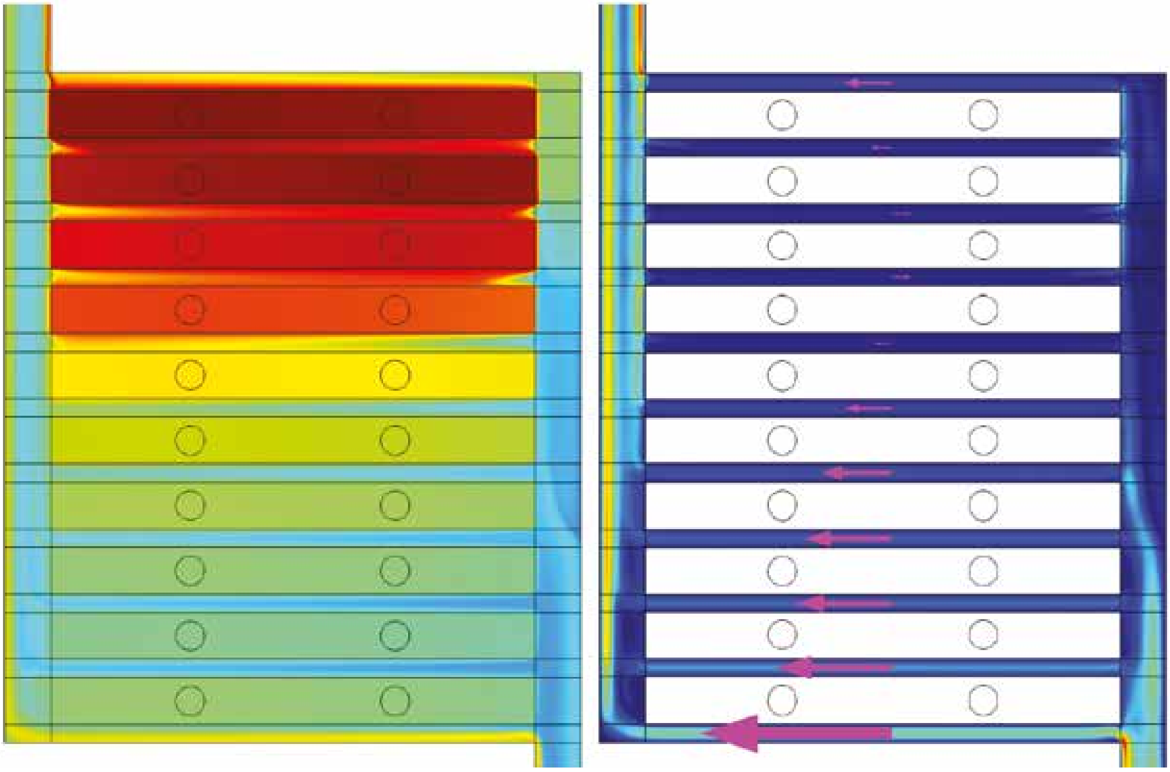


The importance of thermal design to transformer lifetime

Experience from scrapped transformers

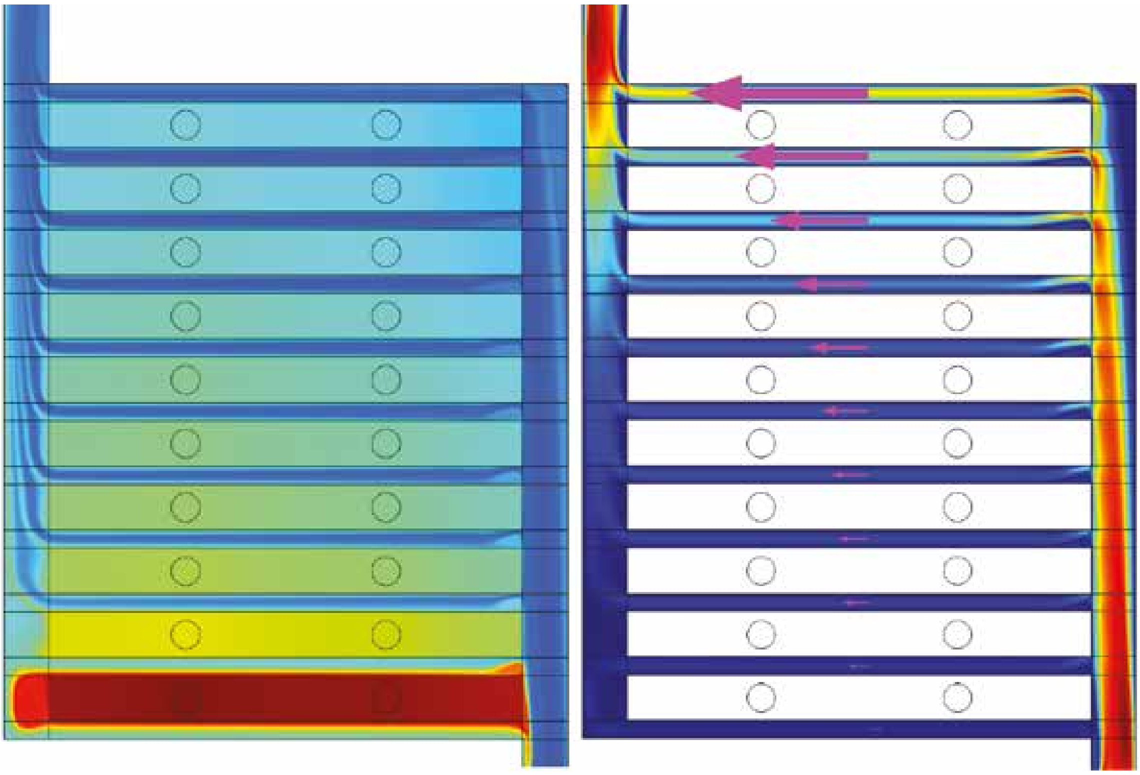
Although anecdotes and individual case studies can be misleading on their own, sometimes they can spark a train of thought or a line of research that does help our understanding. This is true in the case of the relationship between transformer thermal design and transformer lifetime. Specifically, during my time at National Grid, I had to conduct failure investigations on two particular units that stayed in my mind. The first was very old, approaching 50 years in service and was indeed one of the first 275 kV units ever built. It had a very simple ONAN / OFAF (see IEC 60076-2) cooling arrangement with no directed oil flow inside the tank. Although the oil was pumped through the coolers (if the thermostatic control called for it), once inside the tank, it was allowed to find its own way to and through the windings. The thermostat, an early winding temperature indicator (WTI), relied on current from a current transformer heating an oil pocket at the top of the tank, to give a crude indication of winding temperature. This transformer was unfortunate-

