Condition Monitoring and Diagnostic Assessment of Transformers

Document Version
Accepted author manuscript

Citation for published version (APA):
Wang, Z., Liu, Q., Jarman, P., Wilson, G., Hooton, R., Walker, D., Dyer, P., Krause, C., Smith, P. W. R., Gyore, A., Martin, R., Mavrommatis, P., & Noakhes, J. (Accepted/In press). Condition Monitoring and Diagnostic Assessment of Transformers. In *CIGRE*

Published in:
CIGRE

21, rue d'Artois, F-75008 PARIS
http : //www.cigre.org

A2-109

CIGRE 2016

Condition Monitoring and Diagnostic Assessment of Transformers

Z.D. WANG, Q. LIU
The University of Manchester
UK

P. JARMAN, G. WILSON, R. HOOTON
National Grid
UK

D. WALKER
Scottish Power
UK

P. DYER
UK Power Networks
UK

CH. KRAUSE
Weidmann
Switzerland

P.W.R. SMITH
Shell Global Solutions
UK

A. GYORE, R. MARTIN
M&I Materials
UK

P. MAVROMMATIS, J. NOAKHES
TJH2B
UK

SUMMARY

Condition monitoring and diagnostic assessment of transformers is a useful tool for managing power networks. When managing a large fleet of ageing transformers, asset managers have to be more innovative to integrate the data from a variety of condition monitoring systems into the decision-making process. Collective research efforts on this topic were made by a transformer research consortium in the United Kingdom. This paper provides an overview of the research in the following three aspects: analysis of large oil databases from field transformers, detection of methanol in oil as an advanced paper ageing indicator and transformer thermal modelling using computational fluid dynamic (CFD).

Observations from oil database analysis included a generic early degradation phenomenon, testing frequency of the common parameters, correlation of these parameters with transformer age as well as data interpretation in terms of incorporation of sampling temperature and potential revision to standardised values. Laboratory ageing experiments confirmed the suitability of methanol as a potential early paper ageing indicator in both an inhibited conventional mineral oil and a new inhibited gas-to-liquid hydrocarbon based oil. Measurements of methanol for UK field transformers showed a general increasing trend with ageing. Oil flow distribution in the windings has a direct impact on the cooling performance. CFD simulations and dimensional analysis were performed to study the occurrence of reverse flow in the winding. It was found that a higher oil flow rate does not necessarily mean a better cooling performance.

KEYWORDS

Transformer, mineral, oil, methanol, GTL, database, asset, management, ageing, thermal.

zhongdong.wang@manchester.ac.uk

1. INTRODUCTION

Ageing of large transformer fleets represents a challenge for utilities. It is understood that the liquid insulation (customarily mineral oil) and the solid insulation (the paper and pressboard) will degrade over time, generating ageing products that are traceable as well as capable of changing insulation properties [1-6]. With the relatively easy accessibility of oil, condition monitoring and diagnostic assessment of in-service transformers are mainly based on testing transformer oil and interpreting the subsequent results [7]. Specifically regarding the parameters that can be tested, results interpretation and recommendation of corrective actions, an international standard IEC 60422, titled “Mineral Insulating Oil in Electrical Equipment – Supervision and Maintenance Guidance” is commonly used as a reference [8].

Figure 1 illustrates the oil test parameters that are grouped into Type I (Routine), Type II (Complementary) and Type III (Special Investigative) tests according to IEC 60422 [7, 8]. Apart from that, Figure 1 also shows the parameters customarily measured by UK utilities (marked by asterisk) [7, 9]. Note that IEC 60422 does not include relative permittivity and furans. Nonetheless, relative permittivity is also a dielectric parameter that is usually acquired together with dielectric dissipation factor tests [9]. As for furans, particularly for 2-FAL, they are useful to indicate paper degradation in transformers [9].

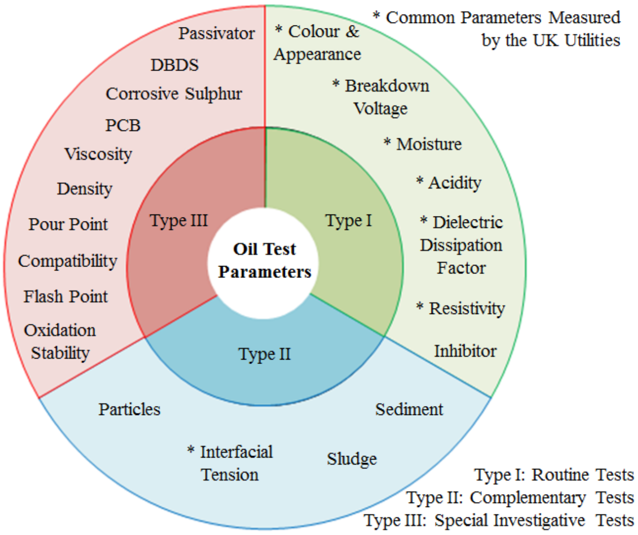

Figure 1: Oil test parameters for transformer ageing assessment [7, 8]

With records of different oil test parameters, comparisons can be done in relative to the recommended value ranges stipulated in IEC 60422 for interpreting transformer oil conditions as good, fair or poor [8]. The interpreted condition can then be used to facilitate decision making on actions suitable for managing transformer assets. There have been various editions of IEC 60422, in 1973, 1989 and 2005 preceding the current 2013 edition [8]. The progressive accumulation of operational experience and research worldwide has allowed continual improvement of the standard in terms of incorporation of different voltages, various condition classes, coverage of more parameters, revision to recommended value ranges and testing frequency [8].

