TRANSFORMING POWER ASSET MANAGEMENT

# Accurate Determination of Transformer Insulation Risk and Remaining Life

*A stubborn pre-requisite for data-driven optimised lifelong management*

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## *Abstract*

There are many varied methods used in industry to manage the ever-increasing number of aged transformers in the world fleet caused by the industry-wide squeeze on capital expenditure. These range from annual or biennial manual oil testing to high accuracy on-line multi-gas DGA analysis.

Understanding the state of a transformer and its optimum operating envelope throughout life requires analysis from a wide range of perspectives. Theoretically transformer aging should be pro-actively optimised, however this is rarely achieved due to a poor understanding of the true state of the internal paper insulation. The cause of this poor understanding is the affordability of suitably accurate analysis techniques and often little understanding of usage history. Once paper insulation is degraded, the risk of operation becomes excessively high and the transformer should be scrapped. This decision is dependent upon an accurate understanding of insulation state, the risk appetite of the owner organisation, plus the risk profile of the specific installation. Without accurate information on insulation state, the asset manager has little option but to be conservative. This drives premature replacement decisions industry wide.

Maximising transformer life requires (a) minimisation of damage throughout life, and (b) management of use in accordance with risk during the end-of-life phase.

Water ingress and excess temperature events throughout life are the main drivers of irreversible damage to paper insulation. To manage a transformer reliably, especially during end-of-life, requires a clear understanding of current insulation state. Moreover, forecasts of insulation state are also needed for the alignment of increasing risk of failure with managed organised replacement.

However, neither can be usefully achieved using the industry standard - manual oil testing, as it provides a myopic, sporadic and distorted picture of insulation state until significant failure modes are evident.

To manage aging in accordance with usage requirements and long-term goals, continuous monitoring is essential for careful, responsive and appropriate maintenance and operational management. In addition, continuous real time data is also capable of minimising the risk of catastrophic failure.

This paper discloses new techniques using affordable IoT solutions which enable the water content and polymer age of the insulation to be accurately tracked over life with accuracy. These techniques are based on state-of-the-art sensor and IoT technologies and complete transformer insulation system modelling theory. It also discusses how many transformers can be safely operated at name plate ages far older than traditionally accepted. The proposed technology solves the challenge of identifying critical implicated insulation condition of transformers and the most appropriate operating envelope to maximise their life until replacement.

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## Introduction

The demand for accurate health assessment of transformers has driven considerable research over many decades. The dominant aim is to provide a means to assess the state of the paper insulation and the insulating fluids easily, cheaply and without unacceptably affecting operation. Of special interest has been understanding the information that can be ascertained from oil samples. The attraction of an oil sample is that it can be completed relatively simply with other routine maintenance work while the transformer remains on-line.

Sampling the oil directly is an excellent way to complete an accurate assessment of the state of the oil itself. Its exact current characteristics can be analysed to any detail required in a suitably equipped laboratory. This same process can look for other breakdown products also which indicate very concerning electrical discharges or paper charring. Considerable work has been invested over the years to understand how to interpret the indicators present in sampled oil (References [1] and [2] being foundation examples). However, using the oil sample to assess the true state of the insulating paper in the absence of any final failure mode signatures (e.g. in terms of its mechanical strength and insulating qualities) is very difficult.

Understanding how the mechanical state of the paper affects transformer performance has also been widely studied over decades. At start-of-life, the paper insulation within a transformer consists of long intertwined cellulose chains which make it structurally strong, tough and durable for mechanical and electrical stresses.

Over time, chemical breakdown of these chains ultimately makes the paper mechanically weak, brittle and unable to withstand normal operating mechanical stresses, caused mainly by heating cycles and transient electrical forces. Cracks and breaks become more probable, and with them, the risk of electrical breakdown and structural instability under high (although not necessarily unexpected) electrical stresses. *Figure 1* shows the relationship between DP and the tensile strength of standard Kraft paper (Cigré [3]).

Notwithstanding these challenges, the problem of transformer aging has an even more complex dimension. The state of the paper other than its polymer age (in particular its water content) affects the insulating qualities of the transformer in a number of important ways. The paper over time in fact becomes a store of any water created or entering the transformer. Water in the transformer oil is effectively mopped up by the paper. This leaves less than a few percent of the total transformer water in the oil at any time, masking the true progress of water ingress.