ABSTRACT

According to the evidence gathered from many large scrapped transformers over the years, some transformers seem to have aged thermally at much higher rates than others. This discrepancy cannot always be ascribed to the operating conditions, and it has become clear that some units have much higher internal temperatures and consequently more rapid ageing than expected. This column explores some of the potential reasons for this, some of the research that has been carried out and some of the considerations and techniques that can be applied to avoid problems in the future.

KEYWORDS

cooling technology, windings, oil cooling, hot-spot, thermal design, transformer lifetime



ly damaged when an oil valve was left closed after maintenance, resulting in thermal expansion rupturing an internal barrier. Subsequently, pressure relief valves were fitted to similar designs to prevent this. Now, the transformer had admittedly had quite an easy life from the loading point of view, but it was still quite a surprise to find the paper in very good condition, much less than halfway through its lifetime, according to DP (degree of polymerisation) measurements.

The second transformer was a much newer unit, in service for only around 15 years before it suffered a winding failure. Again, the loading had not been very high, certainly less than 100 %, but this time the paper was at the end of its life, actually flaking off the conductors when it was scrapped. This experience got me asking why were these transformers behaving so differently? This was an important question for the asset management of other similar transformers on the system, so research projects were started to understand both the range of different lifetimes and the possible causes of the variability. As always, the research throws up new avenues to explore and is still ongoing, but some of the key results shed light on potential thermal design and manufacturing issues that can drastically shorten the life of a transformer.

Example from experience: a 50-year-old unit had insulation in very good condition while another 15-year-old unit had insulation thermally aged to end-of-life

Hot-spot temperature calculation and the hot-spot factor

The key to the thermal lifetime of a transformer is the temperature of the hottest part of the hottest winding, this is, of course, a function of the ambient temperature and loading history, as well as the design. The real form of this function is complex and incorporates many factors, but it has been reduced to a relatively simple form in the standards, for example, IEC 60076-7. This simplified function works reasonably well in many cases, and it can be argued that, in general, it has served the industry well. However, it depends on some design parameters, principally the hot-spot factor, which can be subject to significant errors.

Fundamental to the problem of transformer thermal design is the lack of real information about the winding hot-spot temperature. The temperature rise test from IEC 60076-2 measures top and bottom oil temperature, and average winding temperature, inferring the hot-spot temperature from these measurements and the design hot-spot factor. The hot-spot factor is intended to allow for the hot-spot temperature being higher than might be straightforwardly calculated from the average difference between winding and oil temperatures. Often the hot-spot factor is taken as a 'standard' factor of between 1.1 and 1.3, but this can be a poor estimate. It does not take into account the established fact that the hot-spot factor, as well as the hot-spot position may change with ambient temperature and loading conditions [4]. Of course, for larger and more important transformers, it is possible to use fibre optic temperature sensors to measure the temperature at a few spots within the transformer. However, neglecting the accuracy of the measurement system, the measurement must be lower than the actual hot-spot temperature if the sensor is not properly in close thermal contact with the hot-spot itself. This is hard or impossible to achieve be-

The key to the thermal lifetime of a transformer is the temperature of the hottest part of the hottest winding, which is a function of many parameters

cause the location of the hot-spot can only be calculated or guessed at from the design. Moreover, as the sensor is not generally welded to the conductor, there is always a temperature drop between the conductor and the sensor. This is usually has a small effect, but it can be significant if the sensor is poorly installed.