In this paper, the research findings on oil database analysis of UK in-service transformers are summarised; detection of methanol as a paper ageing indicator is investigated in both laboratory experiments and UK in-service transformers, in particular for its applicability to a new inhibited gas-to-liquid based oil; finally computational fluid dynamic (CFD) based thermal modelling illustrates the effect of oil inlet velocity on the flow distribution and hot-spot temperature.

2. TRANSFORMER OIL DATABASE ANALYSIS

Database analysis was performed on eight oil test databases contributed by three UK utilities. The databases contain historical oil test records of the UK in-service transformers which are mineral oil filled and normal Kraft paper insulated. These transformers are mostly free breathing with silica gel breathers and operate at primary voltages of 33 kV, 132 kV, 275 kV and 400 kV.

2.1 DATABASE CLEANING

Large oil test databases contain a huge source of information but database cleaning is necessary prior to analyses to avoid misleading conclusions. Common aspects to be considered include removal of erroneous entries, consistency check of applied measurement procedure, and identification of known contamination issues and consideration of oil reclamation/regeneration history [10]. In addition, pre-processing of the database can be useful for identifying any potential anomalies that could affect a larger proportion of the population. An early degradation phenomenon in the in-service transformers analysed is one such issue that was identified regardless of designs, loadings and even operating voltage levels [11].

Figure 2 illustrates the points, showing the trends of acidity with in-service age for 33 kV populations that are with and without early degradation transformers. As detailed in [11], this early degradation phenomenon was not just observed for 33 kV transformers, but also for 132 kV, 275 kV and 400 kV transformers from the three UK utilities considered. In addition to the different voltages and the different utilities, other oil test parameters like dielectric dissipation factor (DDF) and 2-furfural (2-FAL) do exhibit the same phenomenon also [11]. Further investigation revealed that this phenomenon was neither due to different manufacturers, nor different loading levels, but most probably due to a change in oil chemistry occurring from the late 1980s to the early 1990s caused by the introduction of severer oil refining techniques (e.g. hydro-treatment) that could have depleted natural oxidation inhibitors present in oil [11]. With realisation of such a phenomenon, asset managers could then incorporate this information to formulate different strategy/framework for managing this group of affected units [11].

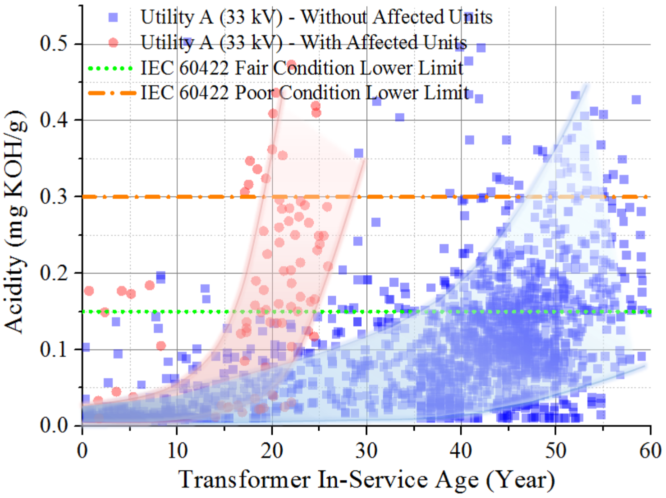

Figure 2: Different projected ageing trends for populations with and without early degradation units [11]

2.2 POPULATION ANALYSIS

With the focus now on “cleaned” transformer oil test databases, Table 1 displays the parameters recorded and their respective aggregated average testing frequencies from analysing eight oil test databases corresponding to multiple voltage levels. As an example, a value of 0.5 indicates an average of 1 measurement per transformer per 2 years aggregated from databases of the same voltage level [8, 9].

From Table 1, AC breakdown voltage (BDV), moisture, acidity and 2-FAL are commonly tested across all databases at different voltage levels [9]. Other observations are the generally increasing testing frequencies for higher voltage transformers and the greater number of parameters tested for a database related to 275 kV and 400 kV units. These observations suggest greater attention by the utilities on higher voltage transformers due to their higher capital cost and their greater importance in supplying larger downstream loads in the network [9].

Table 1: Aggregated average testing frequencies [9]

Parameter	**Aggregated Average Testing Frequency (No. of Tests/No. of Units)/Testing Period**		
	33 kV	132 kV	275 & 400 kV
	3 Databases	3 Databases	2 Databases
BDV	0.35	0.69	0.55
Moisture	0.36	0.69	0.95
Acidity	0.35	0.65	0.80
2-FAL	0.35	0.65	0.57
DDF	X	X	0.27*
Resistivity	X	X	0.35*
IFT	X	X	0.24*
Colour	X	X	1.20*
Permittivity	X	X	0.27*

* From one database

For the population trend analyses of each parameter with age, Spearman's correlation can offer a statistical evaluation. Figure 3 depicts the magnitude of Spearman's correlation with age with a value closer to one indicating a stronger correlation with age [9, 12].

