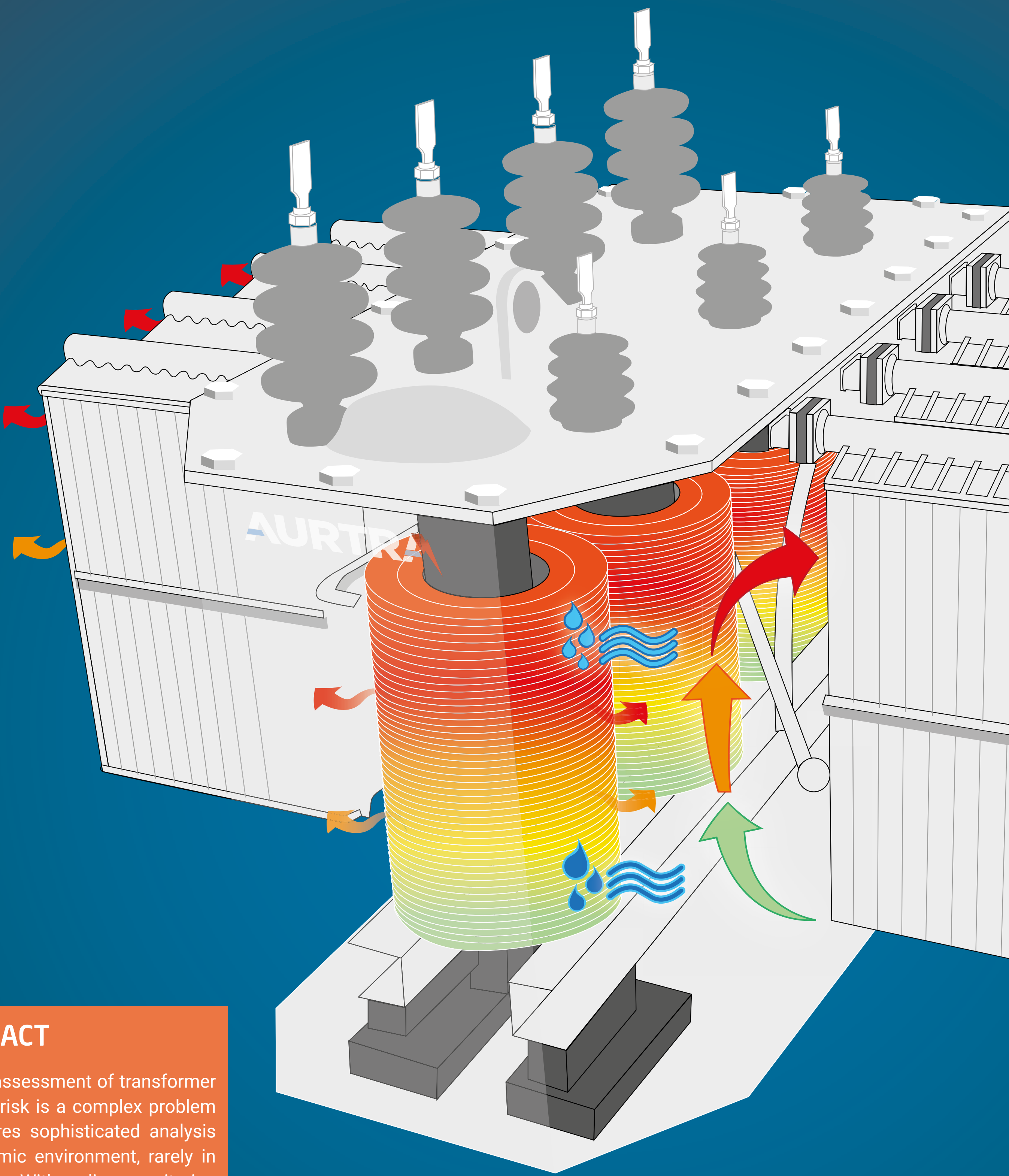


ABSTRACT

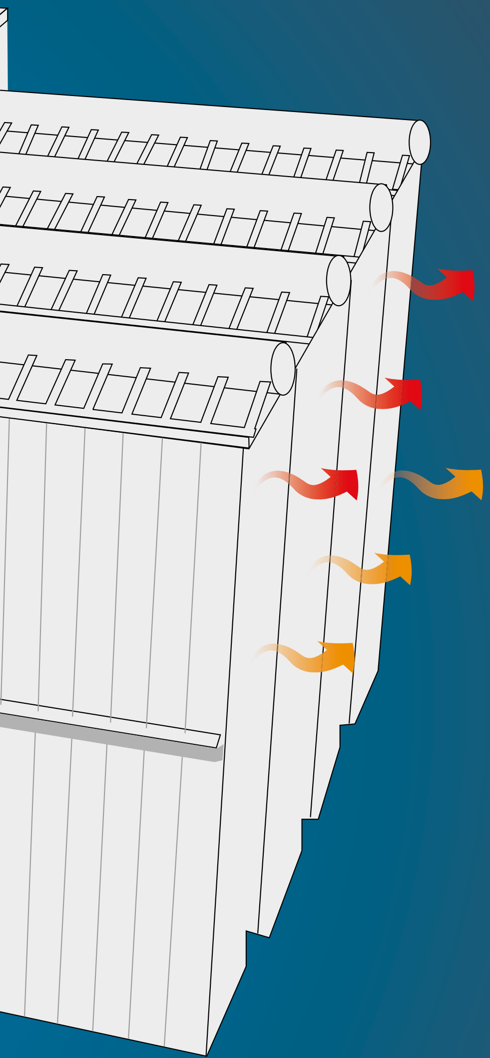
Accurate assessment of transformer insulation risk is a complex problem that requires sophisticated analysis of a dynamic environment, rarely in equilibrium. With online monitoring and an understanding of the detailed relationship between temperature and water activity in both the paper and oil, a complete and useful automated assessment is possible.

KEYWORDS

aging, condition monitoring, depolymerisation, insulation, moisture

Moisture and temperature are the biggest drivers of irreversible transformer aging

Like the complex excitation and loading of an electrical power system, equilibrium is rarely achieved



Accurate determination of transformer insulation risk and remaining life

Introduction to insulation breakdown

Moisture and temperature are the biggest drivers of irreversible transformer aging. The critical issue is that temperature causes polymer chains in the paper to break down. At start-of-life, the paper insulation within a transformer consists of long intertwined cellulose chains, which make it structurally strong, tough and durable to resist mechanical and electrical stresses.

Over time, chemical breakdown of these chains ultimately makes the paper mechanically weak, brittle and unable to withstand normal operating stress. This stress is caused mainly by heating cycles and transient electrical forces. Cracks and breaks become more probable and the risk of electrical breakdown and structural instability increases. Eventually, the structural strength of the paper and pressboard cannot withstand the mechanical stress, and the electrical insulation role it plays is compromised, resulting in a failure of the transformer. Moisture exacerbates this ageing effect. For example, perfectly dry Kraft paper (< 0.5 % moisture and medium oxygen [1]) operated at 80 degrees will last > 20 years before it is critically damaged. Add 2 % moisture and the usable life left falls to 3 years. Add 4 % moisture and it falls to just over one year.

Measuring temperature and moisture

Measuring the temperature of a transformer is relatively easy, in comparison with measuring the water content of the paper. For example, sensors can be located throughout the transformer winding. Alternatively, close estimates can be made from measuring the top oil temperature as it exits the core or enters the radiator.

On the other hand, assessing the water content is much more difficult. Precision requires sampling the paper, which is not possible without removing the transformer from service. Using the measurements from the oil is far more difficult. Water Content of Oil (WCO) vs Water Content of Paper (WCP) relationships have been developed and refined for decades by some of the best practitioners and researchers. Unfortunately, these methods remain prone to serious error for fundamental reasons discussed below.