Understanding how the moisture in the paper affects the insulating quality of the paper and the oil is not straight forward. Moisture accelerates paper polymer breakdown directly, therefore accelerating end-of-safe-life. In addition, water in the insulation directly limits the safe operating envelope of the transformer in many ways. Firstly, water can cause bubbles of liquid or water vapour to form under certain conditions [11]. These processes are directly related to the extent of the moisture in the paper. In addition, water movement in and out of the paper under different temperature profiles affects the breakdown strength of the oil – which can cause highly hazardous short-lived states.

*Figure 1*
*DP vs Tensile Strength CIGRE [3]*

# Accuracy of Insulation Assessment from Oil Sampling

Due mainly to a lack of sufficiently low-cost alternatives, a great deal of work has been invested over the years to estimate water state of a transformer using periodic oil samples.

Unfortunately, even after all these decades and decades of work, oil sampling is generally agreed to be a very poor way indeed to assess the polymerisation level, Water Content of Paper (WCP) and safe operating envelope of a transformer (Ortiz [4], CIGRE [1], Patki, [5] and Du [6] ).

The central issue is that when the oil is sampled, a great deal of the data that is needed to interpret the sample is lost, distorted or unknown, creating a large margin of error.

Firstly, of critical importance to an oil sample is the exact oil temperature. Unless the exact temperature of the oil at the time of measurement is known, the implications of the water content of the oil, in terms of the water content of the paper, are lost. Unfortunately, an accurate, relevant record of the oil temperature is nearly impossible to measure as the sample is usually taken at the bottom rather than at the important top (or better Hot Spot) location, as more often than not, both are inaccessible for electrical safety or practicality reasons. The common solution is to estimate the temperature or to use the temperature read on an inaccurate transformer temperature gauge, which is often old and out of calibration. Both solutions are sufficiently inaccurate to make interpretation of the sample nearly useless.

Secondly, the water content of the oil is actually highly related to the recent (past weeks) of load history of the transformer. For example, if the transformer is in a heating cycle (i.e. its top temperature is rising on average over a number of days), then on average, the water in the oil will be higher than the equilibrium state, which is needed to estimate paper characteristics. The cause is that in a heating cycle, water is expelled more quickly out of the hot areas of the winding insulation (high temperature makes the water more active) than it can be absorbed into the cooler areas of the transformer. This process leaves high levels of water in the oil during the transition period in comparison to equilibrium. Conversely, during a transformer cooling cycle, the top of the winding will try to absorb water from the oil more quickly than the cooler areas can supply water. Thus, the oil is left temporarily with a lower water content than that of an equilibrium state. This water movement dynamic is continuous. It occurs over the daily, weekly and seasonal cycles. This makes interpretation of the water content of a single sample almost impossible.

In addition to this fact, the ability of the oil to absorb water is affected by the impurities in the oil. New pure oil is very hydrophobic. However, as the oil ages due to thermal stress, oxidation and acidities, certain chemicals are formed which improve the oil's ability to absorb water. The amount of water in the oil therefore will depend on its ability to absorb water from the paper in a way that is unrelated to the water content of the paper.

Finally, paper performs differently when new as compared to old. Old paper, with a given water content, will leave a lot more water in the oil than new paper, as the paper gets less absorbent as it ages. Consequently, a given water content of the oil could be as a result of wet new paper or relatively dry old paper. Without knowledge of the insulation degree of polymerisation (DP), interpretation of the sample becomes inaccurate.

In addition to using the oil sample to understand the water issues within a transformer, it is also commonly used to provide an estimate of the DP. The established method for estimating DP from an oil sample is to use certain chemicals, i.e. 2-Furan, in the oil which are caused predominantly by cellulose breakdown. The build-up of these chemicals is then related to the likely extent of breakdown.

Again, considerable work of many decades has been invested into characterising the chemicals (furans in particular). However, again it is generally agreed throughout industry that this is quite a poor method in practice (Du [6]), although it can be shown to be quite accurate in the controlled environment of the laboratory. *Figure 2* provides the results published in Ding [7] for the UK power network. Additional similar data is provided in CIGRE report [3] which documents Laboratory aging tests of paper against furan generation. As shown, suffice it to say, this relationship is very noisy.

