A Field Study of Two Online Dry-Out Methods for Power Transformers

Key words: power transformers, molecular sieves, cellulose cartridge filters, moisture equilibrium curves, dielectric response analysis, Karl Fischer titration

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Dry-out methods for transformers, using cellulose cartridges and molecular sieves, were compared. The latter are preferable for keeping a dry transformer dry, whereas the former are more efficient in drying a wet transformer.

Introduction

Water slowly accumulates in transformers through various mechanisms, e.g., slow decomposition of paper insulation, contact between humid air and oil in a free-breathing conservator, and penetration through degraded sealing and absorption when the transformer is opened for maintenance [1].

It is important to minimize water accumulation within a transformer for several reasons. Water speeds up deterioration of the paper insulation, increases the probability of partial discharge between the windings, and reduces the dielectric strength of the oil, thereby increasing the chance of winding failure [2].

Several methods have been developed to remove water from the oil (and hence from the paper insulation) of power transformers during operation. Among them are freeze-drying, heat and vacuum treatment, and the use of molecular sieves and cellulose cartridge filters [3].

In this article, we compare the effectiveness of the cellulose cartridge filter and molecular sieve methods. Two identical transformers with similar insulation wetness were used. We estimated the water content of the paper (WCP) insulation from (1) the water activity of the oil, (2) the dielectric response of the transformer, and (3) the water content of individual paper samples determined by Karl Fischer titration. We also measured the acid number of the oil, its interfacial tension, dielectric strength, furan content, dissolved gas content, and particle count.

Methods of Online Transformer Dry-Out

Cellulose Cartridge Filters

In this system, the oil is passed through cellulosic paper filters, an example of which is shown in Figure 1. Paper is hygroscopic and therefore absorbs water from the transformer oil. The absorbed water is then removed from the cartridge by circulating the transformer oil through a heated vacuum-extraction unit.

The filters used in this work were designed to remove particles larger than 1 μm. The removal of conductive particles, such as metals, carbon, and wet fibers, from the transformer oil is advantageous because these particles reduce the dielectric strength of the oil and thereby increase the chance of insulation failure. The filters also remove aging products from the oil, such as acids and sludge, thereby extending transformer life [4]. However, a CIGRE Working Group report (WG 12.17 Particles in Oil) warns that paper filters can themselves sometimes be a source of small cellulose particles, so utilities must be aware of the limited service lifetime of the cartridge [3]–[4]. In this work, the particle content of the oil was counted before and after dry-out, to investigate whether cellulose fibers from the filter had contaminated the oil.

Molecular Sieves

A molecular sieve is an absorbent material containing tiny pores of uniform size, as shown in Figure 2. The material in

the sieves used in this work is a zeolite, a microporous aluminosilicate mineral with a pore size of 0.4 nm. Molecules with a diameter less than the pore size are absorbed.

The moisture is removed from the oil as it passes through the pores as a result of intermolecular (polar-polar) bonding. A molecular sieve can adsorb up to 20% of its own weight in water. Its absorption capacity decreases with increasing oil temperature, from 18–20% at 20°C to 3–4% at 100°C [5]. Molecular sieves can be regenerated by heating to a temperature above 130°C and purging with a carrier gas [6].

The product used in this study consisted of three cylinders filled with molecular sieves capable of removing up to 9 L of water. The system also incorporated an inline filter for trapping particulate matter larger than 10 μm, thereby increasing the dielectric strength of the oil.

Methods for Estimating the Water Content of Transformer Paper Insulation

Three methods were adopted to estimate the WCP during the dry-out process. The first used the water activity of the transformer oil (A_w) determined by a water-in-oil transmitter, and the second relied on dielectric response analysis. In the third method, the WCP was measured directly using a Karl Fischer instrument. These methods are described briefly below.

Water Activity of Transformer Oil

The WCP was estimated using the temperature (T) and A_w. The latter is the amount of water in the oil relative to the amount present at saturation. Relative saturation (RS) is the same as water activity but expressed as a percentage:

$$RS = 100\, A_w. \tag{1}$$

The A_w of the oil in equilibrium with the paper is equal to the water vapor pressure over the paper (P_w) divided by the water vapor pressure of pure water (P'_w) at the same temperature [7]:

Figure 1. A cellulose cartridge filter.