The diffusion phenomenon

Moisture in transformers is mostly contained in the paper. WCP is measured as a percentage (or parts per 100). WCO is measured in parts per million, ppm. Take the example of a modest size transformer, which may have 1000 kg of paper and 3000 litres of oil. At 3 % WCP, this equates to 30 kg total of moisture in paper. At 3 % WCP, the WCO at normal operating temperatures will be between 10 and 50 ppm, which equates to a maximum of 150 ml of total water in the oil. As a useful rule, 95 % of the moisture in a transformer is in the paper.

The balance between the moisture in the paper and the moisture in the oil is a simple molecular diffusion phenomenon. Effectively, when there is a difference in water pressures across a boundary, water molecules will move from the area of higher pressure to lower pressure. This mathematical theory was developed by Adolf Fick in 1855 (specifically Fick's second law). The pressure of the water in a material divided by the pressure above liquid water, at the same temperature, is by definition the relative saturation or water activity (a_w) [2]. Therefore, the water activity difference across a boundary is in fact the driving force for diffusion (as the denominator is constant). Further, when the water activity in each of the materials either side of a boundary are equal, no diffusion occurs. This is when the materials are in equilibrium.

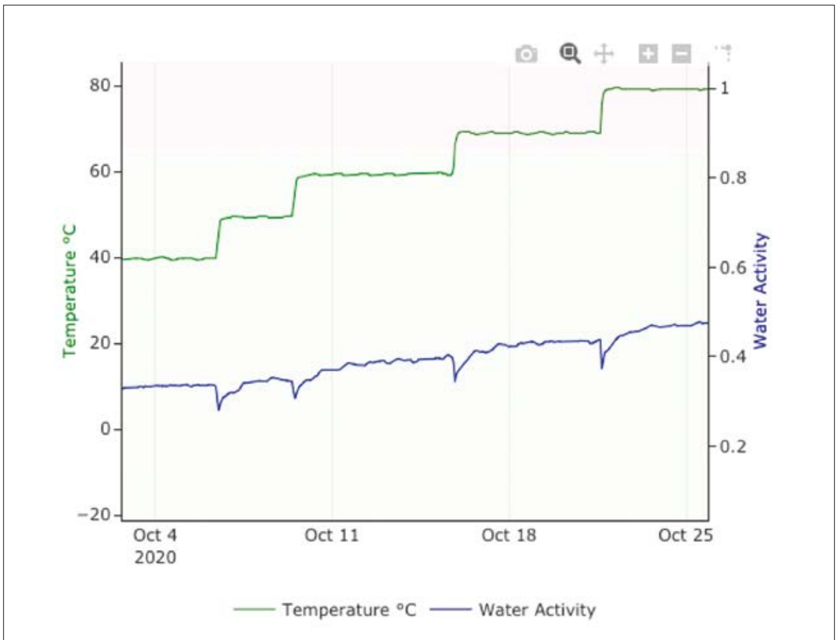


Figure 1. Water activity response to 10 °C temperature steps using 4 % wet Kraft paper in an oil bath

