NON-DESTRUCTIVE DP ANALYSIS OF KRAFT PAPER FROM SHELL-TYPE POWER TRANSFORMERS

Patrick BAIRD
GnoSys UK Ltd – UK
p.baird@gnosysgroup.com

Henryk HERMAN
GnoSys UK Ltd – UK
h.herman@gnosysgroup.com

Gary STEVENS
GnoSys UK Ltd - UK
g.stevens@gnosysgroup.com

Annelore SCHAUT
Laborelec – Belgium
annelore.schaut@laborelec.com

ABSTRACT

Rapid, cost-effective, non-destructive diagnosis of power transformer condition is an increasingly important area of asset management – this includes the need to be able to estimate the aged condition of the coil insulation non-destructively. This is necessary to assess the reliability and potential risks presented by transformers in a particular population as well as gauging the prospective life expectancy of individual transformers.

A portable fiber-optic spectroscopic probe system has been developed which can achieve this quickly by determining the degree of polymerization (DP), an indicator of degradation, to an accuracy of 40 DP units in the presence of the insulating oil. The system uses a hand-held optical probe that gathers spectral information which is analysed using dedicated multivariate analysis software. Following calibration and measurement trials in the laboratory, the instrument has been used in the field, to provide DP values based on in-situ measurements of the exposed windings of de-tanked transformers, and can also be used to determine water content.

The method is still in development, but already it is highlighting ageing differences between core and shell-type transformers.

These values have been validated against DP measurements using conventional viscometric methods.

INTRODUCTION

The coils of power transformer windings are insulated with Kraft paper and immersed in mineral oil. This insulation paper degrades over time due to thermal stress, oxidation and moisture content. The main constituent of the paper is cellulose, in which the degree of polymerisation (DP), a measure of the average length of the cellulose chains, is related to the mechanical performance of the paper which decreases with age [1]. Indirect methods of estimating DP which analyse furfural or dissolved gas content of the surrounding oil only give a crude value for the entire transformer winding. Methods that are typically used for direct measurement of DP, such as tensometry or viscometry of the paper are destructive, time consuming, expensive, and rely heavily on precise laboratory practice.

NON-DESTRUCTIVE METHOD

Vibrational spectroscopy, which includes infrared (IR) and Raman methods, is particularly suited to identifying and quantifying molecular structures rapidly and non-destructively. The spectroscopic data can also provide information on the local environment seen by particular molecular bonds and this gives access to sample crystallinity and chain interactions. However, both methods have some limitations when investigating paper, relating to depth of penetration, sampling area and fluorescence. Near-infrared (NIR) spectroscopy (800 to 2500 nm wavelength) is dominated by overtones and combination bands of organic compounds, and is a suitable method for cellulosic materials [2]. The vibrational bands are sensitive to neighbouring interactions and so access the important intra- and intermolecular bonds that relate to fibre strength and crystallinity. There is also a correlation observed between the colour and strength of paper – there is a link between the "brownness" of paper and its degree of polymerisation. The colour comes from electronic vibrations in the visible region (350-800 nm) relating to various degradation products of the cellulose, and since the absorption coefficients of these can be very high, colour changes can be seen at ppm levels of degradation products. However, this is often not a sufficient criterion – papers from different sources do not necessarily behave similarly, and the use of thermally-upgraded and resin-coated papers can obscure the correlation. Since both spectral regions are clearly important, our methodology includes the whole hyperspectral region from the visible to NIR to examine, classify and analyse cellulosic materials [3]. A benefit of this method over standard IR is that glass and quartz fibre-optics are transmissive in this region and thus enable the spectroscopic probe to be some distance from the analyser, which, in addition to portability, ruggedness and ease-of-use, is readily applicable to field work on de-tanked transformers [4]. Our portable instrument, TRANSPEC™, consists of integrated miniature spectrometers and a diffuse reflectance probe with fibre-optic and electrical connections, shown in Figure 1.