The importance of cooler controls

Knowing something about the loading and ambient temperature conditions over the lifetime of a transformer, taken together with the aged state of the paper on scrapping, can allow a retrospective calculation of the hot-spot factor. This was done for a range of transformers, and the results of this study, which are summarised in Fig. 1, show an astonishing and extreme variety of hot-spot factors [1]. Some of this variation is explained by uncertainties in the technique, but even so, it points to some very worrying thermal underperformance against the usual expectations. Why could this be?

One critical issue is the setting and operation of the thermostat that controls the cooling on most of the population of transformers reported in this study. The practice of mixed ONAN/ODAF cooling is very prevalent on larger transformers in the UK and some other parts of the world. This mixed cooling regime usually uses some kind of sensing and control system to bring the forced and directed cooling system (fans and pumps) into operation as the transformer warms up. The intent is to balance the electrical load, lifetime and maintenance of the cooling system against the transformer lifetime reduction and higher system losses that occur as the transformer temperature increases. Traditionally, this is done using a winding temperature indicator (WTI) which senses the top oil temperature and the load current and outputs a temperature that is supposed to be representative of the winding hot-spot temperature. As indicated before, early incarnations of the WTI consisted of a thermometer in a heated thermometer pocket at the top of the transformer with the heater supplied from a current transformer in series with the winding. The latest WTIs are digital processors with a sophisticated set of control and monitoring functions and contain a detailed thermal model of the transformer.

In the sense that it is a device that takes real-world inputs and then uses a digital model to determine a derived quantity useful to the operation of the plant, the WTI could perhaps be called 'a digital twin' of the transformer, to use a popular term.

The operation of the WTI tends to cause a plateau in the relationship between load and temperature of operation between the minimum load that causes the cooling to cut in and the load at which the cooling is in continuous operation. This is shown schematically in Fig. 2. There is a close link between the lifetime of the transformer and its operating temperature, and for most network transformers, the temperature plateau occurs at loads that cover the normal operating range. This means that the setting of the WTI and the quality of the thermal model it contains turn out to be very critical to the lifetime of the transformer. If the hot-spot factor included in the model is underestimated, then not only will the hot-spot be at a higher temperature than assumed in the design, but also the WTI will fail to bring the cooling on soon enough at moderate loads so the ageing rate will be disproportionately increased even if the transformer never sees high loadings.

It is particularly relevant to remember that the thermal model changes when the oil flow is changed from ON to OD (turning on the pumps). This is known as gradient switching since the primary WTI setting is the load-dependent temperature increment (gradient) which is added to the top oil temperature to allow for the temperature difference between the oil and the hot-spot. This is generally taken to be proportional to current squared in OD designs where oil flows are constant, and a lower exponent (often a power of 1.6) in ON designs to allow for the increase in cooling flows as the thermosiphon effect gains speed at higher temperatures. The gradient setting incorporates the hot-spot factor either implicitly or explicitly, and this is

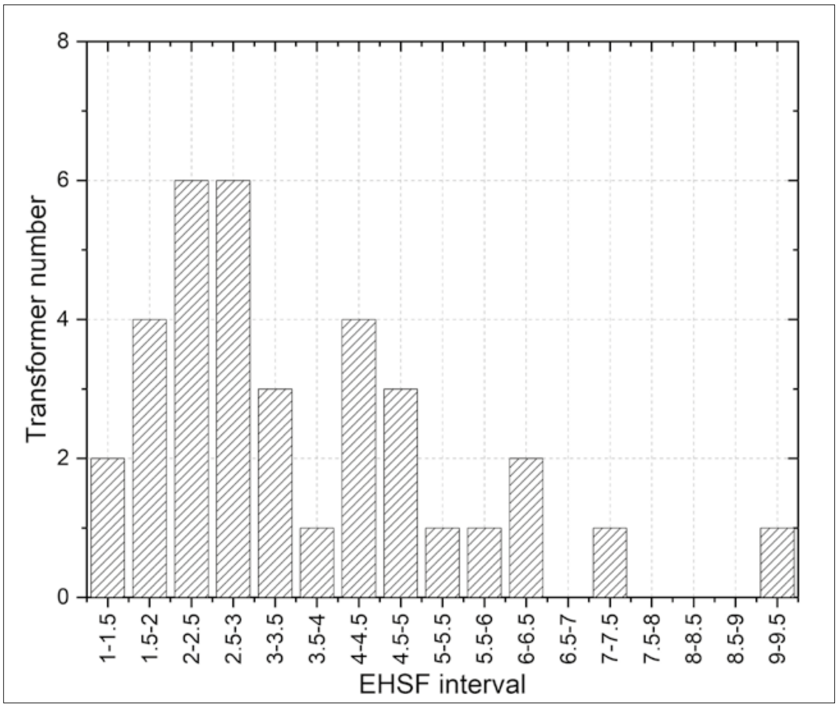


Figure 1. Distribution of effective hot-spot factors (EHSF) derived from the insulation condition and loading history of 35 scrapped transformers [1]