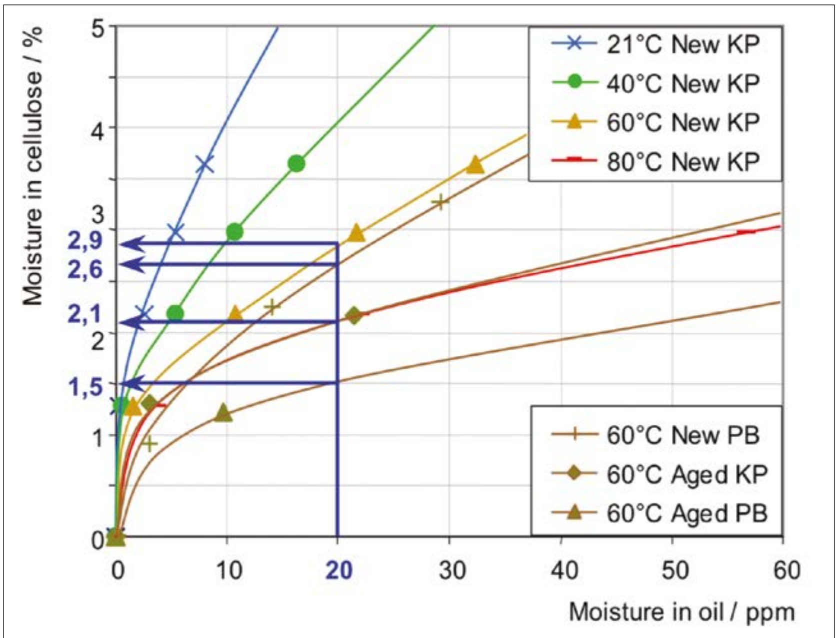


Figure 2. Example chart showing changes in moisture saturation of old and new pressboard [3]

As most of the moisture in a transformer is within the paper, only a very small amount of the total moisture in the paper needs to migrate to the oil to completely saturate it. In essence, the paper controls the moisture seen in the oil, not the other way round. If the paper's water activity is greater than the water activity in the oil, then moisture will move out of the paper and raise the water activity in the oil to match. Very little moisture is needed to move out of the paper to achieve this - much less than is needed to materially change the water content of the paper.

So, when in equilibrium (i.e., when water migration across the boundary between the oil and the paper stops), then the water content of the oil will be a direct indication of the water content of the paper, as their water activity will be the same. Unfortunately, equilibrium rarely occurs in an active transformer due to its oscillating load, plus there are further complicating factors to consider.

A complex relationship

Some of the complex issues to consider when analysing moisture in a transformer include:

1. The relationship between WCO and water activity is complicated and highly dependent on the type, age, pollutants, and additives within the oil. As a result, relating WCO to water activity in the oil around the paper is problematic.
2. The relationship between water activity and water content within the paper is dependent on paper quali-

ties including paper type, degree of polymerisation (DP), manufacturing process and surface finishes.

3. Water activity in the oil decreases with temperature (for constant water content in ppm), but actually increases with temperature in paper (water becomes more active in paper as the temperature increases), so any equilibrium is short-lived and highly dynamic in an operating transformer.
4. Hot paper holds much less moisture than cold paper at the same a_w, so as the oil circulates in an operating transformer, it is passing layers of paper with differing water content at different temperatures and at different states of equilibrium, generating a complex set of moisture movements.
5. Diffusion as a result of differences in water activity across the paper / oil interface increases with temperature. This means that in hot areas moisture equilibrium is achieved quickly (in terms of hours), but in cold areas it is very slow (days or weeks).
6. In summary, the assessment of water in the paper in a functioning transformer where the load and ambient temperatures are continuously changing is very complicated.

Aurtra HealthSense automates this complex dynamic WCP analysis using data from the low cost HealthSense Sensor

Dynamic moisture movement

To better understand moisture movement in a transformer, it is useful to consider it in terms of a moisture pump. Moisture in the hot (top) sections of the transformer is highly mobile in comparison with the cold sections (as explained previously, the diffusion rate increases with temperature). Changes in the top temperature, pump moisture into the oil or draw moisture out of the oil much more quickly than cold areas. As a result, when an "at-equilibrium" transformer's top temperature increases, the water activity of the paper at the hot top will respond accordingly (and increase) and moisture will quickly begin to diffuse out of hot paper in an attempt to reach equilibrium with the hot oil (where water activity will have fallen with the increase in temperature). See Fig. 1 showing a test of wet Kraft paper in an oil bath exposed to sudden temperature changes and the resulting effect on water activity.

When that "changing a_w oil" circulates down to the cold sections, its higher moisture level will be out of equilibrium with the colder areas of the transformer (where temperature does not change greatly as it is close to ambient).

Diffusion at the lower bottom temperatures is slow in comparison, so this non-equilibrium state lasts a relatively long time, until the colder sections absorb the extra moisture. As the moisture is absorbed into the cold sections, the hot sections release more moisture until a new equilibrium point is found. If the tempera-

Figure 3. Aurtra HealthSense Sensor installed in top fill valve

With Aurtra HealthSense, these complex analyses are immediately available to assess, track and forecast the insulation state and life left across the transformer fleet

ture of the top sections falls before equilibrium is reached, the reverse process starts immediately, and the oil moisture content remains continuously out of balance with either the hot or cold areas.