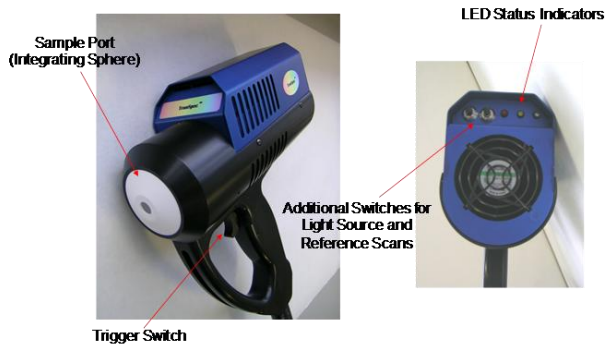

Figure 1: Diffuse reflectance probe with integrating sphere

The diffuse probe, incorporating an integrating sphere, is particularly important for paper to reduce the effects of winding, directionality and tension within the paper structure which can affect the reflectance. The probes currently used are hand-held contact devices. Detanking of transformers allowing access to the paper insulation is infrequent, and generally only available at start-of-life and end-of-life, so another important factor is for an analyser to be modular and capable of using optical probes that can easily be inserted into intact transformers, and a new design of endoscopic immersion probe is under development. Due to the great variety of possible interactions, a multivariate statistical analysis (MVSA) method is used in the analysis, in which a calibration model is constructed for measurement of DP, water content and mechanical properties. Calibration data is provided using "conventional" viscometric methods and then correlated to the spectral information obtained when scanning the insulation. This is unlike the traditional spectroscopic approach of band assignation. MVSA utilises all the spectral data and looks for the most parsimonious approach to correlating spectral, chemical and mechanical information. A schematic of the method is shown in Figure 2.

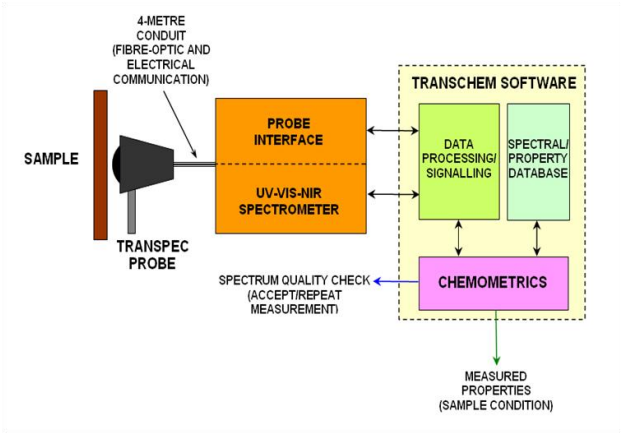

Figure 2: Non-destructive spectroscopic analysis method

MVSA methods used in this analysis are principal component analysis (PCA), for looking at sample-related spectral variation, and principal component regression (PCR), for constructing spectroscopic DP prediction models using samples with known DP (measured using viscometry) as calibration. The quality of the correlation between spectroscopy and viscometry depends on a number of factors, the most important being the quality of spectra and calibration data. Examples of spectra obtained from de-tanked transformer coils are shown in the plot in Figure 3, in which some prominent features are labelled.

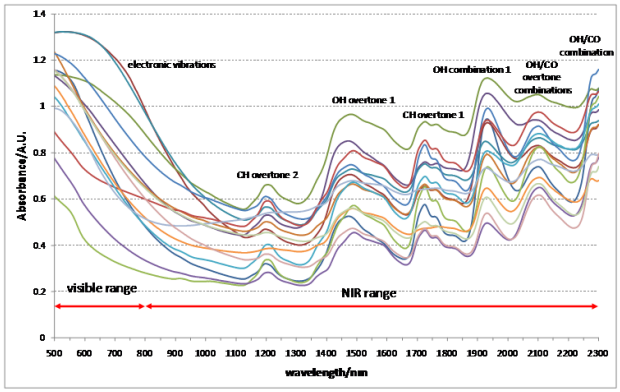

Figure 3: Spectra of transformer coils

SHELL-TYPE TRANSFORMER ANALYSIS

Shell transformers are a design in which the magnetic core encloses the windings. They are selected for applications where compactness, robustness to short circuit and suitability for low and high voltages and impedances are important. For the most recent application, coil sections were obtained from shell-type transformers that were previously installed in nuclear power stations (Transformers 1-3) and a shell-type transformer from a coal/biomass power plant (Transformer 4). Viscometric DP values were obtained for some of the samples for the purpose of calibration, covering a range of DP. The DP range for the aged paper was approximately 220-1020 DP units, with most of the values below 800. Some of the coils were selected for repeat viscometry measurements, resulting in different values, suggesting the possibility of variation in DP within the same coil section. The coils were insulated with kraft paper, which in many cases was coated in a layer of varnish. Some of the samples were very dark in colour due to carbon content, but this condition did not necessarily correlate with low DP. Samples which are very black in colour cannot be measured accurately with visible-NIR spectroscopy due to their large absorbance over a wide wavelength range. Some examples are shown in Figure 4. The set shown on the left includes some very dark (carbonated) paper; the set on the right shows the presence of a varnish coating. All the shell transformers investigated so far have shown evidence of varnish, whereas across the many core-type transformers we have investigated in previous work, only one example had varnish coating on the insulating paper.

