1 Hz due to the bandwidth of measuring electrometer, mechanical switching of voltage source and the rise time of the source. Since the time domain measurement is a wide band measurement, they are very sensitive to noise (chemically induced currents and power frequency) making it difficult to measure low loss materials. Similarly these measurements are very sensitive to earlier applied voltages.

Frequency domain response measurements include capacitance/ tan(δ) over a wide frequency domain (dielectric spectroscopy). Here, a sinusoidal voltage with an arbitrary frequency is applied across the insulation and the current is measured. Frequency domain measurement is very convenient for both low and high loss systems. Frequency domain measurements are insensitive to chemically induced currents and earlier applied voltages. It is a narrow band measurement, so that filtering gives good noise performance especially at higher frequencies. In frequency domain measurements, measuring frequencies can be selected to avoid power frequency and its harmonics. Since the measurements can be carried out at higher frequencies, it is easy to detect fast polarization processes as well. Based on the relative advantages of frequency domain it was decided to measure power transformer insulations in frequency domain.

THEORY BEHIND RESPONSE MEASUREMENTS

In the frequency domain measurements, the relationship between the applied voltage $V(\omega)$ and the measured current $I(\omega)$ can be written as:

$$V(\omega) = Z(\omega)I(\omega)$$

where, $\omega = 2\pi f$ and $Z(\omega) = 1/i\omega C(\omega)$. Thus it can be simplified as:

$$I(\omega) = i\omega \underline{C}(\omega)V(\omega)$$

The capacitance $\underline{C}(\omega)$ is a complex quantity and relates to the complex permittivity of the material $\underline{\in}(\omega) = \in'(\omega) - i\in''(\omega)$.

Then the equation can be written in the following form (Helgeson 1997):

$$\underline{C}(\omega) = C'(\omega) - iC''(\omega) = C_0\{\in'(\omega) - i\in''(\omega)\}$$

where, C_0 represents the vacuum or geometrical capacitance.

Usually, characteristic of the insulation in frequency domain is described by its complex susceptibility $\underline{X}(\omega) = X'(\omega) - iX''(\omega)$ and is related to the complex relative permitivity by following relation (Helgeson 1997):

$$\underline{\in}(\omega) = \{\underbrace{\in_{\infty} + X'(\omega)}_{\in'(\omega)} - i\underbrace{[X''(\omega) + \frac{\sigma_0}{\in_0 \omega}]}_{\in''(\omega)}\}$$

where, ε_0 and σ_0 represent respectively the permitivity in vacuum and DC conductivity of test object.

Similarly in time domain, the characteristic of the insulation is described by its response function f(t). The f(t) and $\chi(\omega)$ are interrelated by the Fourier transformation and its inverse as follows (Jonscher 1983):

$$X'(\omega) = \int_0^{\infty} f(t)\cos(\omega t)dt$$

$$X''(\omega) = \int_0^{\infty} f(t)\sin(\omega t)dt$$

$$f(t) = \frac{2}{\pi}\int_0^{\infty} X'(\omega)\cos(\omega t)d\omega$$

$$f(t) = \frac{2}{\pi}\int_0^{\infty} X''(\omega)\sin(\omega t)d\omega$$

This relationship is only valid if the system can be considered as a linear system. In general, power transformer insulation is treated as a linear model.

The derived complex capacitance (from measured current and voltage) includes its geometrical capacitance C_0. Since C_0 is unknown and it differs from transformer to transformer, the measurements of complex capacitance cannot be directly used for comparison of the results. However, loss tangent written by the equation, $\tan(\delta) = \frac{C''(\omega)}{C'(\omega)} = \frac{\epsilon''(\omega)}{\epsilon'(\omega)}$, is independent of C_0 (Helgeson 1997).

The loss tangent can be directly derived from measured currents (see Fig. 1b). In this study, it was decided to use loss tangent measurement for the interpretation of the results.

FIELD MEASUREMENTS

Different types of transformers were selected from CEB installations as listed in Table 1. The complex capacitance and the loss tangent were measured with a dielectric spectrometer "Programma-IDA-200". The frequency range from 1 kHz down to 0.1 mHz was used. In this measurement, the transformer insulation between high voltage (HV) winding and low voltage (LV) winding was selected. High potential (100 V) terminal of the instrument was connected to HV winding, while low potential and guard terminals were connected to the LV and tank of the transformer respectively as shown in the Fig. 1a. The oil and the winding temperatures were recorded with the measurements. Just after the test, the insulation resistance was also measured with an analogue insulation Megger.

