It is important to have effective methods to assess the serviceability of a transformer after key events in its life. This may be after transport to site, after closing onto a fault, or after a protection trip.

Internal inspection often reveals little about the winding condition and the decision to re-energise or scrap has to be done relying on having effective and reliable diagnostics. This practical paper gives examples for the effective use of transformer diagnostics, assessing the dielectrics and thermal and mechanical condition of the transformer.

Infrastructure development has not kept pace with load growth. This leads to T&D systems carrying more load than originally intended, overstressing critical components. Knowledge of equipment condition is critical to allowing this load to be carried safely and economically. Increasing risk means that we need a better understanding of the capability of assets – in the case of this paper we concentrate particularly on transformers.

Without a clear understanding of transformer health we may take unnecessary risks and the consequences may be severe – in terms of reliability, cost and, most important, safety. Much of the present power system was installed through the 1950s to 1970s. The equipment was built on manufacturing knowledge and techniques available at the time, and is now coming towards the end of its ‘design’ life. It was designed for a peak load of no more than 70 - 80% of installed capacity, whereas the load is approaching or exceeding 100% of capacity in many cases. California, Chicago and Auckland New Zealand being cases where severe power outages resulted.

System operators are being asked to do more and more with the same infrastructure and it is up to plant engineers to allow them to do so when possible. Occasionally the engineer has to arrange to do more with less just so as to keep the lights on.

So it is becoming more and more incumbent upon plant engineers to understand the health and capabilities of key assets – and in particular, transformers. Only then can risks relating to the system be reduced. Consequently, any activity relating to transformers which helps provide information about the transformer must be seen as part of a knowledge gathering process to manage risk.

Routine maintenance is a basic but key part of the process – providing early alerts as to ‘anomalous’ behavior or possible asset health risks. Routine maintenance is the broadband, broad focus loop of condition assessment, providing a general indication as to transformer viability. Routine dissolved gas analysis (DGA) and regular Doble (Power Factor) testing are two of the most commonly used such techniques.

When further data is required narrower focus techniques such as sweep frequency response analysis (SFRA) are more appropriate. These provide far more detail and are the second, detailed, loop.

Inevitably it is economics which govern those most undervalued of resources available to the engineer, time and attention. With fewer engineers to work on more and more equipment with less and less support it is critically important to focus on both important and urgent matters.

Making the best possible decision relating to a transformer with little impact on system reliability will probably not be as important as making a quick decision about transformer viability in a critical position. Decision making becomes a balance between the ‘necessary’ and the ‘sufficient’ – and the data needed to support decisions with minimum uncertainty is critical to the engineer.

**Fig. 1: Power factor results**

<table>
<thead>
<tr>
<th>Insulation</th>
<th>A phase</th>
<th>B phase</th>
<th>C phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>HV to earth</td>
<td>4,155 pF</td>
<td>3,945 pF</td>
<td>4,173 pF</td>
</tr>
<tr>
<td></td>
<td>0.57%</td>
<td>0.89%</td>
<td>0.60%</td>
</tr>
<tr>
<td>HV</td>
<td>13,018 pF</td>
<td>1,00%</td>
<td></td>
</tr>
<tr>
<td>phase to phase</td>
<td>185 pF</td>
<td>200 pF</td>
<td>0.7%</td>
</tr>
<tr>
<td></td>
<td>0.07%</td>
<td>0.17%</td>
<td></td>
</tr>
<tr>
<td>HV to LV</td>
<td>3,736 pF</td>
<td>3,730 pF</td>
<td>3,699 pF</td>
</tr>
<tr>
<td></td>
<td>0.35%</td>
<td>0.43%</td>
<td>0.34%</td>
</tr>
<tr>
<td>LV to earth</td>
<td>11,164 pF</td>
<td>0.49%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.38%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Fig. 2: Ultrasonic location**

Data from testing should not be gathered for its own sake – we gather data to support a decision. The better the data, the better the decision should be. It is an economic decision to invest in collecting data which is both necessary and sufficient to make a key decision. But decisions are rarely clear and there is a degree of uncertainty related to each – is it safe? Is it good enough to be used as a spare? Is it likely to fail in the next few weeks? Gathering appropriate data reduces uncertainty, and we should gather enough data to reduce the uncertainty to an acceptable level – a risk management procedure.

Data must also be collected on a timely basis – that is to say, it must be available when needed rather than ‘just too late’. In real life decisions relating to transformers may not be clear cut, they may be rushed, information may be incomplete. Reduction of uncertainty is key to efficient and economical decision making.
The role of transformer testing

The first question when assessing the health of a transformer relates to context, why are we performing any tests in the first place? A transformer which has tripped out of service must be treated with more caution than one which is taken out for routine maintenance.