also different for the two cooling modes. It is the ON gradient setting in the WTI that determines when the coolers come on and the OD gradient setting that determines when they switch off, so if either is underestimated, the lifetime of the transformer will be negatively impacted. Of course, this is all made worse if the WTI 'cooler on' setting has been increased in a misguided attempt to save electricity drawn by the coolers from the site supply. The effect on the lifetime of an incorrectly set WTI is shown in Fig. 3 [2].

Therefore, it is very important for all transformers, and doubly so for transformers with WTI switched cooling, that the hot-spot factor is correctly calculated. This calculation is normally done by using a finite element electromagnetic model of the transformer windings, or a simpler model to determine the eddy current heating of each turn due to the magnetic flux it experiences. It is very often the case that the conductors in a core type transformer have a larger axial (vertical) than radial (horizontal) dimension. This, combined with the tendency of the magnetic flux in the winding to have a bigger radial component at the ends of the winding, means that the top and bottom turns generally have the highest loss. The ratio of the highest loss to average loss is then used to calculate the hot-spot factor. Unfortunately, this is not the end of the story, because, of course, the temperature of an individual turn depends not only on the heat input but also on the cooling efficiency. This also varies to a greater or lesser extent depending on the position of the conductor in the oil flow system. Although the IEC 60076-2 standard attempts to separate the eddy loss and cooling factors, in fact, they are closely related because the temperature and power loss of an individual conductor or disc also affects the cooling oil flow. So the use of 'S' (cooling efficiency) and 'Q' (eddy loss) factors as components of the hot-spot factor, although highlighting the principle are not in fact very useful for detailed thermal calculations.

Understanding oil flow in disc-type windings

Many disc-type windings in core type transformers incorporate a directed oil flow system that forces oil between the discs in groups called passes, alternately horizontally inwards and horizontally outwards, directed by washers blocking the oil flow alternately on the inside and the outside of the winding within cylinders that direct the flow vertically up the winding past the discs. The general arrangement is shown in Fig. 4. This set-up is equivalent for each pass to having a header (the vertical duct) supplying a number of parallel hydraulic paths (the horizontal ducts between the discs). Typically, for example, in a radiator, the header would have a much higher cross-section and lower hydraulic resistance than the parallel paths it serves. This would tend to equalise the flows in those parallel paths. However, in the case

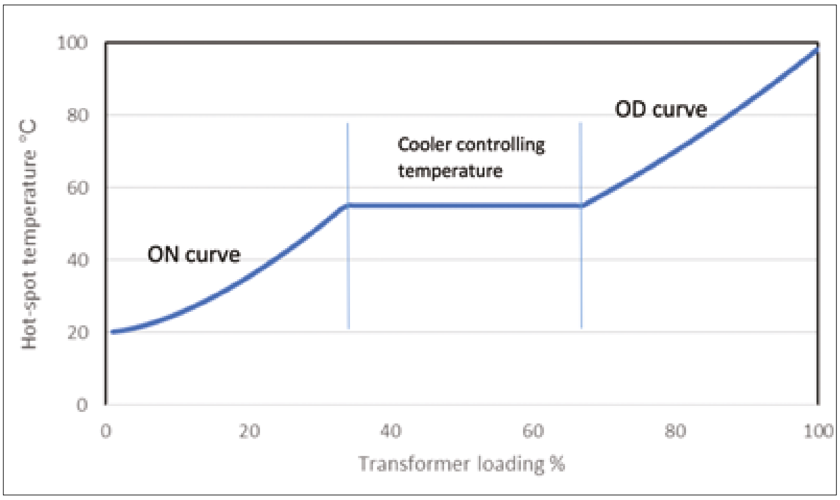


Figure 2. Illustration of hot-spot temperature vs transformer loading for an ONAN / ODAF transformer with an idealised cooling control system

If the ON and OD gradient settings that govern the cooler on and off switching temperatures are not set correctly, the transformer lifetime can be negatively impacted