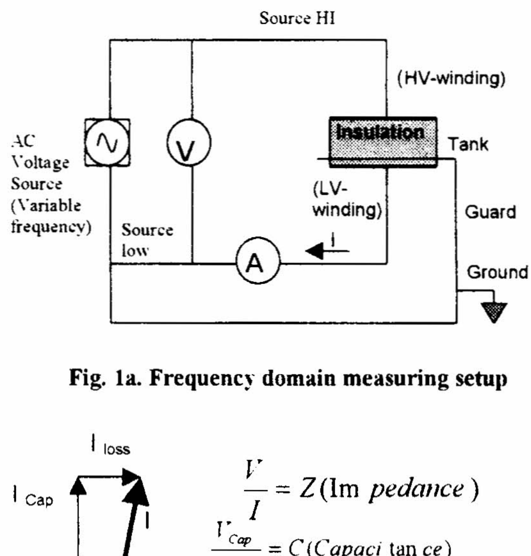
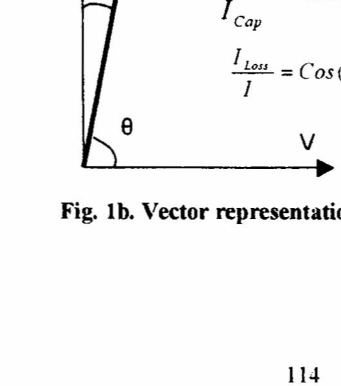


Fig. 1a. Frequency domain measuring setup



$$\frac{V}{I} = Z(\text{Im}\,pedance)$$

$$\frac{I_{Cap}}{j\omega V} = C(Capaci\tan ce)$$

$$\frac{I_{Loss}}{I_{Cap}} = \tan(\delta) - (Loss\tan gent)$$

$$\frac{I_{Loss}}{I} = Cos(\theta) - (Powerfacto\,r)$$

Fig. 1b. Vector representation of measurement

Table 1. Summary of 3-phase oil-paper transformers

NO	LOCATION	YEAR	POWER [kVA]	VECTOR GROUP	VOLTAGE [kV]
A1	Ukuwela	1973	350	ZNYN11	33 /0.4
A2	Kothmale	1995	100	DYN11	33 /0.4
A3	Ukuwela	1983	200	ZNYN11	33 /0.4
B1	Ukuwela	1974	500	DYN1	12.5 /0.4
B2	Ukuwela	1974	500	DYN1	12.5 /0.4
B3	Ukuwela	1974	500	DYN11	33 /0.4
B4	Kothmale	1983	500	DYN11	11 /0.4

RESULTS AND DISCUSSION

Fig. 2 shows the characteristics curves of new and aged (26 yrs) transformers. According to the past experience (Lapworth and Heywood 2000), the frequency domain results on power transformers could be described as follows; starting from the high frequency, as the frequency is reduced the dielectric loss first falls and then starts to increase (lower curve in Fig. 2). After the loss peak, the loss tangent falls and then rises again (upper curve in Fig. 2). This type of full characteristic could only be observed in one curve over a frequency range of 10^{-6} to 10^{-6} Hz. The line from loss minimum to point of inflection is called as 'oil line' (Lapworth and Heywood 2000).