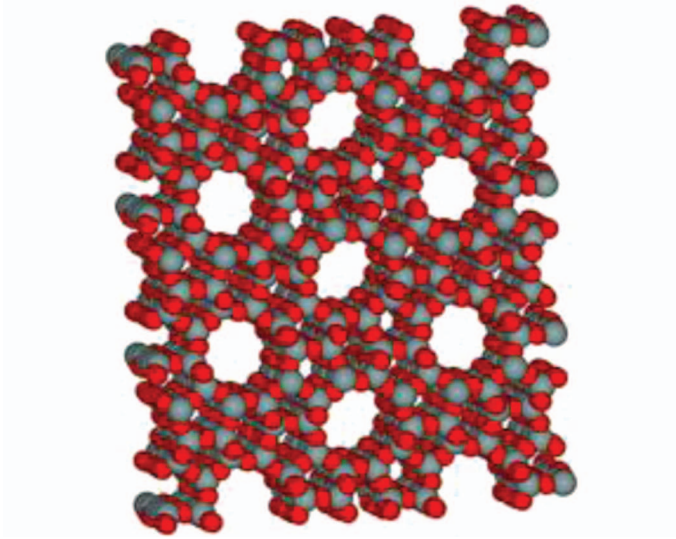

Figure 2. The microporous molecular structure of a zeolite molecular sieve.

$$A_w = \frac{P_w}{P'_w}. \tag{2}$$

P'_w (in kPa) can be approximated at any oil temperature T (in °C) using the August-Roche-Magnus formula [8]:

$$P'_w = 0.6112 e^{\left(\frac{17.67T}{243.5+T}\right)}. \tag{3}$$

The WCP, expressed as a percentage, may be calculated using the water-paper equilibrium formula [9]:

$$WCP = 2.173 \times 10^{-7} \times P_w^{\,0.6685} \times e^{4725.6/(T+273)} \times 100. \tag{4}$$

The WCP is thus a measure of the amount of water on the surface of the paper in thermodynamic equilibrium with the oil. However, true equilibrium is not reached in a transformer because the internal temperature is constantly fluctuating. It was assumed in this work that the departure from equilibrium was not large. WCP values obtained in this way are given in Table 3 and in Figures 9 and 10.

Dielectric Response Analysis

Dielectric diagnostic methods measure the polarization and the conductivity of the transformer insulation (oil and paper), which change with temperature, moisture, and aging [10]. The measurement is influenced by the geometry of the insulation, e.g., the ratio (volume of axial cylindrical pressboard barriers)/(volume of the oil).

Several commercially available instruments are suitable for dielectric response analysis based on the recovery voltage of the transformer, measurement of polarization and depolarization currents, and frequency domain spectroscopy. The instrument used in this study performed frequency domain spectroscopy. It measured the dissipation factor (tan δ) of the oil-paper insulation over the frequency range 10^{-4} to 10^{3} Hz, from which the

WCP can be estimated. The paper does not need to be in thermal equilibrium with the oil, but the transformer needs to be taken out of service for measurement. The oil temperature is needed for the calculation, and because it varies around the transformer, care must be taken in selecting a value.

Karl Fischer Titration

The Karl Fischer titrator (Mitsubishi CA-06 moisture meter with VA-06 vaporizer) is an analytical instrument that measures the mass of water in a paper sample by coulometric titration [11]. The sample is held at 140°C in an oven in the instrument. The released moisture is transferred into the titration cell by a carrier gas, where its mass is determined by chemical titration. This is a direct measurement, as opposed to the other indirect methods, but samples cannot usually be obtained from an operating transformer on a regular basis; the transformer has to be opened and the paper removed from the winding, which weakens the insulation capability of the paper.

The Transformers

Two nominally identical 49-year-old free-breathing transformers, with high moisture levels, were used (Figure 3). Transformer 1 (Tr1) was dried using a cellulose cartridge filter system, and transformer 2 (Tr2) was dried using molecular sieves.

The efficiency of each dry-out unit in lowering the water content of the oil was assessed using two moisture probes, one installed at the inlet to the dryer and the other at the outlet. A digital mechanical-type flow meter, installed downstream of the dryer, continuously monitored the flow rate of the oil (Q) in liters per hour. The total water removed (in liters) is given by

$$\text{total water removed (L)} = \sum\left(\frac{PPM_{\text{in}} - PPM_{\text{out}}}{10^6} \times Q\right), \quad (5)$$

where PPM_{in} is the hourly average water content of the oil in parts per million (ppm) at the inlet of the dryer, and PPM_{out} is the corresponding quantity at the outlet. The summation extends over the total number of drying hours.