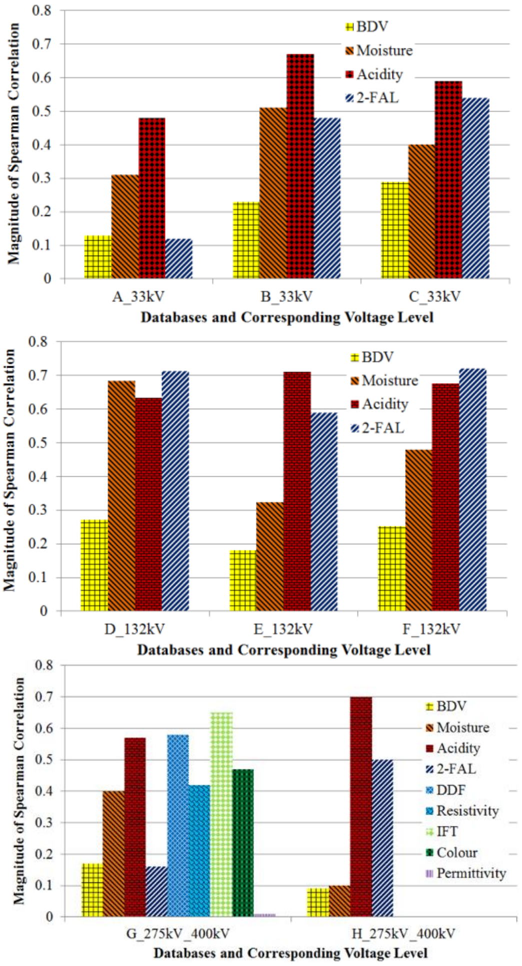

Figure 3: Magnitude of Spearman's correlation (a) 33 kV, (b) 132 kV, (c) 275 kV & 400 kV [9]
*A – H represent different databases

Condition monitoring based on a single parameter is not advisable but the correlations with age seen statistically can give some insights into how well the parameters represent ageing [7]. For oil ageing, acidity is perhaps the most essential from its clear increasing trend with age and its high average Spearman's correlation magnitude [9]. As for paper ageing, 2-FAL is the current option based on historical oil test database analysis [9]. Other useful parameters are moisture, DDF, resistivity, interfacial tension (IFT) and colour. DDF which has a similar Spearman's correlation magnitude as acidity could have a similar degree of representing ageing as acidity [9]. Resistivity, IFT and colour on the other hand have good Spearman's correlation magnitudes but may be more useful for early ageing stages [9].

2.3 DATA INTERPRETATION

With moisture having a long testing history, additional interpretation could involve temperature which could also be used to subsequently better interpret BDV [9, 10, 13]. Consideration of temperature has also been covered in IEC 60422 [8], but the recording of oil sampling temperature for in-service transformers is still not widely practiced [7, 13]. This might hinder proper interpretation of moisture results which indirectly affects the interpretation of BDV measurements as well [10, 13]. With moisture solubility of the oil changing with oil temperature, the moisture and BDV measured in laboratory conditions might not reflect well the oil's wetness or dielectric strength in an in-service transformer [10, 13]. In addition to changes in transformer loading levels, investigations revealed that different seasons and hence different ambient temperatures throughout the year impart an influence on oil sampling temperature which in turn culminated in a parabolic tendency in moisture measurements [13]. This is illustrated by Figure 4 showing how moisture measurements are higher in the months of June, July and August (summer period) regarding UK in-service transformers.

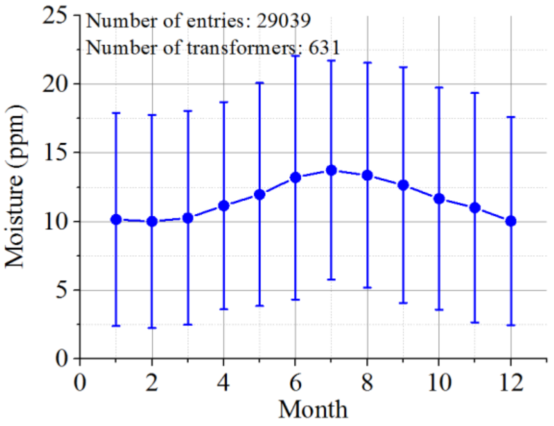

Figure 4: Monthly moisture measurements of in-service transformers [13]

To incorporate oil sampling temperature, moisture can be interpreted in terms of relative humidity (RH) which is the ratio of measured water content to moisture solubility (a function of oil temperature) [10, 13]. As detailed in [13], this interpretation could mitigate the seasonal influence on moisture as a whole which was also supported by observations from online RH sensor data [13]. Apart from that, moisture interpretation incorporating temperature actually revealed that the oil is not as wet as previously thought based on its original moisture measurement as demonstrated in Table 2 [13]. This improved interpretation of moisture with temperature incorporation can also be adapted to revise BDV after understanding the generic relationship governing BDV and RH [13]. The revised BDV as also seen in Table 2 shows that the oil dielectric strength is not as low as initially interpreted.

Table 2: In-service transformer example for demonstration of moisture and BDV revision [13]

Transformer Age: 15 Years, Oil Sampling Temperature: 57 ℃		
Moisture	Measured Water Content @ 20 ℃	21.5 ppm
	Relative Humidity @ 20 ℃	38.7 %
	Relative Humidity @ 57 ℃	9.7 %
Breakdown Voltage	Measured Breakdown Voltage @ 20 ℃	57 kV
	Breakdown Voltage @ 57 ℃	78 kV

In addition, there might be a need for revising the current IEC 60422 recommended value ranges for either DDF or resistivity [7]. This is due to the mismatch in condition interpretation which can be best illustrated by referring to the yellow star in Figure 5. If interpreted based on resistivity, the condition is Poor; but if the judgement is based on DDF, a fair condition is interpreted. This condition mismatch issue could be due to how separate data pools of DDF and resistivity were used for establishing the recommended value ranges for these two related parameters [7]. With both parameters now recorded for in-service transformers of a particular UK utility, the data show a clear deviation from the IEC 60422 condition criteria line [7]. With the help of these in-service data and understanding of the theoretical relationship between DDF and resistivity, revision to the recommended value ranges could be helpful to facilitate better interpretation of DDF and resistivity data.