The same test results may be given different significance in each case. Tools available for assessing transformer health are both complementary and overlapping.

Generally, a transformer has three broad areas where testing can provide information – dielectric, thermal and mechanical.

Dielectric problems relate to dielectric strength of insulating materials. These may be degraded for a number of reasons, worn insulation through vibration, moisture ingress, paper ageing. Dielectric problems mean that nominal voltage may not be applied to the transformer safely and the transformer can no longer perform its required task.

Mechanical problems relate to damage on windings resulting from transportation or severe electrical faults. Damage to windings does not necessarily mean that the transformer is not serviceable, it does mean that the basic structure of the transformer could be weakened and the transformer is less likely to withstand another fault. The transformer may be bent, but not broken. The decision in this case is whether it should be returned to service, whether on line monitoring should be applied and under what conditions and restrictions it must be placed with respect to loading.

Thermal problems may be as a result of a mechanical displacement or a dielectric problem within the transformer, inappropriate or poor cooling regimes, or may be related to design. The transformer may be able to perform at nominal voltage and current, but overheat due to poor heat dissipation leading to premature thermal ageing and increased likelihood of early failure.

These three issues cover most situations, however, due to the nature of transformer incidents, the three situations are often confused. In this paper we concentrate on the main transformer windings rather than the accessories – bushings, coolers, pumps and tap changers, though these may also cause transformer failures and reduced capability.

Test methods

In condition assessment of transformers it is common to follow a simple double-loop approach – making use of broadband, broad focus techniques on a routine basis and narrow focus techniques as a means for further investigation or to gain more details.

Common routine tests should include DGA and Doble testing (power factor testing) so as to give an overall indication of health. It is valuable to include a cursory visual and auditory inspection. Does the transformer look and sound ‘OK’. Several severe incidents have been identified and possibly catastrophic situations averted when alert site staff have noted transformers which did not sound right.

More detailed testing may include DC winding resistance, transformer turns ratio (TTR), exciting currents, partial discharge detection and so on.

Increasingly owners and operators of transformers are relying on frequency response analysis (FRA) to provide crucial data relating to transformer mechanical condition [2, 3]. The technique is decades old and problems of repeatability in results have lead to uncertainty. It is only now with the successful use of a sweep frequency approach that robust results have been produced. Sweep frequency response Analysis (SFRA) is now the de facto standard for FRA as this is the only way to guarantee the three R’s of FRA testing: range, resolution and repeatability.

Case studies

In this paper it is assumed that power factor and SFRA techniques are available to transformer engineers. SFRA testing techniques – open and short circuit testing, variation with tap position, inter-winding tests are described in more detail on the SFRA resource center on the Doble website (www.doble.com).

The case studies here illustrate the added value which diagnostics provide by reducing the uncertainty in decisions made relating to transformers.

Case 1: Dielectric breakdown

A 35 year-old 100 MVA 275/33 kV autotransformer tripped on Buchholz during a thunderstorm where there was a lightning strike at the adjacent substation. It was from a series with a good service history and previous DGAs had not indicated any problems.

The three phase Doble test indicated a dielectric problem. The phases were then split in the diverter (located at the neutral end. These (Fig. 1) clearly show a problem with phase B.

Question – could the transformer be repaired on site?

This transformer was then tested using back energisation by means of a mobile generator and transformer. Ultrasonic location using contact transducers on the tank indicated the site of the problem to be at the top of the winding on B phase (Fig. 2).

Internal inspection was undertaken and the site of a breakdown located at the connection to the winding. With due regard to the age of the unit and the extent of the damage a decision was made to scrap the unit.
In this case diagnostics had confirmed the presence and location of the fault, allowing an effective engineering judgment to be made.

**Case 2: Thermal issues with mobile substations**

Two 28 MVA mobile substations were used to provide reserve capacity and replacement capability in case of the loss of a regular substation. One of the substation transformers started to show signs of thermal problems – increased DGA levels for methane, ethane and ethylene. A decision was taken to perform an internal inspection which this revealed metal filings on windings, worn bolts associated with the tap changer and the whole tap changer assembly being loose.

SFRA testing showed anomalies on two windings using both open circuit and short circuit tests. These were the two outer phases and the variation was found to relate to compressive failure (hoop buckling) on both of the windings. This knowledge was applied to the next transformer, where SFRA revealed the same symptoms on just one winding (Fig. 3). Other test results were acceptable.