Figure 3. Transformer 1 used for this study.

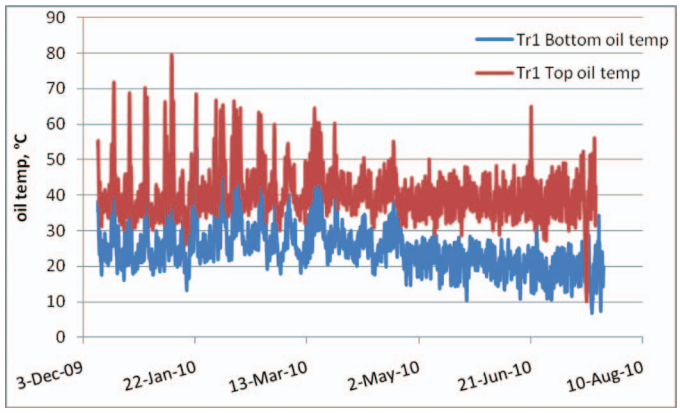

Figure 4. Oil temperature at the top and bottom of transformer 1 (Tr1).

The moisture sensor expresses oil wetness as A_w or as water content of the oil (WCO, in ppm). The two are related by

$$A_w = \frac{WCO}{10^{\left(A - \frac{B}{(T+273.16)}\right)}}, \quad (6)$$

where T is the temperature of the oil (in °C), and A and B are the solubility coefficients of the oil [12]. The transformer oil had been replaced in 2005 with Nynas 10GBN (Nynas, Stockholm, Sweden), so the solubility coefficients for that oil were used, i.e. $A = 7.0895$ and $B = 1569$.

The effectiveness of the two dry-out methods in reducing WCP was assessed using two additional moisture sensors installed at the top and bottom of the tank of each transformer.

Oil screen tests were performed before and after dry-out to detect changes in the quality of the oil. Silica gel breathers were installed on the transformers on 3 November 2009, before dry-out commenced, to prevent moisture ingress from the conservator system. Dry-out commenced on 9 December 2009.

Results

Dry-Out of Tr1 Using Cellulose Cartridge Filters

The online data for Tr1 using a cellulose cartridge dry-out system are presented in Figures 4 and 5. The top of a transformer

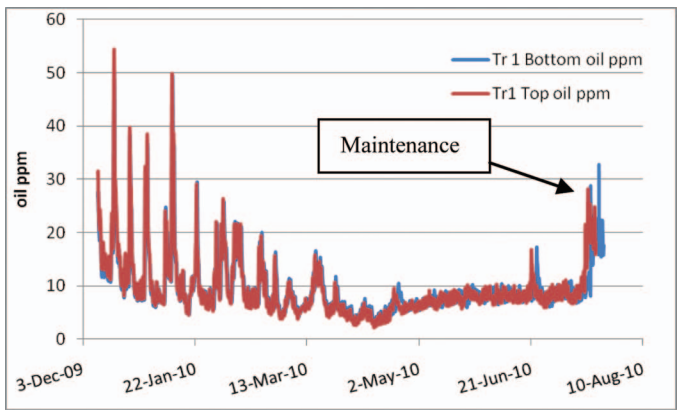

Figure 5. Water content of the oil at the top and bottom of transformer 1 (Tr1).

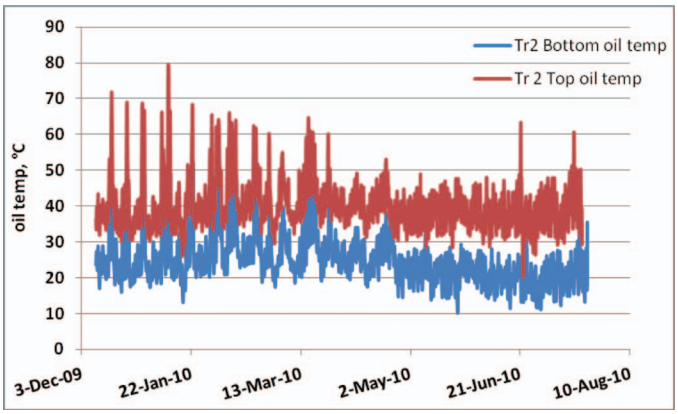

Figure 6. Oil temperature at the top and bottom of transformer 2 (Tr2).

is normally hotter than the bottom; the oil temperature peaks are caused by increased loading (Figure 4).