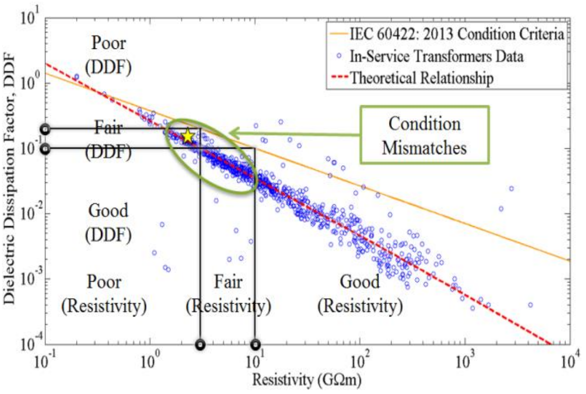

Figure 5: In-service DDF and resistivity data with IEC 60422 condition criteria line [7]

3. ALTERNATIVE PAPER AGEING INDICATOR

Ageing assessment of kraft paper is important in condition monitoring as its irreversible ageing nature has made it a lifetime determining factor for power transformers. However, measuring ageing state of paper through tensile strength or DP is difficult in field transformers mainly due to the poor accessibility of paper samples. Therefore, chemical compounds dissolved in oil that arise from paper ageing are measured to indicate the ageing state of the paper. Carbon gases and 2-FAL are such paper ageing indicators in transformer oil [14, 15]. However, each of them has their own drawbacks such as generation of carbon gases from long-term oil oxidation and difficulties in observing early ageing of paper with 2-FAL [16]. Therefore efforts have been made to look for alternative paper ageing indicators such as methanol and ethanol [16].

Methanol has shown a linear variation with paper ageing and a higher amount of generation than the conventional ageing indicator 2-FAL during the early ageing period [16]. In addition, a higher amount of methanol generation has been observed from the ageing of cellulose than from the by-products of cellulose ageing such as glucose and levoglucosan. Therefore it has been suggested to use methanol to indicate early ageing state of paper [16]. This section presents the results of laboratory ageing experiments and in-service aged oil measurements.

3.1 LABORATORY AGEING EXPERIMENT

Laboratory ageing experiments were conducted using ordinary kraft paper and two different oils including an inhibited mineral oil, Nytro Gemini X, and an inhibited gas to liquid (GTL) technology based oil, Diala S4 ZX-I. Ageing experiment with oil and paper was conducted by putting 200 g of dried oil and 10 g of dried paper into 250 ml sealed glass bottles with small air headspace inside. Samples were aged at 120 ℃ inside an air circulating oven for up to 280 days. Glass bottoles taken out of the oven during the ageing period were cooled down in room temperature for 72 hours before the measurements for equilibrium purpose.

3.1.1 DP of paper

Degree of Polymerisation (DP), indicates the average number of monomer units in the cellulose polymer, and is often used to indicate the mechanical strength of paper insulation. Figure 6 shows the variation of DP of paper aged in the mineral oil and the GTL oil. DP of the paper samples aged in both oils reduces from ~1100 to ~200 in an exponential manner during the ageing period. At the same ageing period, paper aged in both oils shows similar DP values, which indicates that the paper ageing rate is similar between the two oils for this experiment.

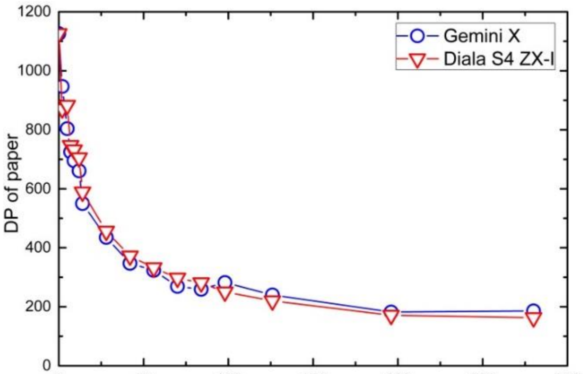

Figure 6. DP of paper at 120 ℃ oil-paper ageing experiment [17]

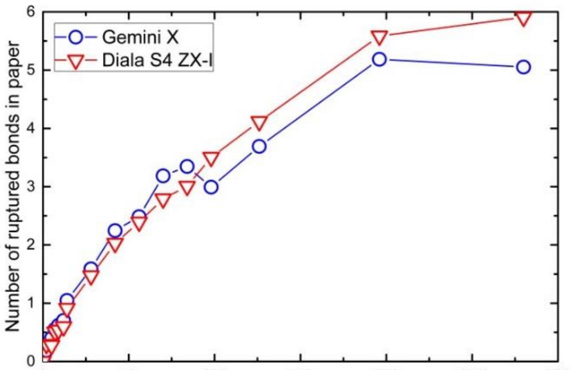

Figure 7. Number of ruptured bonds in paper at 120 ℃ oil-paper ageing experiment [17]

Not only the macroscopic properties such as mechanical strength, but also the microscopic structure can be used to characterise paper ageing. Average number of glycosidic chain scissions per cellulose polymer (NS) is just such a molecular level property which is being used mostly to investigate kinetics of paper ageing [18, 19]. NS is calculated from the DP measurements. Figure 7 shows the NS against the ageing duration for the paper samples aged in the mineral oil and the GTL oil. NS in paper shows a seemingly linear increase trend during early stage of ageing and then increases at a slower rate at the late stage. This could be attributed to the moving of paper ageing from non-ordered amorphous regions to well-ordered crystalline regions.