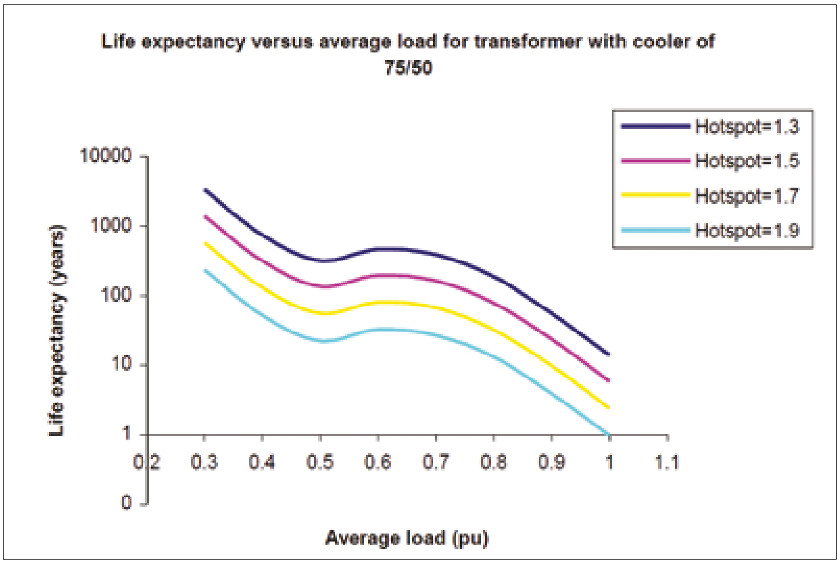


Figure 3. Life expectancy vs load calculated using representative daily load and ambient temperature profiles for an ONAN / ODAF transformer with a cooler on the temperature of 75 °C, a cooler off temperature of 55 °C and a WTI set with a hot-spot factor of 1.3 for a range of actual hot-spot factors [2]

Under some conditions, simple thermal-hydraulic network models might fail to accurately predict hot-spot temperatures according to CFD and physical model results

of a transformer winding structure, the size of the vertical ducts is severely limited by dielectric considerations because a large oil gap next to the conductor edges is dielectrically weak. Under normal oil flow conditions, this poor hydraulic situation can be accommodated because, in truth, the cooling requirements of most transformers are relatively modest compared, for example, with a jet engine or a power electronic device, but under high-flow and low-flow conditions it is a problem that must be understood to avoid serious miscalculation of performance.

Many traditional design tools for relating the duct geometry, power loss in each turn, and oil flow to hot-spot temperature, rely on a thermal-hydraulic network model. Such a model equates the thermal flow paths to an electrical model, where pressure is considered as voltage, flow as current, and also equates hydraulic resistance to electrical resistance to determine the flows in each duct. These models work well for many designs, and it is even possible to ignore the fundamental phenomena of fluid inertia and buoyancy while obtaining reasonably accurate results over a limited range of conditions. Unfortunately, if the conditions inside the real transformer lie outside the range of validity of the model, the results derived from the model will diverge from reality. This is, of course, true for any model of a physical system, so it is very important to explore and understand that range of validity.

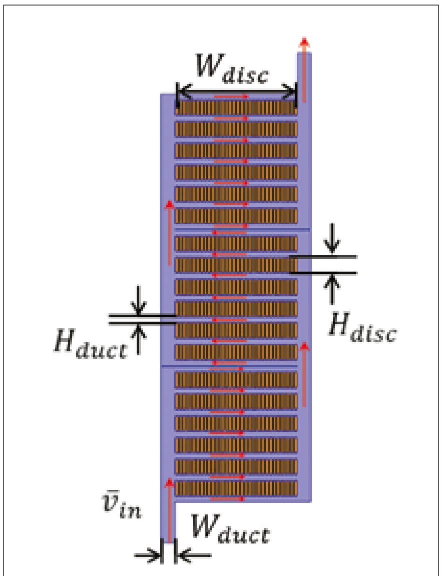


Figure 4. General arrangement of cooling flows within a winding with six disks per pass, showing the important geometry and dimensions for modelling the flow

Understanding oil flows in disc-type windings has been the focus of work at the University of Manchester and elsewhere using computational fluid dynamics (CFD) and physical models [3-5]. These models can incorporate all the relevant fluid flow parameters and phenomena so that the limitations of simplified models can be determined and those models improved, or at least indications can be given when CFD is required to obtain accurate predictions. In very simplified terms, at high flow rates which might occur in pumped oil cooling systems, or when high powers are dissipated in natural cooling systems with low flow rates, it is possible to get very uneven flow distributions in the horizontal ducts, even to the point of stagnant or reverse flow in some ducts. Under these circumstances, not only is the hot-spot factor very high but also simple thermal-hydraulic network models will significantly underestimate it, leading to all the WTI setting problems outlined above and to an overestimation of the transformer's rating and lifetime.

To look at this in more detail, a physical transformer model or rig was set up at Manchester, complete with a laser particle image velocimetry measurement system that can measure the oil flows within the ducts of a representative portion of a winding. The winding itself was represented by heated plates complete with thermocouples to measure temperature. The rig was equipped with a pump and oil flow measuring system to vary flow rates, and a radiator and oil heater to achieve steady oil inlet temperatures. In parallel, a CFD model of the rig was used to understand the results by sweeping the important parameters over the range of values likely to be found inside a transformer, to be able to generalise the findings using dimensional analysis.