The initial WCO in the tank before dry-out was approximately 30 ppm. After 4 months of drying, a total of 10 L of water had been collected from the cellulose filters. After 5 months (21 April 2010), a total of 12 L of water had been collected, the WCO had decreased to 5 ppm, and the dry-out was stopped (Figure 5). The WCO then began to increase slowly because of the redistribution of water from the inner layers of the thick insulation.

The transformer was switched off on 17 July 2010, and the oil level was lowered to approximately 3000 L for maintenance. When the oil was returned to the transformer, the WCO increased substantially. Much of the water removed from the oil by drying was reintroduced from the air.

Dry-Out of Tr2 Using Molecular Sieves

The data for Tr2, obtained using a molecular sieve dry-out system, are shown in Figures 6 and 7.

The initial WCO was 26 ppm at the drier inlet and 10 ppm at the outlet. After 4 months (22 March 2010), the corresponding figures were 13 and 10 ppm, respectively. Further reduction in WCO was slow, suggesting that the sieves had become saturated. The sieve cylinders were therefore replaced after 5 months (21 April 2010). The cylinders that had been removed were weighed to determine the mass of water absorbed by the sieves (Table 1).

Table 1. Molecular Sieve Cylinder Weights (kg)

	Before dry-out	After 5 months	Increase
Cylinder 1	37.4	39.0	1.6
Cylinder 2	37.4	39.4	2.0
Cylinder 3	37.2	39.6	2.4
Total			6.0

The total weight of water removed by the sieves was 6.0 kg. Because the three cylinders together were capable of removing 9 L (9 kg) of water, it is likely that the sieves were approaching saturation, which would have slowed the drying of the oil.

The total amount of water removed by the molecular sieves was calculated using data from the moisture probes installed upstream and downstream of the dryer, the oil flow rate, and (5). The results are shown in Figure 8. Unfortunately, in some instances the oil flow rate was less than the minimum rate measurable by the oil flow meter; thus the mass of water removed was underestimated, i.e., 4.7 L (Figure 8) compared with 6.0 L (Table 1).

The saturation of the molecular sieves can be seen more clearly in the WCP traces of Figures 9 and 10 (Tr2). The molecular sieves became saturated 2 months after being installed in December 2009 (i.e., by March 2010) and 1 month after being replaced on 21 April 2010 (i.e., by June 2010). (It was assumed that the molecular sieves had become saturated when the steady reduction in WCP ceased.)

Effect of Each Dry-Out Method on Oil Properties

The oil was tested before and after dry-out to determine whether the two methods affected the oil quality. The results of the tests are summarized in Table 2:

(1) The cellulose cartridge filter reduced the particle count in the oil (particle size 5 to 100 µm), and the molecular

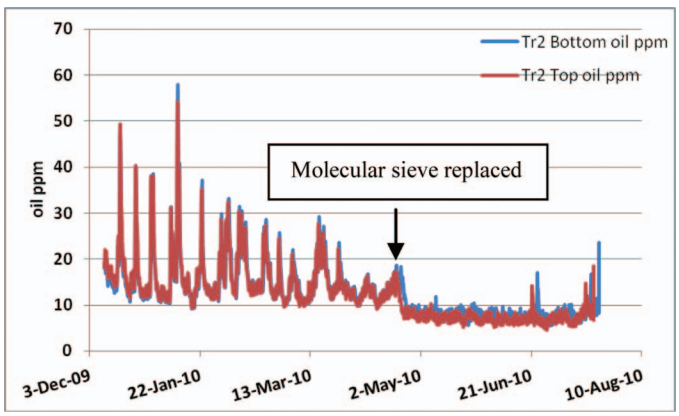

Figure 7. Water content of the oil at the top and bottom of transformer 2 (Tr2).

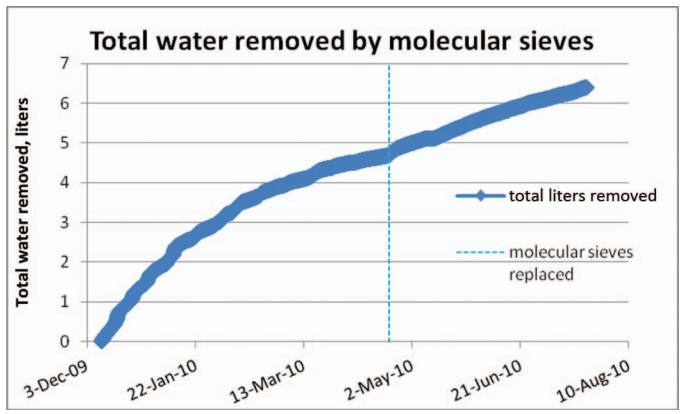

Figure 8. Total water removed by molecular sieves, calculated from (5) using moisture probe data and the oil flow rate.