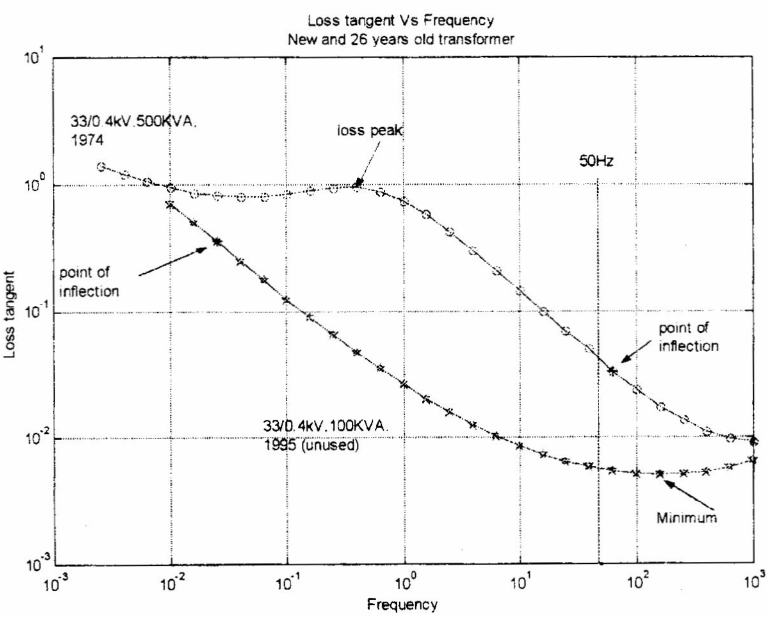


Fig. 2. Frequency domain response of new and aged transformer

Different parameters could be used to interpret the results obtained from frequency domain. Some of them are loss minimum, loss peak, point of inflection, gradient at point of inflection, loss tangent at 50 Hz, and the depth of dip (Lapworth and Heywood 2000, Course materials 2000).

Over the range of frequencies that represent the oil line the conductivity of oil dominates the loss tangent (Lapworth and Heywood 2000), so the position of this line depends on oil resistivity being higher for lower resistivity oil. The improved resistivity of the oil lowered the oil line. The upper and lower parts of the oil line describe the moisture content of solid insulation. For cases involving good oil condition, the oil line appears to extend very long where it may not practically possible to obtain the information of solid moisture content in the measured range.

The frequency at which this point of inflection occurred is said to be dependent on oil resistivity, the amount of board in the duct, and the temperature (Lapworth and Heywood 2000). The improved resistivity of the oil shifts the point of inflection to lower frequencies (Fig. 2). As temperature increases the point of inflection is shifted to higher frequencies but the value does not change (Lapworth and Heywood 2000).

The loss minimum is said to be dependent on moisture content, being higher for higher moisture content. As temperature increases the loss minimum is shifted to higher frequencies but the value does not change (Lapworth and Heywood 2000).

Though there is a clear definition for loss tangent at service voltage in different standards, there is still no classifications for low voltage loss tangent measurements. However, the loss tangent at power frequency is simply classified into four categories in the simple form, as follows; good:- $\tan(\delta)<1\%$, reasonably good:- $1\%<\tan(\delta)<2.5\%$, bad:- $2.5\%<\tan(\delta)<5\%$, very bad:- $\tan(\delta)>5\%$ (Neimanis 1997).

Fig. 3 shows frequency variariation of $\tan(\delta)$ for transformers B1, B2, B3 and B4. Table 2 shows summarized $\tan(\delta)$ values for all transformers. According to the Fig. 3 and Table 2 the transformers B1, B2 and B3 might have higher moisture content while transformer B4 shows lower moisture level based on the loss minimum. The loss tangent at 50 Hz of these transformers are higher than B4. Also in B4 the point of inflection is not visible, which implies very low moisture content. In the transformer B3, the loss minimum is not visible in the measured range. Though the oil line lies at higher level in B3, it is not possible to interpret, based on the oil line because the measured temperature is little higher than the others. On the assumption of the value of loss minimum as well as the visible loss peak, B3 may have the highest moisture content in solid insulation than the others. According to the CEB records B2 has been loaded for a longer period than B1. Similarly, the oil line lies higher for B2 than for B1. Based on those results, it is likely that the insulation of B2 has deteriorated than that of B1.