3.1.2 2-Fal and methanol in oil

2-FAL in oil was measured through high performance liquid chromatography (HPLC) according to the direct injection technique in ASTM D5837. Figure 8 shows variation of the conventional paper ageing indicator 2-FAL in the mineral oil and the GTL oil. 2-FAL in both oils shows a similar exponential increase with ageing. At the end of the ageing experiment, the mineral oil shows around 35 ppm of 2-FAL and the GTL oil shows around 45 ppm. The exponential nature of 2-FAL could be attributed to their generation from cyclic by-products of cellulose ageing, which are likely to be generated at the latter stage of ageing [20].

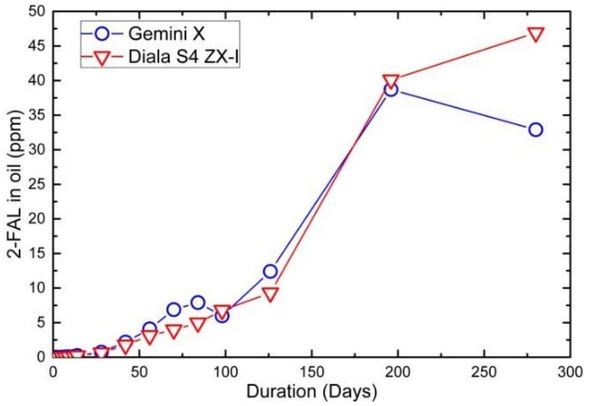

Figure 8. Variation of 2-FAL in oil during the ageing experiment conducted at 120 ℃ [17]

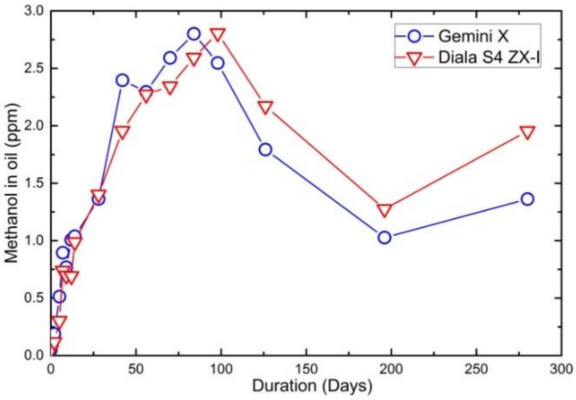

Figure 9. Variation of methanol in oil during the ageing experiment conducted at 120 ℃ [17]

Methanol in oil was measured using a HS-GC-MS unit [21]. Figure 9 shows the variation of methanol in oil with ageing. Methanol shows a rapid increase to around 1 ppm in the first 14 days and then it increases at a slower rate up to 2.8 ppm in the next 80 days. However after about 100 days of ageing, methanol in oil decreases with time reaching around 1.2 ppm at around 200 days and then increases upwards in value slightly. Similar reduction in methanol has been observed during other ageing experiments [22]. An interesting fact about the reductions is that they have been observed only at the late stage of paper ageing (DP ~200) which is almost the end-of-life of the paper. The exact reason for the reduction is not yet understood. One may suggest that modification of the partitioning of methanol between oil and paper due to a build-up of oxidation by-products in oil could be the reason for the reduction [22]. In addition to partitioning, instability of methanol could contribute to the reduction. Methanol which is a primary alcohol can react with carboxylic acids producing esters, which is called the esterification process. Although proper experiments have not been conducted to prove this effect, acids and esters such as formic acid, methyl formate and methyl acetate have been observed during paper aging which could be involved in the esterification of methanol [16].

3.1.3 Paper ageing indicator

It was suggested that methanol is generated from the scissioning of 1,4-β-glycosidic bonds of cellulose [16]. NS in paper is the parameter which is related to the scissioning of glycosidic bonds. Therefore, the variation of methanol in oil against NS was plotted in Figure 10. Furthermore, variation of 2-FAL during early ageing period (NS<3) was also shown in Figure 10 for comparison purpose.

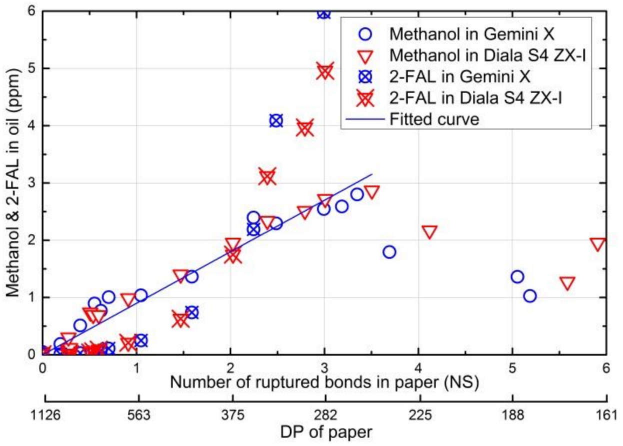

Figure 10. Variation of methanol (NS up to 6) and 2-FAL (NS up to 3) against the number of ruptured bonds in paper obtained from the ageing experiment at 120 ℃ [17]

As expected, methanol shows a linear variation with NS, till the NS reaches ~3.5 (DP~250). Furthermore, the amount of methanol is higher than 2-FAL till the NS reaches ~2 (DP~375). This confirms the previous finding [16] that methanol is suitable for indicating early ageing state of paper. On the other hand, variations of methanol and 2-FAL against paper ageing are independent from the oil types studied in this ageing experiment. This suggests that both chemical indicators can be applied to paper ageing assessment in the new gas-to-liquid based oil without any modifications, which is an advantage for this alternative oil.