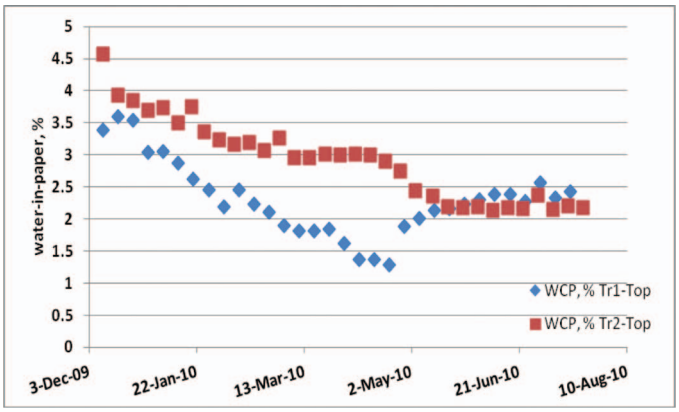

Figure 9. Comparison of water content of the paper (WCP) for transformer 1 (Tr1) and transformer 2 (Tr2), top.

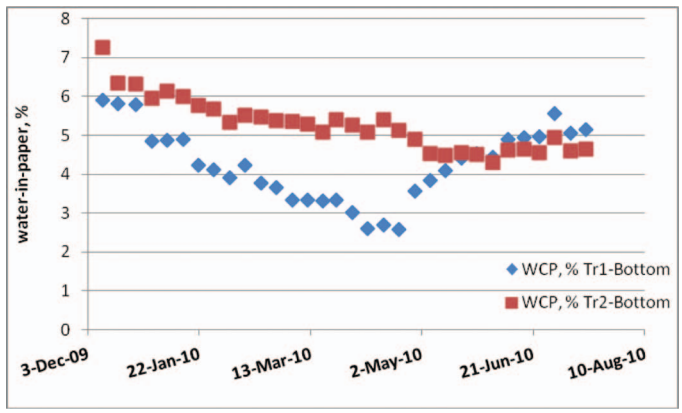

Figure 10. Comparison of water content of the paper (WCP) for transformer 1 (Tr1) and transformer 2 (Tr2), bottom.

sieves removed particles larger than 25 μm (determined by the online filter choice).

(2) As expected, following a reduction in WCO and particle count, the breakdown voltage of the oil increased from 22 to 74 kV for Tr1 (cellulose cartridges) and from 34 to 80 kV for Tr2 (molecular sieves). The molecular sieves decreased the acid number from 0.04 to 0.03 mg of KOH/g and increased the interfacial tension of the oil from 25 to 30 mN/m. (The interfacial tension is a measure of the concentration of soluble polar contaminants in the oil.) The cellulose cartridges did not change the acid number or the interfacial tension.

(3) Furans were removed by both systems, with implications for estimates of the degree of polymerization of the paper insulation [13]. Furans are large molecules that are unlikely to pass through the pores of the sieves, although some may bond to the surfaces of the sieves.

(4) The cartridge filters caused a reduction in the concentration of dissolved gases, probably because of the vacuum process used to dry the cartridges. The limited number of samples did not permit a confident decision on whether the molecular sieves affected the dissolved gas concentration. To answer this question, it would be necessary to monitor the dissolved gases over a longer period online [14]–[16].

Water-in-Paper Assessment

The WCP was measured before and after dry-out, using three methods. The results are summarized in Table 3.

(1) Using A_w of Transformer Oil

The WCP in Tr1 and Tr2 was calculated using an average weekly temperature, water activity data, and (2), (3), and (4). The results are plotted in Figures 9 and 10.

(2) Using the Dielectric Response

The temperature of the oil at the top of the tank, as measured by the moisture probe, was used to calculate the WCP. It is interesting that the WCP values found by dielectric response analysis (Table 3) from measurements made on 29 October 2009, 12 December 2009, and 8 May 2010 (Tr2) are close to the average of the top and bottom values calculated using the A_w equations (2), (3), and (4). However, the dielectric response value (8 May 2010, Tr1) is considerably higher than the top/bottom average; the reason is unclear.