High oil flow conditions

Taking the high flow rate condition first, it turns out that the two most critical parameters to obtaining a reasonably even distribution of flows in the horizontal ducts (for a given number of ducts per pass) are the ratio of the vertical duct width to the horizontal duct width and the Reynolds number of the oil flow at the inlet to the vertical duct [3]. The Reynolds number is the ratio of the inertial forces to the viscous forces in the liquid flow, and it increases with flow rate.

$$\text{Reynolds Number} = \frac{\rho u_m D_h}{\mu} = \frac{u_m D_h}{\nu} \quad (1)$$

Where:
u_m - the average velocity of the oil at the winding pass inlet
D_h - the effective hydraulic diameter of the winding pass inlet
ρ - the oil density
μ - the dynamic viscosity of the oil
ν - the kinematic viscosity of the oil

With a relatively narrow vertical duct and a high flow rate, the oil flow effectively fails to make the turn from vertical flow to horizontal flow into the lowest duct of the pass, and the oil here can stagnate or even flow backwards as it is entrained in the vertical flow under the influence of the Bernoulli effect. This condition is illustrated in Fig. 5 and 6. This means that, contrary to the expectations of a simple thermal-hydraulic network model, as the oil is pumped faster, there comes the point where the hot-spot factor starts to increase as the flow slows and stops in the lowest horizontal ducts in the pass. The result of much experimentation and modelling is shown in Fig. 7, showing the relationship between the hot-spot factor and Reynolds number for the OD condition. This knowledge should make any designer or operator think very carefully before trying to increase the rating of a transformer by increasing the oil flow. In fact, unless a very detailed knowledge of the internal flow dynamics is obtained first, I would say never increase the pump capacity of a transformer on-site. When designing new transformers, it is hard to make a specific rule for a Reynolds number where further investigation is required, because it depends on winding geometry. However, a high number of discs per pass, a relatively small vertical duct width, and a Reynolds number over 500 at the pass inlet should be looked at carefully.

Low oil flow conditions

At low inlet oil flows, more representative of the natural convective oil flows between the transformer and the radiator when there is no oil pump, it is possible to get an effect called 'a hot streak'. This occurs when the oil flowing up the vertical duct is heated by the lower discs in the pass and increases velocity under the influence of buoyancy. As the oil heats, it expands, becomes less dense, and tends to rise. Although vital for naturally cooled transformers, in the extreme, this chimney effect can cause the oil in the top horizontal ducts in the pass to slow, stagnate and even reverse direction. This is illustrated in Fig. 8 and 9. The critical ratio here is the Richardson number, which is an indication of the relative importance of buoyancy to the inertial forces in the oil flow.

$$\text{Richardson Number} = \frac{g\beta_{\mathrm{T}}(T_{\mathrm{aw}} - (T_{\mathrm{to}} + T_{\mathrm{bo}})/2)D_{\mathrm{h}}}{u_{\mathrm{m}}^2} \qquad (2)$$

Where:
g - the acceleration due to gravity
T_{to} - the top oil temperature of the winding (in this case 3 passes)
T_{bo} - the bottom oil temperature of the winding
T_{aw} - the average winding temperature
β_T - the coefficient of thermal expansion of the oil

Note: The definitions of u_m, D_h, and the temperature difference (T_{aw}-(T_{to}+T_{bo})/2) are the ones used to derive the numbers in the figures, but the choice of definition needs careful consideration for other geometries and the critical values of Reynolds and Richardson numbers will depend both on the choice and the specific geometry.

If the correct parameters are chosen to calculate it (see reference [4] for the equations), at a Richardson number of one, buoyancy forces start to dominate the flow pattern within the pass. This is shown for a particular case in Fig. 10. It is interesting to note that at low Richardson numbers a hot-spot factor of less than one is possible if the temperature difference between the hot-spot and the top oil is less than the difference between the average winding and the average oil. The problem is getting even worse by having a very high number of discs in a pass, which is a temptation in order to reduce the overall hydraulic resistance of the winding. Evaluating the Richardson number over the range of operating conditions for a new design and, if it is approaching unity, making a special effort to model the heat transfer in detail considering buoyancy effects probably using CFD can help to spot problems. It is of special note that the position of the hot-spot and value of the hot-spot factor can change depending on the power level and ambient temperature.

As always with research, as some questions are answered and others appear.