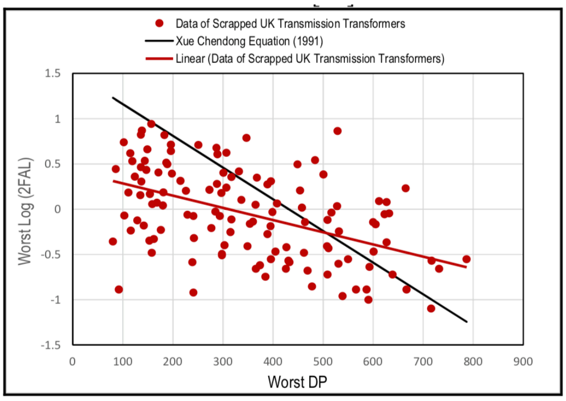


*Figure 2*
*Example data on the relationship between Furans and DP showing results of Autopsy data from retired transformers from UK[7].*
*Black Line shows the Chendong Furan to DP relationship [8].*

The practical issues of relating furan analysis to DP are many:

- Furan chemicals within the oil can be produced and destroyed by a number of chemical reactions, some directly related to aging, some not;
- The furan content of the oil is dependent on characteristics of the aging process. For example, furans are generated in polymer breakdown more efficiently at different paper aging temperatures than others.
- Furan measurement relies on the transformer oil reflecting the true furan levels in the paper. However only a proportion of the generated furans ever enter the oil and many factors affect the consequential equilibrium levels achieved (ref *Figure 3)* including:
    1. The equilibrium furan concentration in the oil is dependent on the ratio of aging paper to total paper and oil volume in the transformer.
    2. The furan content of the oil is dependent on the water content of the paper and oil and also somewhat the levels of other chemicals, including carbon dioxide.
    3. Replacement or topping up the oil will dilute the total furan levels within the transformer and permanently distort the signature. Multiple such events over years will totally destroy the signal.
- There are a number of relationships used to relate furans to age. All these relationships are empirical (although some attempts have been made to relate them to creation rates from basic chemical processes), constructed from limited laboratory tests or field observations, highly debatable and provide wildly varying results between themselves. Certain relationships are preferred (and frequently quoted), such as the Chendong relationship (a useful review is provided in Nikosenye [9]). Others are not. Nevertheless, the basis for the preference seems at best arbitrary, when all the reference material is considered.
- Any resulting DP estimate generated by furan analysis provides an indication of the aging of the insulation, as the furan content in the oil is a blurred indicator of equilibrium concentration achieved as a result of aging in small areas of the transformer which then diffuses throughout. This observed concentration is then compared to average aging from experimentally-derived ppm data. As a result, and contrary to popular belief, it does not provide the limiting age of the transformer (which would sensibly be the worse-case DP or hotspot age). Some of the empirical relationships (Pahlavanpour [10]) do attempt to calculate hot spot age directly. However, this method seems to estimate a more conservative age than the commonly-used relationships (e.g. Chendong) which do not attempt to do so (making interpretation of furans even more bewildering).

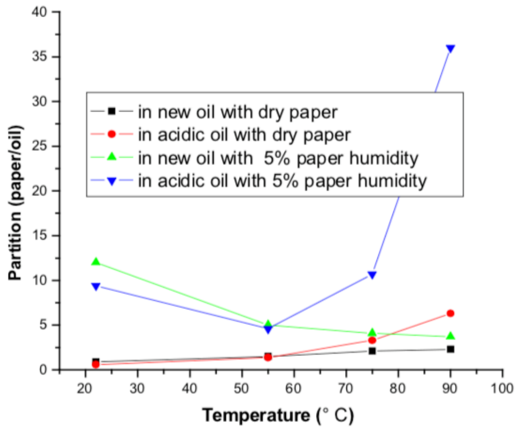


*Figure 3*
*Furan paper to oil ratio for different oil states CIGRE [11] showing Furan content in oil is highly related to the water content of the oil*

As described previously, *Figure 2* compares actual data from a large group of UK transformers at retirement Ding [7]. The DP measurements were the lowest DP paper sampled from each transformer against the latest furan measurement from an oil sample. The black line shows the Chendong relationship. The red line shows the linear regression of all points. As concluded in the report, the DP level indicated by this (the most commonly used Chendong relationship) was not unreasonable, however it does overestimate the DP of the worst locations within the transformer significantly. Approximately 66% of the observations are more than 200 DP less than that indicated by the Chendong line (a critically important error if the difference is between 400 (significant life left) and 200 (arguably end of life), for example).

Given that the furans within the oil of a transformer will, in time, be the average furan level generated in the hottest areas but distributed across a wider area of the transformer paper, it is reasonable to consider such a relationship better estimates the average top DP of a transformer, rather than the hotspot. This conclusion is supported by the work of Mullerova [12] which matched Chendong-based DP estimates to actual DP in a number of decommissioned transformers. It is not surprising then that the observed worse case DP (presumably from the hot spots of the transformers) will be significantly lower.