(3) Using Karl Fischer Titration

Tr2 was opened on 2 August 2010 and a 1-mm-thick piece of pressboard, with dimensions 70 × 10 mm and an approximate mass of 1.1 g, was taken from the bottom of the transformer, phase A, between the LV windings. This sample was unavoidably exposed to air (relative humidity = 56%, temperature =

Table 2. Effect of Dry-Out on Oil Properties.[1]

Tr1: Cellulose cartridge filters	Tr2: Molecular sieves
1. Reduction in particle count.	1. Removal of larger particles (>25 μm).
2. Increase in breakdown voltage, but no change in acid number or interfacial tension.	2. Some increase in breakdown voltage and interfacial tension, and a decrease in acid number.
3. Removal of furans.	3. Removal of furans.
4. Reduction in dissolved gas concentration.	4. Uncertain reduction in dissolved gas concentration.

[1]Tr1 = transformer 1; Tr2 = transformer 2.

Table 3. Water Content of Paper (%) Estimated by Three Methods.[1]					
Item	**Transformer**	**Date**	**Water activity of transformer oil (top/bottom)**	**Dielectric response**	**Karl Fischer (direct measurement)**
Before dry-out	Tr1	29 Oct. 2009	4.0/6.0	5.1	NA
	Tr2	12 Dec. 2009	4.0/6.3	5.4	NA
After dry-out	Tr1	8 May 2010	2.1/4.0	4.3	NA
	Tr2	8 May 2010	2.4/**4.5**	3.6	NA
		2 Aug. 2010			**4.3** (bottom)
[1]Tr1 = transformer 1; Tr2 = transformer 2.					

16.1°C) for 112 min (after the oil had been removed from the transformer tank) before being sealed in a small glass jar (30 mL) with a Teflon seal. The jar had been washed and dried overnight at 110°C.

The water content at the surface of this sample was measured by removing a thin slice from the surface and carrying out Karl Fischer titration in accordance with AS 1767.2.8-2008 [11]. The water content inside the pressboard was then measured by splitting it in half and removing another thin slice from the freshly exposed surface for titration. The water contents of the surface and center of the pressboard were 4.2 and 4.3%, respectively, suggesting that the water was evenly distributed through the volume.

It was necessary to determine how much water the pressboard had absorbed during exposure to the air before the Karl Fischer titration measurements were made. The moisture absorption rate of oily pressboard was evaluated using another piece of pressboard approximately 0.7 mm thick and measuring 1 × 1 cm. It was dried and then exposed to air (relative humidity = 36%, temperature = 26°C) for 24 h. Its water content [water content of the pressboard (WCPB)] increased from an initial value of 0% to 0.55% in 112 min (Figure 11). However, the moisture absorption rate decreased as the WCPB increased. It follows that, for the pressboard sample from Tr2 with an initial WCPB of 4%, very little moisture would have been absorbed from the air before the Karl Fischer titration.

The WCP value at the bottom of Tr2, measured on 2 Aug 2010 by Karl Fischer titration, was close to that obtained for the same transformer on 8 May 2010 using the water activity equations.

Assessment of Dry-Out Methods

Both the cellulose cartridge filters and the molecular sieves were effective in lowering the WCP. However, because of the use of different oil pumps, the two systems operated at different oil flow rates, namely, 1041 L/h for the cellulose cartridges and 141 L/h for the molecular sieves. Thus, the drying rates were not directly comparable.

An advantage of the cellulose cartridge system is that the cellulose cartridges can be automatically regenerated at set intervals, thereby avoiding the need for replacement. The molecular sieves need to be replaced when saturated, i.e., after approximately 30 days for a transformer with WCP >4%.

The moisture/temperature transmitters, positioned before and after the dry-out units to measure the temperature and WCO, were useful in assessing the efficiency of each system. The moisture probes installed at the top and bottom of the tank of each transformer, to estimate the WCP, were also useful in indicating when the molecular sieves needed to be replaced.

Moisture removed during dry-out could easily be replaced through absorption from the air during transformer maintenance. It follows that maintenance procedures should be carefully controlled to minimize moisture absorption.