Like the complex excitation and loading of an electrical power system, equilibrium is rarely achieved. Understanding the state of the transformer (moisture levels at different locations) from a single sporadic "oil-test" observation is therefore like trying to understand the dynamic state of a power system using a single point measurement. You know something, but not quite what.

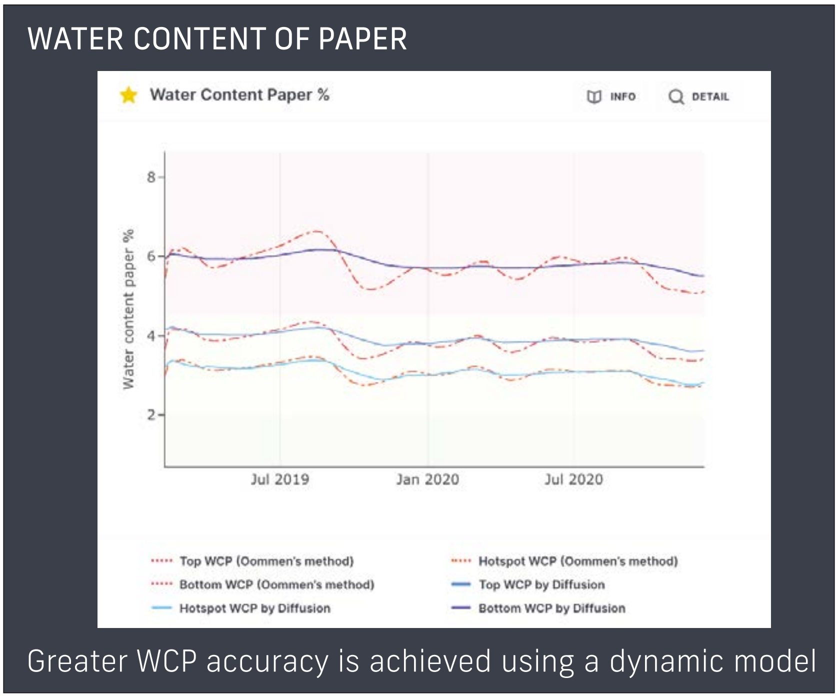


Figure 4. Aurtra HealthSense Water Content of Paper Analysis

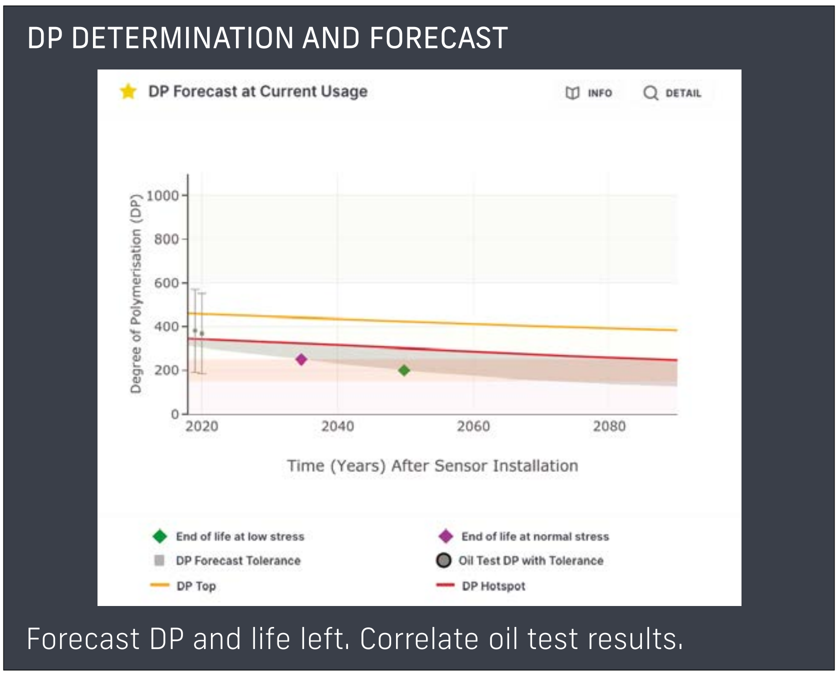


Figure 5. Aurtra HealthSense DP Analysis and Forecast

Online monitoring is key to accuracy

Water content of the oil is a function of the oil's ability to hold moisture at the specific a_w and is driven by the a_w and WCP of the hottest paper in the transformer. Importantly, a_w is the driving parameter not WCO. Measuring WCO therefore provides an indication of the a_w in the hot areas but it is complicated by the oil's characteristics and the dynamic state of the pumping process. Averaging over time helps to remove the effects of the dynamic processes, but this requires continuous monitoring, not spot observations. Systems that directly measure the a_w, together with the top temperatures, provide a much greater level of accuracy in WCP estimation and therefore consequential calculations such as paper age and life left.

Unfortunately, the ability of the paper to hold moisture at a given a_w is also complicated by the paper age (DP). As paper ages (DP decreases), its ability to hold moisture reduces. Moisture is absorbed by new paper primarily as a surface layer within the inter- and intra-fibre spaces attracted by the oxygen within the polymer chain. Layers of moisture build on top of this surface layer with decreasing stability to generate the complete moisture absorption capability of the material. As the paper ages, the chains are broken down and the water attachment sites, inter- and intra-fibre spaces destroyed. Fig. 2 shows the relationship between typical new and aged Kraft and PB paper.

Complex computational problem solved