## Resolving WCP and DP in an Operational Transformer

Rather than oil sampling with all the challenges identified above, the measurement of water saturation of the oil is a modern approach that significantly improves the accuracy of both water content and age (DP level) calculations throughout life. As described in detail in many publications including Koch [13] and Martin [14], if water saturation is measured continuously with temperature, the errors associated with temperature accuracy and the moisture solubility of the oil can be mitigated significantly. If the measurements are made sufficiently regularly to cover all the temperature movements of the transformer, then the equilibrium points can be obtained to calculate accurate Water Content of Paper (WCP) from laboratory-generated equilibrium charts.

Further, using heavy processing over time (now available inexpensively using cloud-hosted processing systems such as those run by Aurtra), the response of the paper can be accurately pattern-matched to the appropriate water activity moisture equilibrium curves (an example for Pressboard is shown in *Figure 4* (Koch [13]), supported by work by Liao [15] and Oommen [16], for example, to resolve the true WCP and effective DP level of the transformer.

The technique Aurtra uses for achieving this matching is to continuously monitor the transformer for instantaneous points in time where the oil water activity is in equilibrium with the paper of interest (usually the top paper – based on a theoretically valid moisture movement model). A series of such points in a stable condition can be utilised for describing an equilibrium curve corresponding to the age of the paper being observed. A more mathematically complicated method involves an equilibrium model of the transformer as a whole, which will achieve the highest level of correlation between the observed movements of Water Activity ($a_w$) with temperature and load, when the multi-dimensional age profile within the model matches the true age profile of the winding insulation. Aurtra uses highly-developed patented variants of both methods to generate a best estimate for effective insulation age.

These same techniques can be used to calculate state predictions throughout the transformer through a combination of direct measurement and heat/circulation models (e.g. discussion in Vasilevskij [17] and Jarman [18]). Thus, providing a vastly improved multi-dimensional (in space and state parameters) picture of transformer state for asset management planning.

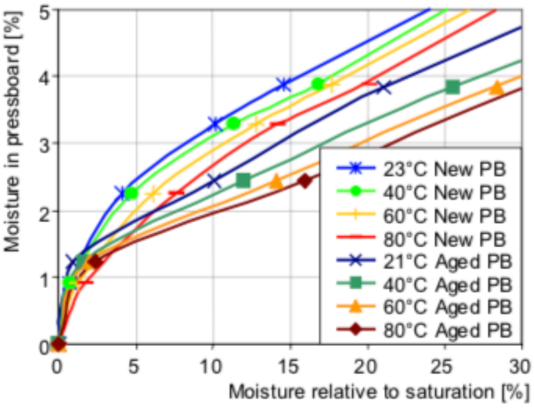


*Figure 4*
*Example Chart showing the changes in moisture Saturation of Old and New Pressboard (Figure taken from Koch [11])*

## Maintaining an Accurate Picture of DP Over Life

Even with the benefits of the Aurtra method of calculating DP and WCP using continuously sampled data, variations between transformers in practice means that the accuracy of any one technique is probably insufficient to be suitable as the sole driver of a best practice data-driven management process.

With the aim of determining state over life Gordon [19] documented a technique where he used IEC top and hot spot DP predictions to estimate life using the life lost mathematics (based on WCP) first described by Emsley [20]. However, degradation is far more sensitive to temperature and water content than the accuracy of general predictive methods or general historical records can address. The physics of the degradation processes within transformer insulation mean the aging rate increases or decreases by nearly a factor of two with changes of temperature of as little as six degrees. As a result, over any reasonable period of time, any understanding of the likely paper insulation age of a transformer from cumulative aging becomes very difficult to gauge.

*Figure 5* provides the example of a transformer whose effective average hot spot temperature is 54 degrees versus 60 degrees over life (using a WCP model for the Hot Spot which starts at 0.5% at new and rises to a maximum of 3.5% after 50 years). This plot was made using the Life Lost mathematics from Emsley [20] with the A value relationships of Martin [14]. As shown, the DP threshold of 400 is reached after just 30 years for 60 degrees and 47 years for the slightly lower 54 degrees. End of life moves from 52 years for the higher to nearly 90 for the lower. The level of accuracy needed to separate these two scenarios is neither generated by the IEC loading guide calculations, nor provided by most asset histories.