**Question – should the transformer be returned to service to provide support to the system during high load periods?**

Given the acceptability of other results, and the indication from SFRA that the compressive failure was the only problem, a decision was made that the transformer could be returned to service. However, there would be an increased risk of failure if the unit was subjected to a large fault because the winding was already somewhat compromised. Given the state of the compressed winding it would be sensible to provide a risk/safety zone around the transformer when it was in service and refurbish the unit when conditions allowed.

Six months later the unit was taken to a repair shop and dismantled. The compressive failure on one winding was revealed (Fig. 4) and the winding rewound.

In this case SFRA allowed a suspect transformer to be tested, diagnosed and subsequently remain in service to provide system support through a critical time.

**Case 3: Dielectric concerns – SFRA on a new transformer**

A new 50 MVA transformer gave suspicious Doble test results during commissioning – the low side windings had a power factor approaching 0.8 after factory values had been acceptable.

**Question – had anything moved within the transformer during shipment which could have contributed to the suspect power factor, or was this related solely to dielectric condition?**

SFRA was used to test the transformer. Open and short circuit tests were done which provided a wealth of information relating to the mechanical condition of the windings. Results between phases were very consistent and indicated that it was unlikely that anything had moved within the transformer (Fig. 5).

In this case the tests showed that shipping impact resulting in mechanical damage was unlikely to be a cause of the elevated power factor. The transformer was returned to the factory for a repeat dry out procedure. This lowered the power factor to an acceptable level and the unit was then returned to site for service.

**Case 4: Rapid diagnosis of a shorted turn**

A transformer tripped out of service at the same time as a nearby surge arrester failed. It was not known whether the transformer failed, leading to a power surge which destroyed the arrester,
or whether the arrester failed leading to the transformer trip. A rapid test was needed to provide information on the viability of the transformer.

SFRA was used to test the three phases and showed two things, a shorted turn existed on one phase and there had been some severe winding movement.

Questions – should the transformer be subject to further testing to identify viability of the unit, and should it be marked down for repair?

The SFRA results showed that not only was there a severe problem (Fig. 6) but it was unlikely that the unit could be fixed quickly, if at all.

The economics of rewind versus scrapping were tilted toward scrapping as there was seen to be substantial winding movement on a 30 year old transformer. It was possible that the rest of the infrastructure within the unit had been compromised – the risk to future viability was too great.

In this case SFRA provided rapid and clear data regarding the nature and severity of a fault on a large power transformer. The data were used to make a rapid decision as regards transformer viability, and fed in to the process of capital planning with the decision to scrap the unit.

Case 5: Making best use of data

SFRA is a test which relates to mechanical damage. It can also give an indication when, although the transformer windings have no significant mechanical problems, there may be other problems and appropriate testing is called for.

In this case a distribution transformer had seen a number of nearby line faults in the previous year. DGA levels were rising and there was elevated moisture in oil levels. Routine testing did not indicate any other problems.

Question – had the transformer suffered a fault which damaged the windings and lead to increased DGA levels?

SFRA testing gave, overall, a null result, there were no reference results available but there was no significant indication of winding movement and/or distortion (Fig. 7). Variations found between phases readings were consistent with expectations and previous results from similar transformers. However, close inspection of the short circuit readings at low frequency indicated a variation in resistance between the three phases, with one having a substantially higher resistance than the other two (Fig. 8).

SFRA is not designed to provide a DC resistance value, but the short circuit measurement may be used to indicate what that value is and that a true DC winding resistance measurement should be made.

In this case SFRA testing of the transformer showed no indication of winding movement and/or distortion.

However, SFRA testing indicated a resistance variation which was suspect. A DC resistance set was obtained and the transformer tested. A high DC resistance was confirmed on one phase and the DETC was suspect. On internal inspection substantial coking of the DETC contacts was found and repaired.

Conclusions

Technical decisions relating to transformers require both necessary and sufficient data – a balance which allows for optimum decision making with the minimum of input data. SFRA is developing as a common tool for engineers to support decisions. When performed correctly it provides clear and useful data relating to mechanical condition of transformers. Used in conjunction with other standard electrical tests, SFRA provides data which cannot be determined in any other way. Repeatable measurements provided by systems such as the Doble M5200 allow for reduced uncertainty in decision making and reduced risk in managing critical transformer assets.

Acknowledgements

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[1] For example: www.ferc.gov/industries/infrastructure/01-31-02.pps

[2] "The need for and Use of Techniques to Assess the Mechanical Integrity of Transformer Windings" Dr. A. Wilson & Dr. A. McGrail, 2002 International Doble Client Conference, Boston, USA


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