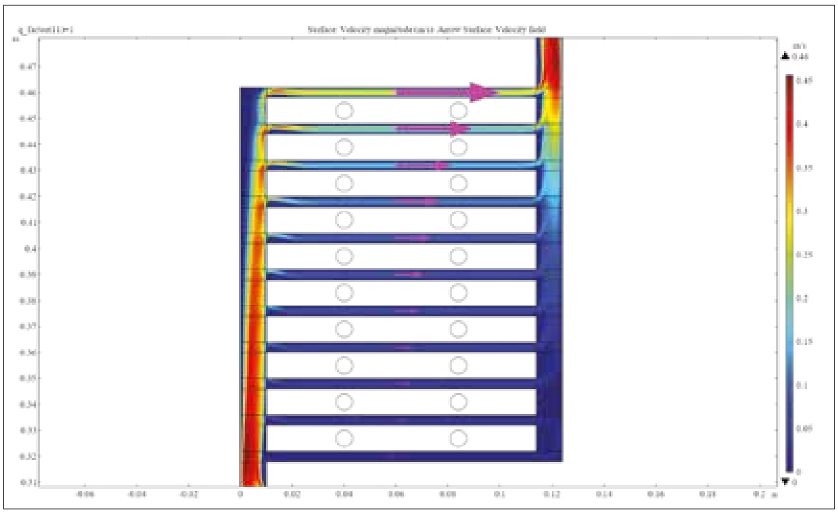


Figure 5. Oil flow velocity in the top pass of a winding model under OD conditions showing reverse flow in the lowest horizontal duct leading to poor cooling of the lowest disc, calculated using 2D CFD

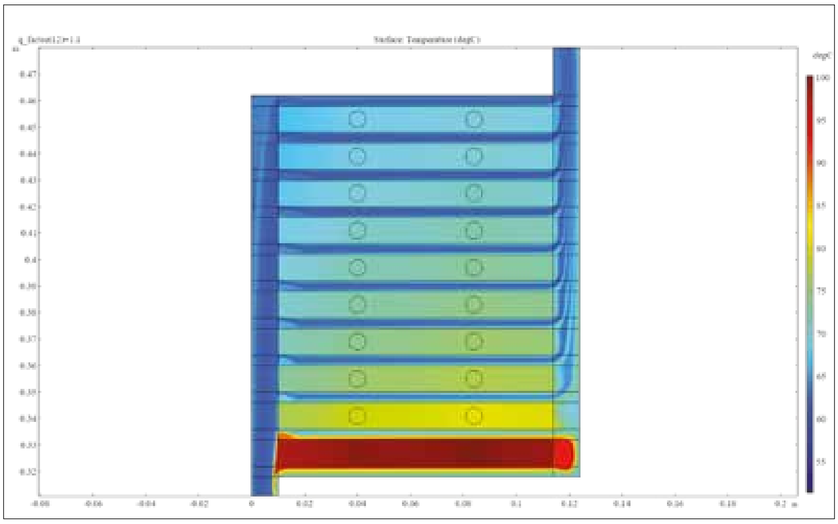


Figure 6. Illustration of the temperatures within the top pass of a winding calculated using CFD for the oil flows shown in Fig. 5

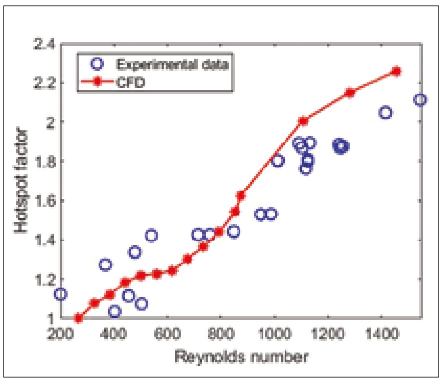


Figure 7. Hot-spot factor vs Reynolds number for the physical winding model (experimental results) and the CFD simulation of the model [3]

Underestimating the hot-spot temperature becasuse of poor thermal design calculations or using high cooler thermostat settings can reduce the lifetime of the transformer

The research effort is now being directed towards a rig and CFD modelling of the complete transformer cooling loop to better understand the interaction of the local flows within the pass to the overall flows between the windings and the cooler. This should help with predicting the effects of, for example, operation with more viscous liquids or at low ambient temperatures.

Conclusion

So what about the transformer with the lower than expected life introduced at the beginning? Although at first baffling, with the new understanding from the research, it can be concluded that, as is often the case, it was a combination of factors. The ON hot-spot factor was underestimated because, with a cooling circuit designed for pumps, the flows were lower than normal for an ON condition leading to overheating of the top discs when the cooler was off. This also delayed the cooler coming on. The OD hot-spot factor was underestimated because the design had been uprated with larger pumps, and this probably caused reverse flows at the bottom of the duct where the very degraded paper was found. This also caused the cooler to switch off too soon. The cooler 'on and off settings' were set higher than normal and, to finish it off, there was some copper sulphide deposition, probably also enhanced by the high temperatures. So, be careful about believing the results of any thermal model (including the WTI) until you have fully understood whether the model is working within the limits of its range of validity.