a) b)

Figure 4: Transformer coil sections from a) Transformers 1-3 and b) Transformer 4

The spectra of insulating paper are of good quality: over most of the spectral range, they are repeatable to about 1 part in 2000. These spectra require some pre-processing before reliable calibration models can be constructed. Smoothing improves the signal to noise. Due to sample-dependent reflectance characteristics, the application of 1) normalization to a cellulose band and 2) multiplicative scatter correction (MSC) both make a significant contribution to the removal of variance that is unrelated to DP. Differentiation is also applied for reducing unwanted baseline effects. PCA performed on spectra from Transformer 4 shows the effect of varnish on spectral information, amongst other trends, as shown in Figure 5.

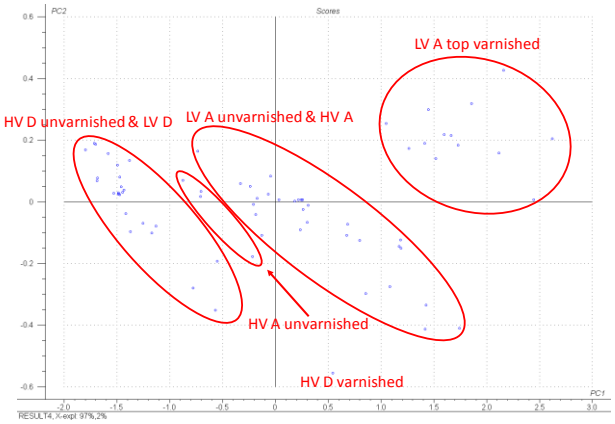

Figure 5: PCA showing clustering of spectroscopic data into groups

It can be seen that for LV coils, the spectra of varnished layers are clearly separate from the other data. For HV coils, the difference between varnished and unvarnished paper is less marked. Data from "A" and "D" sections are clearly distinct from one another. A and D represent regions of the "pancake" (typically an approximately rectangular, vertically-aligned, disc of coils found in many shell-type designs) relating to height from the ground. It was also observed that D sections had significantly higher oil content compared with A. An example of a PCR model using all the available viscometric DP data is shown in Figure 6.

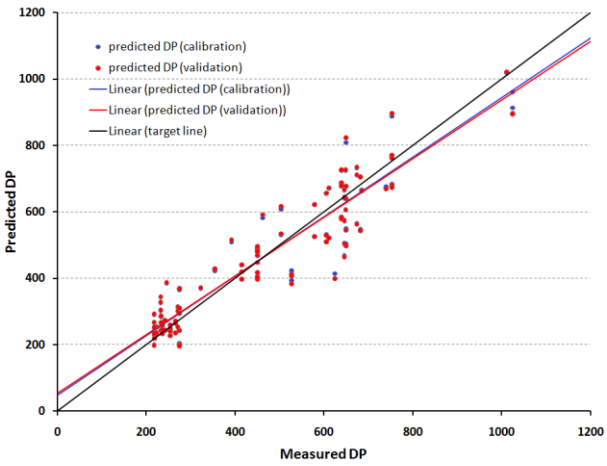

Figure 6: PCR model showing correlation of spectroscopically-measured DP with viscometrically-measured DP

In most cases the validation result is close to the calibration, suggesting a robust model. The model has a standard deviation of ±70 DP units over a range of 800. Investigation of model regression coefficients indicates that this model is highly dependent on spectral features relating to oil, and has little dependence on colour. The lack of dependence on colour is partly due to the presence of dark samples in which the darkness is related to carbon content and not DP. The oil content varies over regions of coils relating to vertical location and may not be correlated with DP in this sense. By removing the oil-related and colour regions and concentrating on regions relating to cellulose crystallinity, a model of similar accuracy, but only half the number of principal components (PCs), can be constructed using this data set. A smaller number of PCs generally suggests a more stable model. This does not mean that the other spectral regions should be discarded in all cases – significant spectral variation has been observed over a wide range of power transformers using the same instrument, and the spectral information relating to DP can vary, suggesting different chemical pathways of cellulose degradation between one type of transformer and another. Some of these transformers cluster into sub-groups which can relate to the size, power rating and loading history of the transformer, in addition to variation in the type of paper insulation and the presence of additives such as varnish or thermal upgrading material [5].