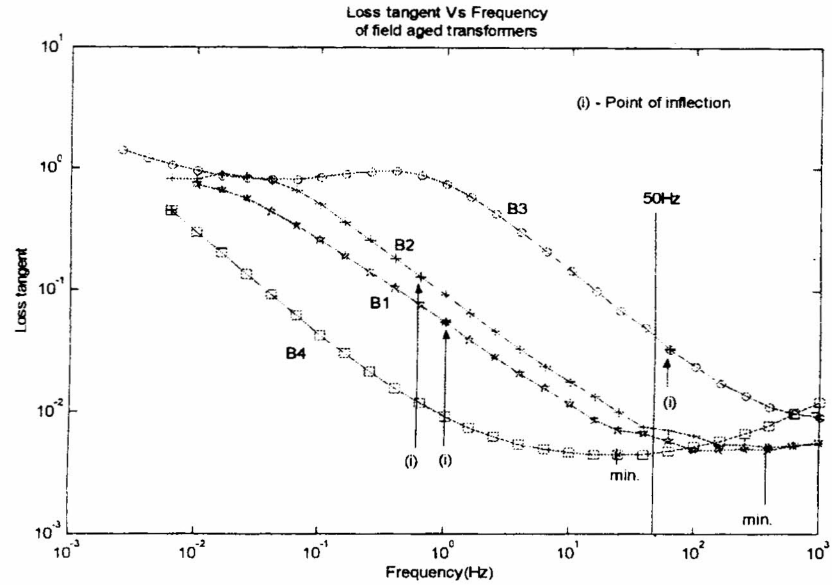


Fig. 3. Frequency domain response of differently aged oil-paper transformers

Fig. 4 shows the response of new, burnt and aged transformers. According to Fig. 4 and Table 2, the burnt transformer A1 might have the highest moisture content. Also loss minimum, point of inflection or even the loss peak is not visible. The loss tangent at 50Hz (3.5%) is in "Bad" range according to the simple classification (Neimanis 1997). The new transformer A2 has the lowest loss tangent at 50 Hz. Also there is no evidence of loss peak. The tansformer A3 has lower loss minimum than A2. This may be due to the percentage amount of paper insulation.

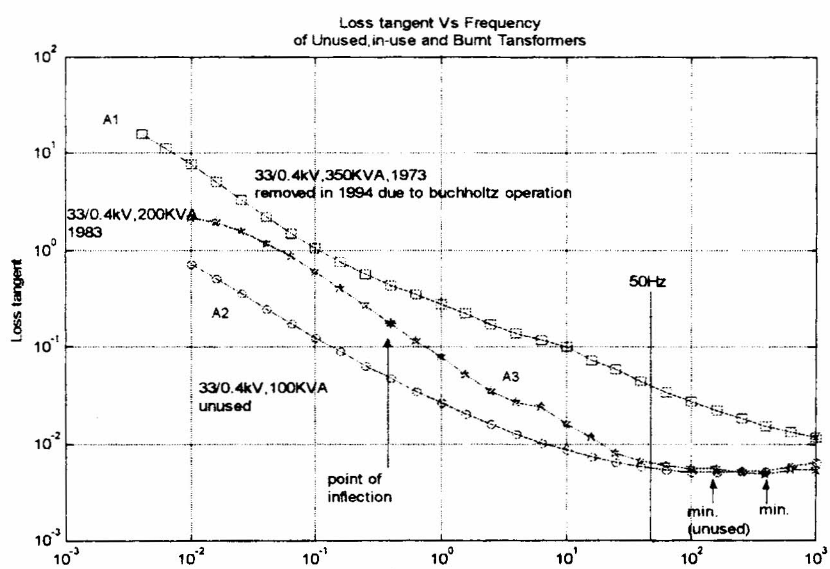


Fig. 4. Frequency domain response of new, burnt and aged (inservice) oil-paper transformers

Based on all these information, frequency variation of loss tangent curves provi useful information about the classification of burnt, aged and new power transformers.

Table 2. Measured parameters of differently aged transformers

NO	T (°C)	LOSS MINIMUM		LOSS PEAK		POINT OF INFLECTION			tanδ (%) at 50Hz	tanδ (%) at 1kHz	tanδ (%)at 1Hz	tanδ (%) at 0.1Hz
		f	tan δ (%)	f	tan δ (%)	f	tan δ (%)	Gradient				
A1	30	--	--	--	--	--	--	--	3.80	1.16	26.70	103.0
A2	30	158	0.503	--	--	--	--	--	0.557	0.646	2.64	12.2
A3	30	398	0.480	--	--	0.398	17.4	0.2560	0.62	0.53	7.75	59.6
B1	30	398	0.483	--	--	1	5.45	0.0263	0.604	0.56	5.35	24.8
B2	30	398	0.516	0.896	1.58	0.631	12.9	0.1024	0.71	0.549	9.04	50.3
B3	38	--	--	0.950	39.8	15.8	10	0.0034	3.95	0.898	72.40	83.4
B4	30	25	0.443	--	--	--	--	--	0.455	1.2	0.922	4.19

CONCLUSIONS AND FUTURE WORKS

Frequency domain response measurement is a useful non-destructive diagnost technique for testing the performance of power transformers. The variation of loss tangent : frequency domain classifies the new and aged transformer insulation. However, it is require to establish margins for this classification by obtaining a large number test results. In future, is expected to perform measurements on power transformers with different aging time ar insulation condition.

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