3.2 SERVICE AGED OIL MEASUREMENTS

Apart from laboratory ageing experiment, methanol in oil was measured for ~190 UK transmission transformers which are free breathing and have ordinary kraft paper as the conductor insulation. Figure 11 shows the measured methanol in these transformers. Measured methanol values are up to 0.5 ppm and show a general increasing trend with transformer in-service age. It is known that the detection of methanol in oil can be highly affected by individual transformer characteristics such as oil-paper ratio and the operating temperature [23]. In addition to the aforementioned factors, in free breathing transformers, methanol (due to its highly volatile nature) could leak through the breather. All these issues point to a need for further work on stability and partitioning study of methanol.

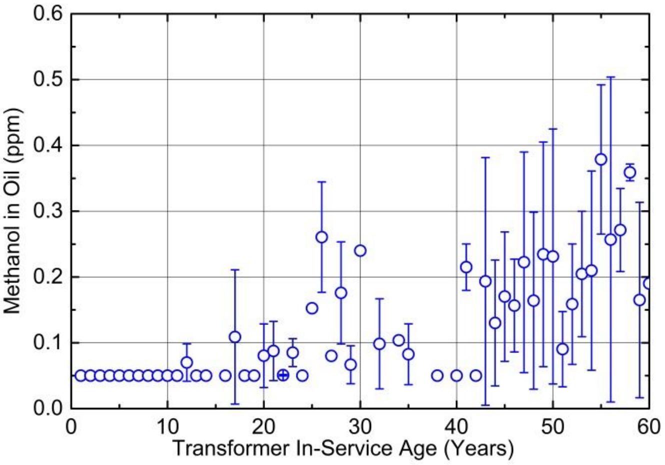

Figure 11. Variation of methanol for in-service aged transformer oil samples

4. THERMAL BEHAVIOUR

Transformer life expectancy is generally determined (with the exception of premature failure due to faults) by the temperature of the hottest point in the winding which is generally referred to as the hot spot. The primary objective of transformer thermal design is to control the hot spot temperature within certain limits, as specified in standards e.g. IEC 60076-2 [24], IEC 60076-14 [25] and IEEE C57.91 [26].

Heat generation and dissipation in the winding are the critical factors which determine the hot spot temperature. Heat generation in the winding is the result of resistive and eddy current losses. Heat dissipation is usually facilitated by oil circulation between the winding and the cooler/radiator. In disc-type transformer windings, flow distribution in the horizontal (radial) cooling ducts should ideally match the loss distribution.

4.1 DIMENSIONAL ANALYSIS ON FLOW DISTRIBUTION IN DISC-TYPE WINDINGS

Dimensional analysis, which has been widely used in fluid mechanics, provides a method of simplifying the relationship between controlling parameters and flow distribution without losing accuracy. After performing dimensional analysis, one may find that parameters that seem to be unrelated are grouped into a dimensionless parameter and different combinations of these parameters can possibly lead to identical effect in a dimensionless sense. In addition, the decrease of the number of parameters by transforming them into dimensionless groups makes parametric sweeps of the controlling parameters much more manageable. With the help of CFD simulations, parametric sweeps of the identified dimensionless parameters were performed. The dimensionless CFD results were then correlated with the identified dimensionless parameters to form predictive correlation equations [27].

By using these correlation equations, the flow distribution of a disc-type transformer winding in an OD (oil directed and forced) cooling mode can be easily investigated. Reverse flow can occur in the winding in an OD cooling mode, as indicated by the experimental work in [28]. Once reverse flow occurs it can reduce the cooling performance because the reverse flow usually leads to a low flow rate and some horizontal cooling ducts may even suffer from stagnant flows.

Since the reverse flow happens initially in the bottom duct of a pass, the correlation equation for flow proportion in the bottom duct can be applied to investigate the criteria for the occurrence of reverse flow in the winding. Flow proportion in a duct is mainly controlled by the Reynolds number (Re) at the pass inlet and the ratio of horizontal duct height (H_{duct}) to vertical duct width (W_{duct}), referred to as α. The variation of flow proportion in the bottom duct with Re and α for the cases presented in [27] is shown in Figure 12. Two regions are distinguished, region 1 is a reversal-free region and region 2 would experience reverse flow. It can be seen that flow proportion in the bottom duct decreases monotonically with increasing Re and α.

4.2 CASE STUDY ON THE INFLUENCE OF OIL FLOW RATE OVER HOT-SPOT TEMPERATURE

It is not true that the higher oil flow rate the better cooling performance. High oil flow rate can result in a lower flow proportion in the bottom duct and even reverse flow, as is illustrated by Figure 12. A case study of a three pass winding with uniform loss distribution was performed with CFD simulations. The variation of hot-spot temperature with pass inlet velocity is shown in Figure 13. As can be seen, there is a value of oil flow rate beyond which a higher hot-spot temperature will result.