VALIDATION

These models are cross-validated across the data set (one sample at a time is left out of the modeling process to help detect outliers), but models can be properly validated by using them to make predictions from spectra taken from a transformer (of similar type) with unknown DP. Following these blind predictions, some of the same samples will have viscometric analysis performed on them to test the ability of the model to predict unknown

samples. The validation samples must be shown to have DP levels that fall within the range spanned by the model. The data for Transformer 4 is more complete than that for Transformers 1-3, and spans a similar DP range. A model was constructed from Transformer 4 data (24 samples, 94 spectra including repeats) and tested on Transformers 1-3: the latter are left out of the calibration completely. The Transformer 1-3 data set had 5 extreme outliers (very dark samples) which must be discarded as the low reflectance from carbon content leaves very little spectral information in the detector signal. The remaining samples are selected for validation of the Transformer 4 model. Some had repeated viscometry, for which an average was used. One of these samples consisted of dark and light paper layers. DP predictions are shown below in Table 1.

Table 1: Blind predictions of DP of transformer coil samples

Sample	Reference (viscometry)	Predicted (spectroscopy)
Sample 0507	246	408
Sample 0511	292	324
Sample 0506	323	333
Sample 0514	355	417
Sample 0517	392	475
Sample 0515	462	527
Sample 0525dark	504	444
Sample 0525light	504	504
Sample 0502	625	415
Sample 0509	685	615
Sample 0527	715	934
Sample 0519	740	662
Sample 0521	1011	995
Sample 0505	1025	763

More than 70% of these predictions are within 100 DP units of the reference value.

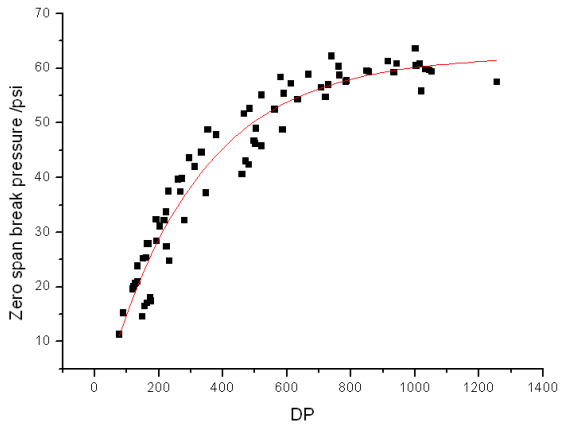

Figure 7: Relationship between zero span test and DP of Kraft paper

ESTIMATION OF TENSILE STRENGTH

Data from previous work has shown a non-linear relationship between DP and tensile strength, as measured by the zero span test. This is seen in Figure 7 which shows an exponential relationship between the two parameters. Using an exponential function fitted through this data set, the tensile strength can be readily calculated, providing this directly from a spectral measurement, if necessary.

CONCLUSION

We have demonstrated a portable instrument and methodology that can be used to non-destructively measure the degraded condition of insulating paper on transformer coils. The method has been tested in the laboratory on coil sections removed from transformers at end of life, and also in the field on de-tanked transformers. The samples analysed here from a number of shell transformers are shown to be of similar type in terms of spectral information, although there are outliers in some cases that need to be excluded from the calibration and prediction process, mainly due to their carbon content. A sizeable database of calibration data has already been gathered from different types of power transformers, and we continue to expand our calibration to cover more shell-type and core-type transformers. With sufficient data input, we anticipate that eventually all or most sample types will be covered by one of our models specific to transformer type, paper type and loading history. We are currently developing an in-situ endoscopic probe that would allow analysis of transformer insulation without the need for de-tanking.

REFERENCES

[1] A. M. Emsley and G. C. Stevens, 1994, "Review of chemical indicators of degradation of cellulosic electrical paper insulation in oil-filled transformers", *IEE Proc. Sci. Meas. Technol.*, vol. 141, 324-334.

[2] M. Ali, A. M. Emsley, H. Herman and R.J. Heywood, 2001, "Spectroscopic studies of the ageing of cellulosic paper", *Polymer*, vol. 42, 2893-2900.

[3] P. J. Baird, H. Herman G. C. Stevens and P. N. Jarman, 2006, "Non-Destructive Measurement of the Degradation of Transformer Insulating Paper", *IEEE Trans. Dielec. Electr. Insul.*, vol. 13, 309-318.

[4] P. J. Baird, H. Herman and G. C. Stevens, 2008, "On-site analysis of transformer paper insulation using portable spectroscopy for chemometric prediction of aged condition," *IEEE Trans. Dielec. Electr. Insul.*, vol. 15, 1089-1099.

[5] P. J. Baird, H. Herman, W. Mortimore and G. C. Stevens, 2010, "Non-destructive and in-situ analysis of cellulose insulating materials in power transformers," *Transformer Diagnostics and Maintenance Symposium*, Helsinki, June 2010.