To complete a detailed and accurate assessment of the moisture profile of a transformer, the age profile of the transformer at top, bottom and hotspot must therefore also be considered in the calculations. This is a difficult computational process which can only be done by means of an iterative solution using an observation-matching algorithm.

Observations of a_w need to be made together with temperature at a sufficient rate to observe the dynamic characteristics of the temperature profile (Nyquist rate). With this information, plus an understanding of the age of the paper at different locations, and the detailed relationship between temperature and a_w in both paper and the oil, it is possible to conduct a complete and useful assessment.

Aurtra HealthSense automates this complex dynamic WCP analysis using data from the low cost HealthSense Sensor (Fig. 3), which measures multiple temperatures, water activity, vibration and RF signals that indicate partial discharge.

Fig. 4 is a HealthSense screenshot example of an automated WCP analysis. As indicated, the analysis considers different diffusion characteristics of the paper at top, bottom and hotspot.

With an accurate, dynamic analysis of WCP, DP Forecast and Life Left can be calculated based on current load profiles as shown in Fig. 5. Scenario forecasts of insulation aging with changing load profiles can also be easily modelled by the dashboard user.

With Aurtra HealthSense, these complex analyses are immediately available to assess, track and forecast the insulation state and life left across the transformer fleet. Insulation failure risk rankings enable the asset manager to engineer data-driven life extension and risk-reduction maintenance strategies (Fig. 6), as well as optimise aged transformer replacement programs (Fig. 7).

Bibliography

[1] Lelekakis, Nick, et al. "Ageing Rate of Paper Insulation Used in Power Transformers Part 2: Oil/Paper System with Medium and High Oxygen Concentration." *IEEE Transactions On Dielectrics And Electrical Insulation*, vol. 19, no. 6, 2012, pp. 2009–2018.

[2] D. Martin et al, *Improving the Determination of Water Content of Power Transformer Insulation Paper near the End of Its Functional Life*, Australasian Universities Power Engineering Conference (AUPEC), 2016, pp. 1–6.