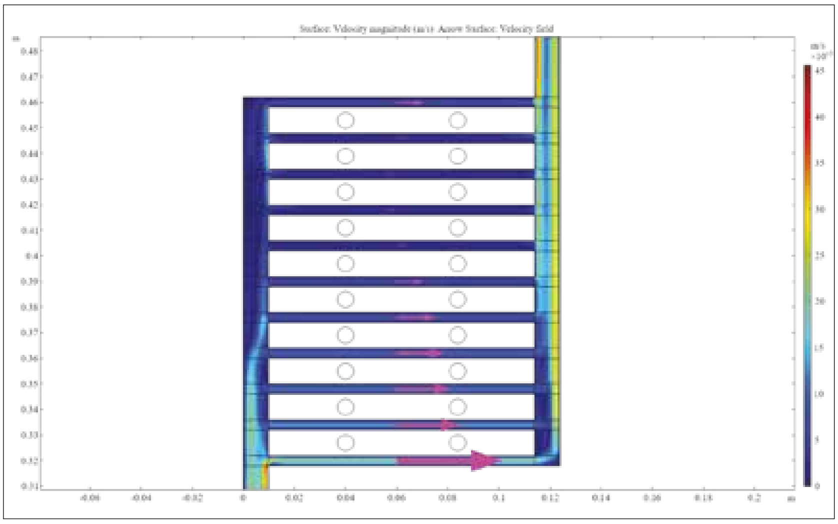


Figure 8. Oil flow velocity in the top pass of a winding model under ON conditions showing reverse flow in the upper ducts leading to poor cooling of the upper discs, calculated using 2D CFD [4]

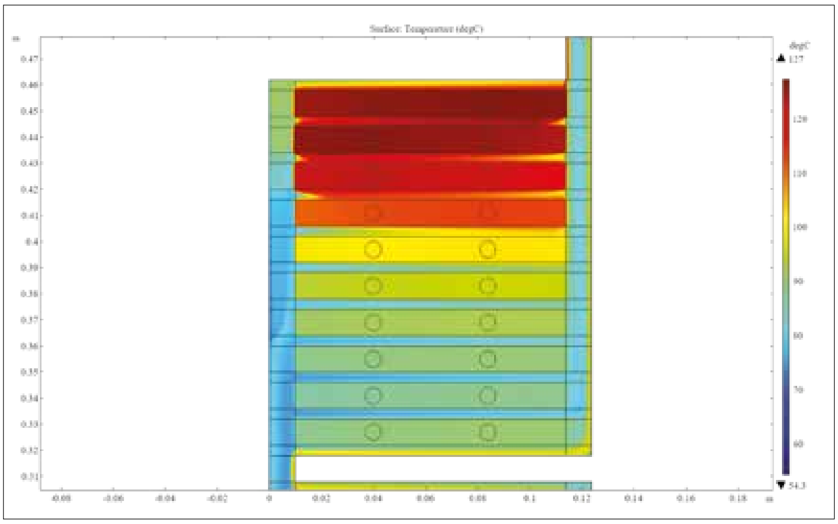


Figure 9. Illustration of the temperatures within the top pass of a winding model calculated using CFD for the oil flows shown in Fig. 8

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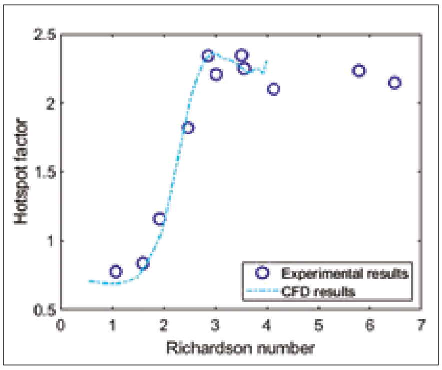

Figure 10. Hot-spot factor vs Richardson number for the physical winding model (experimental results) and the CFD simulation of the model [4]

work at Manchester is being carried out by Sicheng Zhao, under the supervision of Dr Qiang Liu. The University of Manchester transformer group is part of the University Transformer Research Alliance together with The University of Queensland, Tsinghua University, the University of Stuttgart and Xi'an Jiaotong University.

Bibliography

[1] D. Feng, Z. Wang, P. Jarman, *Evaluation of Power Transformers' Effective Hot-Spot Factors by Thermal Modeling of Scrapped Units*, Power Delivery, IEEE Transactions on, vol. 29, no. 5, pp. 2077-2085, 2014

[2] M. T. Ishak, Q. Zhong and Z. D. Wang, *Impact of Load Profiles, WTI Settings and Hot-spot Factors on Loss of Life of Dual Cooling Mode Transformers*, Proceedings of the 16th International Symposium on High Voltage Engineering, Cape Town, 2009

[3] M. Daghrah, X. Zhang, Z. D. Wang, Q. Liu, P. Jarman, D. Walker, *Flow and Temperature Distributions in a Disc Type Winding-Part I: Forced and Directed Cooling Modes*, Applied Thermal Engineering, vol. 165, pp. 114653, 2020

[4] X. Zhang, M. Daghrah, Z. D. Wang, Q. Liu, *Flow and Temperature Distributions in a Disc Type Winding-Part II: Natural Cooling Modes*, Applied Thermal Engineering, vol. 165, pp. 114616, 2020.

[5] S. Tenbohlen et al., *Investigation of Thermal Behaviour of an Oil-Directed Cooled Transformer Winding*, IEEE Transactions on Power Delivery 33.3: 1091–1098, 2018

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