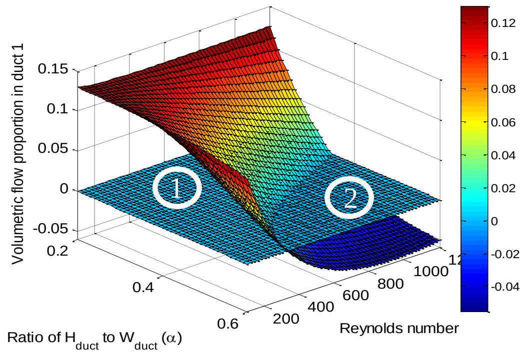

Figure 12. Volumetric flow proportion in bottom duct for different combinations of Re and α . Two regions are identified with region 1 being reversal-free and region 2 experiencing reverse flow [27].

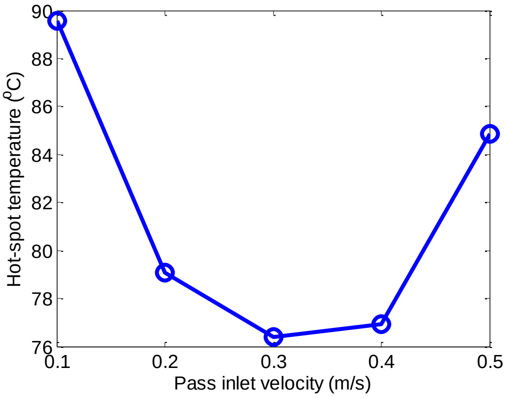

Figure 13.Variation of hot-spot temperature with pass inlet velocity

5. CONCLUSION

In essence, the database analysis work has demonstrated a generic early degradation phenomenon in UK that asset managers need to be aware of. Apart from that, understanding was fostered on the parameters commonly tested. The testing frequencies and correlation of these parameters with age were also studied which could provide insights into how different voltage transformers are managed and how well their ageing tendencies can be reflected by the test parameters. Oil sampling temperature was also advised to be recorded more as it is demonstrated to aid better interpretation of moisture and breakdown voltage records. In addition, database analysis has helped to reveal a potential deficiency in the international standard IEC 60422 in how dielectric dissipation factor and resistivity are interpreted. In brief, analysis on oil databases has improved understanding on how to approach large oil databases, interpret the data recorded and subsequently gain more knowledge on the ageing tendencies of transformer populations, to facilitate transformer asset management.

Suitability of methanol as a paper ageing indicator was investigated through a laboratory ageing experiment conducted with ordinary kraft paper and two different oil types including a conventional mineral oil and a new gas to liquid based oil. Methanol in both oil types increased linearly with paper ageing and was higher than 2-FAL during the early ageing period. This confirms that the new aging indicator methanol is suitable for the alternative GTL based oil. However, it was found that the amount of methanol in both oil types is decreasing at the latter stage of ageing. Even though some other researchers have observed this phenomenon, an exact reason has not yet been found. Some suggest this could be due to a change in the partitioning of methanol due to the oxidation by-products in oil or esterification process from methonal and carboxylic acids reaction.

In addition oil samples obtained from transformers belonging to the UK transmission system was measured for methanol. It was found that most of the transformers have a measureable amount of methanol. However, the amounts were generally less than 0.5 ppm. It should be noted that the amount of methanol in the oil depends on factors such as temperature, oil paper ratio, etc. Furthermore, methanol in free breathing transformers such as in UK could also be reduced due to leakages to the environment through the breather. Therefore all these factors have to be considered in further work to interpret the methanol results.

The method of dimensional analysis was adopted to derive correlation equations for oil flow distribution in disc-type transformer windings in an OD cooling mode. The correlation equation for flow proportion in the pass bottom duct was applied to identify the criteria for the occurrence of reverse flow, an important phenomenon in an OD cooling mode, resulting from a combination of pass inlet flow rate and winding geometry, and resulting in lower oil flow rate and therefore higher hot-spot temperature than expected. Therefore, it is concluded that a higher oil flow rate does not necessarily mean a better cooling performance.

ACKNOWLEDGEMENT

The authors would like to thank the contributions from Mr Shengji Tee, Mr Shanika Matharage, and Mr Xiang Zhang to the transformer research consortium at The University of Manchester, which is sponsored by M&I Materials, National Grid, Scottish Power, Shell Global Solutions, TJ|H2b Analytical Services, UK Power Network and WEIDMANN Electrical Technology.