[3] CIGRE *Moisture Equilibrium and Moisture Migration Within Transformer Insulation Systems*, 2008, A.23

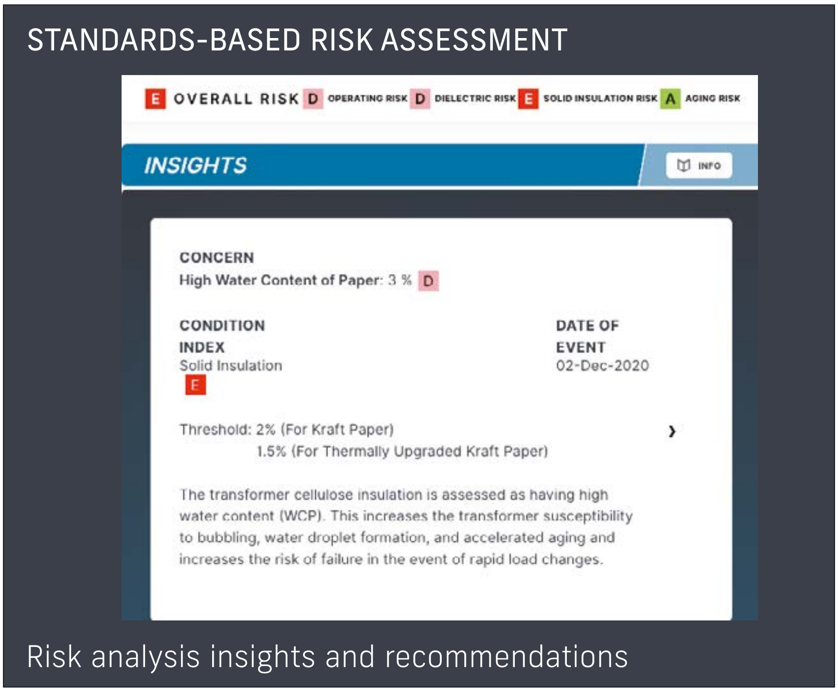


Figure 6. Aurtra HealthSense Insights

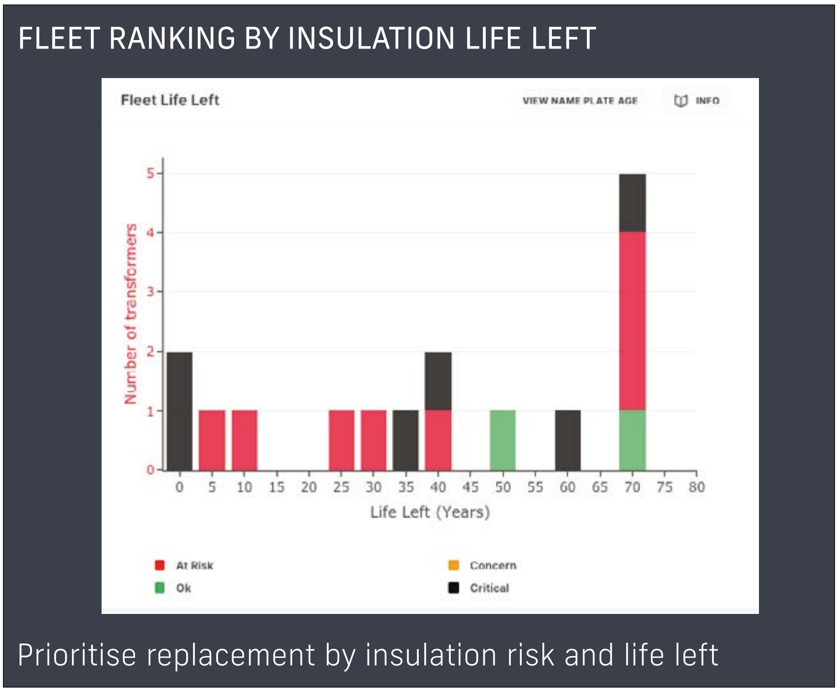


Figure 7. Aurtra HealthSense Fleet Life Left

Author

Richard Harris, PhD

CTO & Founder of Aurtra Pty Ltd. Aurtra is an Australian company focused on providing innovative solutions in asset condition monitoring and assessment to the electricity market. Dr Harris is an experienced technology entrepreneur, having founded a number of successful companies in the telecommunications and high voltage electronics fields. He is the holder of numerous patents and an Adjunct Professor with the Queensland University School of Information Technology and Electrical Engineering.

Contact: ask@aurtra.net