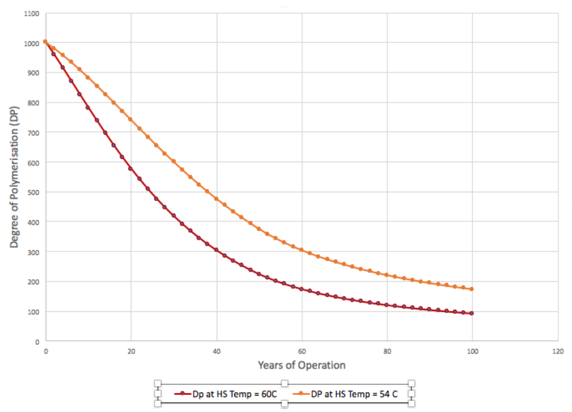


*Figure 5*
*Example Aging rate calculation at 60 and 54 degrees based on water content at Hot spot reaching 3.5% after 50 years and then stabilising with intervention of asset manager.*

If, however, this technique is augmented with a regular, reasonably accurate, independent DP estimate as described above, accuracy can be maintained to a useful level. To demonstrate, a similar calculation as Gordon describes has been completed using the input uncertainties provided in *Table 1.*

| Parameter | σ (Uncertainty) | Comments |
|---|---|---|
| Top Temperature | 2 °C | Measured directly |
| Hot Spot temperature | 5 °C | Calculated from Top Temp |
| Activation Energy | 2000 | Typical 111000 |
| Start DP | 975 | Assumed at installation |
| Error in A value (based on WCP) | 10% | Accuracy determined by A value data and measured WCP |
| Furan DP Prediction | 300 | Based on Chendong (see discussion above) |
| DP from pattern matching | 150 | Aurtra prediction tolerance |

*Table 1*
*Input uncertainties to DP calculation of Figure 6*

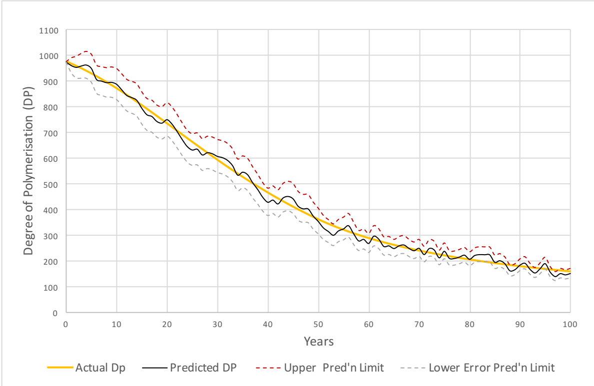


*Figure 6*
*Modelled DP Predictions for 54 degrees HS Temp with error limits using yearly generated DP from Furan analysis + Aurtra WC Pattern Matching.*
*(Note: DP Errors modelled using Randomizer).*

Without independent DP confirmation throughout life, the DP estimate is quite accurate over the first 10 years (< 20%) however it becomes poor over a long-time frame (@ 50 years >100%). With the addition of yearly DP estimates using Furans (with accuracy ±150), and pattern matching from WCP dynamics (as generated by Aurtra's HealthSense insulation management software with an accuracy ±75), accuracy will remain better than 10% (see *Figure 6)*. This method is potentially so effective because the various DP assessment methods are totally independent. This level of accuracy is more than suitable to identify the various life stages of the transformer, and employ management maintenance practices efficiently in line with true internal state.

Conversely, the use of on-line monitoring to accurately and consistently record the temperature and water activity at the time of oil sampling will additionally improve the accuracy of furan analysis (removing some of the sampling inaccuracies including temperature at time of sampling and loading state).

## Summary

The existing method of managing transformers through life using name plate age and basic historical knowledge of load, re-enforced with yearly rough estimates of DP from oil analysis, does not provide an accurate way of positioning an asset on its life curve. This method results in highly conservative and costly end-of-life decision making.

In order to achieve the full potential life of a transformer, understanding its aging profile is critically important so it can be actively managed in accordance with its internal state. Potentially this understanding will enable aged transformers to be confidently kept in useful operation, which historically would be retired (either based on their nameplate age, Furan analysis which indicated they are somewhere in the critical 100 to 400 DP range, or their excessively high water content).

On-line monitoring with advanced WCP and DP processing provides the first really useful and scientifically justifiable method to assess a transformer's insulation state in all critical ways. With all-of-life on-line monitoring, the asset can be accurately positioned in terms of effective true age (DP) and water content, and therefore confidently managed for maximum life at optimal cost.

There is clear evidence that many transformers can be operated to name plate age far longer than traditionally accepted. The application of this technology solves the challenge of identifying which transformers fall into this category, and the most appropriate operating envelope during the last of their life until replacement.

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