Assessment of Water-in-Paper Measurement Methods

The moisture/temperature probes installed at the top and bottom of each transformer facilitated continuous estimation of WCP, using the equilibrium equations. Because the paper condition, e.g., its degree of polymerization, is dependent on its moisture and oxygen content and on the temperature, and because these quantities vary between the top and bottom of the transformer, temperature and moisture probes installed at the top

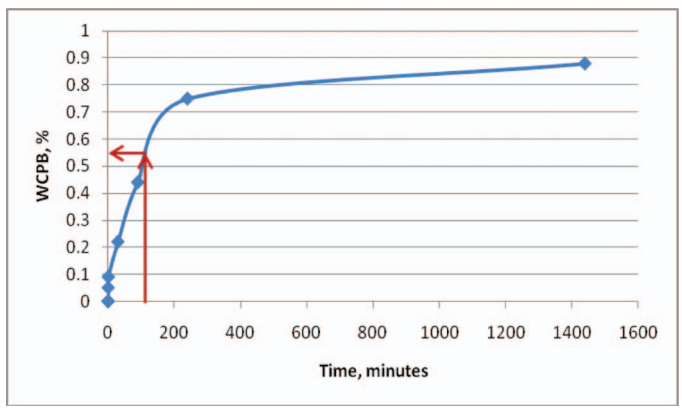

Figure 11. Moisture absorption by 0.7-mm-thick oily pressboard from air (relative humidity = 36%, temperature = 26°C). The arrows indicate the initial rapid increase in water content of pressboard (WCPB) over a period of 112 min.

and bottom of the transformer can be used to compare the paper condition at these locations [13].

The dielectric response method requires the transformer to be switched off, which could be inconvenient for utilities. This method gives an average WCP value for the transformer. The result is very sensitive to the oil temperature; in the 3 hours required to perform the test, the oil temperature could have varied considerably because of changes in ambient temperature (typically 20 to 28°C). The corresponding variation in WCP is not known accurately. The accuracy of this method would be greater in the case of a cold (switched-off) transformer because most of the water would then reside in the paper, not in the oil.

Accurate WCP measurements require accurate paper and pressboard temperatures. However, the transformers in this work were not equipped with appropriately located fiber-optic sensors, so the temperature of the oil had to be used as an approximation of the paper and pressboard temperatures. More specifically, the top oil temperature measured by the moisture/temperature probe before beginning the measurement was used. The oil temperature could also be estimated from the tank surface temperature [16], or by measuring the temperature of the oil stream at a sampling point.

Conclusions and Future Work

The molecular sieves saturated quickly when the initial WCP exceeded 4%, and also after replacement. Their lower rate of water removal suggests that they are more suitable for keeping a dry transformer dry than for drying a wet transformer.

The cellulose cartridge filters were more efficient in drying a wet transformer, i.e., they lowered the WCP faster than the molecular sieves because they operated with a pump using a higher flow rate.

The WCP values differed between the top and bottom of the transformers, and could be estimated using online moisture probes and equilibrium equations. WCP values measured by Karl Fischer titration were in good agreement with those obtained from the A_w equations. Dielectric response analysis gave WCP values averaged over the top and bottom of the transformer.

We plan to investigate whether changes in clamping pressure occur during online dry-out, and if so, to determine safe maximum dry-out levels, i.e., levels that do not lead to loose windings and failure.

Acknowledgments

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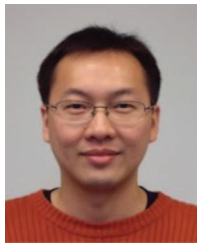
Daniel Martin received the B.Eng. degree in electrical and electronic engineering (with study abroad in Germany) from the University of Brighton, UK, in 2000. He joined Racal Electronics (Weybridge, UK), which became the international electronics company Thales, working on communication and aircraft systems. He left Thales in 2004 to pursue his Ph.D. degree in electrical insulation at the University of Manchester, UK. He investigated the suitability of vegetable oils and synthetic esters as substitutes for mineral oil within large power transformers, and graduated in 2008. His current research at Monash University in Clayton, Australia, is concerned with condition monitoring of transformer equipment, and he lectures in engineering at the university.

Wenyu Guo received his Ph.D. in Computer Science from the University of Manchester, UK, in 2007. He joined Monash University (Clayton, Australia) in 2007, initially engaged in computer vision research. He later moved into computational modeling of power transformers. His current research work is in the areas of thermal modeling and insulation aging of power transformers. He also lectures in the Department of Electrical and Computer Systems Engineering at Monash. He is a member of CIGRE Working Group A2.38–Transformer Thermal Modelling.



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