BIBLIOGRAPHY

[1] "Oxidation Stability of Insulating Fluids," CIGRE Brochure 526, 2013.
[2] I. Fofana, H. Borsi, and E. Gockenbach, "Fundamental investigations on some transformer liquids under various outdoor conditions," IEEE Trans. Dielectr. Electr. Insul., vol. 8, issue 6, pp. 1040-1047, 2001.
[3] S. Okabe, S. Kaneko, M. Kohtoh, and T. Amimoto, "Analysis results for insulating oil components in field transformers," IEEE Trans. Dielectr. Electr. Insul., vol. 17, issue 1, pp. 302-311, 2010.
[4] L. E. Lundgaard, W. Hansen, D. Linhjell, and T. J. Painter, "Aging of oil-impregnated paper in power transformers," IEEE Trans. Power Delivery, vol. 19, issue 1, pp. 230-239, 2004.
[5] N. Lelekakis, G. Wenyu, D. Martin, J. Wijaya, and D. Susa, "A field study of aging in paper-oil insulation systems," IEEE Electr. Insul. Mag., vol. 28, issue 1, pp. 12-19, 2012.
[6] J. Jalbert, R. Gilbert, Y. Denos, and P. Gervais, "Methanol: A Novel Approach to Power Transformer Asset Management," IEEE Trans. Power Delivery, vol. 27, issue 2, pp. 514-520, 2012.
[7] Z.D. Wang, Q. Liu, S.J. Tee, S.Y. Matharage, P. Jarman, G. Wilson, R. Hooton, P. Dyer, D. Walker, Ch. Krause, P.W.R. Smith, P. Mavrommatis and A. Gyore," Ageing Assessment of Transformers through Oil Test Database Analyses and Alternative Diagnostic Techniques," CIGRE SC A2 Colloquium, Shanghai, China, Paper FP0663, 2015.
[8] "IEC 60422 Mineral insulating oils in electrical equipment - Supervision and maintenance guidance (Edition 4.0)," International Electrotechnical Commission (IEC) - Fluids for Electrotechnical Applications Technical Committee, p. 93, 2013.
[9] S.J. Tee, Q. Liu, Z.D. Wang, G. Wilson, P. Jarman, R. Hooton, P. Dyer and D. Walker, "Practice of IEC 60422 in Ageing Assessment of In-Service Transformers," 19th Int'l. Sympos. High Voltage Eng. (ISH), Pilsen, Czech Republic, Paper 423, 2015.
[10] S.J. Tee, Q. Liu, Z.D. Wang, G. Wilson, P. Jarman, R. Hooton, D. Walker and P. Dyer, "Challenges in Oil Test Database Analysis for Ageing Assessment of In-Service Transformers," 50th Int'l. Universities Power Eng. Conf. (UPEC), Stoke-on-Trent, UK, Paper 110, 2015.

[11] S. Tee, Q. Liu, Z. Wang, G. Wilson, P. Jarman, R. Hooton, *et al.*, "An Early Degradation Phenomenon Identified through Transformer Oil Database Analysis," IEEE Trans. Dielectr. Electr. Insul., [in press], June 2016.

[12] D. C. Montgomery and G.C. Runger, “Applied statistics and probability for engineers”, 5th ed., SI version. Hoboken, N.J. : John Wiley, 2011.

[13] S. Tee, Q. Liu, Z. Wang, G. Wilson, P. Jarman, R. Hooton, *et al.*, "Seasonal Influence on Moisture Interpretation for Transformer Ageing Assessment," IEEE Electr. Insul. Mag., [in press], July 2016.

[14] R. Tamura, H. Aneti, T. Ishii, and T. Kawamura, "Diagnostic of aging deterioration of insulating paper," in JIEE Proc. A, pp. 30-36, 1981.

[15] P. J. Burton, M. Carballeira, M. Duval, C. W. Fuller, J. Graham, A. de Pablo, et al., "Application of liquid chromatography to the analysis of electrical insulating materials," presented at the CIGER Session, Paris, 1988.

[16] J. Jalbert, R. Gilbert, P. Tétreault, B. Morin, and D. Lessard-Déziel, "Identification of a chemical indicator of the rupture of 1,4-β-glycosidic bonds of cellulose in an oil-impregnated insulating paper system," Cellulose, vol. 14, pp. 295-309, 2007.

[17] S. Y. Matharage, Q. Liu, and Z.D. Wang, "Ageing Assessment of Transformer Paper Insulation through Methanol in Oil Measurement," IEEE Trans. Dielectr. Electr. Insul., [in press], 2016.

[18] H. Z. Ding and Z.D. Wang, "On the degradation evolution equations of cellulose," Cellulose, vol. 15, pp. 205-224, 2008.

[19] P. Calvini and A. Gorassini, "On the Rate of Paper Degradation: Lessons From the Past," Restaurator, vol. 27, pp. 275-290, 2006.

[20] J. Scheirs, G. Camino, M. Avidano, and W. Tumiatti, "Origin of furanic compounds in thermal degradation of cellulosic insulating paper," Journal of Applied Polymer Science, vol. 69, pp. 2541-2547, 1998.

[21] S. Y. Matharage, Q. Liu, E. Davenport, G. Wilson, D. Walker, and Z.D. Wang, "Methanol detection in transformer oils using gas chromatography and ion trap mass spectrometer," in 18th In'l Conf. Dielectr. Liquids (ICDL), pp. 1-4, Slovenia, 2014.

[22] J. Jalbert, E. Rodriguez-Celis, S. Duchesne, B. Morin, M. Ryadi, and R. Gilbert, "Kinetics of the production of chain-end groups and methanol from the depolymerization of cellulose during the ageing of paper/oil systems. Part 3: extension of the study under temperature conditions over 120 ℃," Cellulose, pp. 1-20, 2014.

[23] J. Jalbert, M. C. Lessard, and M. Ryadi, "Cellulose chemical markers in transformer oil insulation Part 1: Temperature correction factors," IEEE Trans. Dielectr. Electr. Insul., vol. 20, pp. 2287-2291, 2013.

[24] Temperature rise for liquid-immersed transformers, IEC standard 60076-2, 2011.

[25] Liquid-immersed power transformers using high-temperature insulation materials, IEC standard 60076-14, 2013.

[26] IEEE Guide for Loading Mineral-Oil-Immersed Transformers and Step-Voltage Regulators, IEEE standard C57.91, 2011.

[27] X. Zhang, Z. Wang, and Q. Liu, "Prediction of Pressure Drop and Flow Distribution in Disc Type Transformer Windings in an OD Cooling Mode," IEEE Trans. Power Delivery, under review, 2016.

[28] M. Nakadate, K. Toda, K. Sato, D. Biswas, C. Nakagawa, and T. Yanari, "Gas cooling performance in disc winding of large-capacity gas-insulated transformer," IEEE Trans. Power Delivery, vol. 11, pp. 903-908, 1996.