LEARNING FROM FAILURES IN RISK-BASED TRANSFORMER ASSET MANAGEMENT

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Abstract: Transformer failures are negative events that should be avoided at all costs. From the perspective of utility learning, however, failing early and responding to failures are essential steps in transformer asset risk assessment and risk management. Simply experiencing a transformer failure is not sufficient for utility learning. This paper discusses the common causes and modes of failures observed in the scrapped power transformers, and also describes four case examples, showing that transformer teardowns enable any design error or weakness developed over time in service to be uncovered; and knowledge from forensic investigation of faults and failures in transformers not only enable the results from the dissolved gas analysis and electrical condition assessment measurements to be understood correctly, but also provide unique insight into likely end-of-life scenarios for the increasing population of ageing power transformers and therefore offer significant financial and reliability benefits. It is concluded that there is a need to create a culture in which transformer teardown inspection should be every utility's policy and develop an effective learning strategy to verify, validate and enhance transformer asset risk assessments based on learning from any experienced incidents and failures which would help in-depth understanding of transformer end-of-life scenarios and therefore preventing or minimising unexpected incidents and failures.

1 INTRODUCTION

Transformers are normally very reliable and durable HV equipments, but when faults occur they can lead to catastrophically failures, often resulting in the loss of what is the most expensive plant item in a substation. Furthermore, ageing transformer fleet poses considerably increasing risk to network performance and security of electricity power supply and may lead to system outage [1].

While conventional wisdom suggests that transformer failures are negative events that should be avoided at all costs, the authors would suggest that failing early and responding to failure are essential steps in transformer asset risk assessment and risk management. From the perspective of utility learning, it is vital to use root-cause analysis of failures and incidents as a source for learning, and an effective learning strategy to verify, validate and enhance risk assessments based on learning from any experienced incidents and failures would help in-depth understanding of end-of-life scenarios for the increasing population of ageing and deteriorating transformers and anticipating future problems [2-4].

The only means available to precisely determine the ageing state of a given transformer is by what is commonly referred to as a "teardown inspection" of that transformer [5-8]. This paper discusses the common causes and modes of failures observed in the scrapped transformers; describes four case studies with aim to show how transformer teardowns enable any design error/weakness developed over time in service to be uncovered, and also provide unique insight into likely end-of-life scenarios for the increasing population of ageing transformers and therefore offer significant financial and reliability benefits.

2 WHY TRANSFORMERS FAIL

2.1 Cause of failure

In general, transformer failure occurs when a component/structure is no longer able to withstand the stresses imposed on it during service. During the course of its life, the transformer has been suffering the impact of thermal, mechanical and electromagnetic stresses during normal and transient loading conditions. The condition of the transformer deteriorates gradually right from the very beginning, resulting in

(1) Reduction in dielectric strength (ability to withstand lightening and switching impulses);
(2) Reduction in mechanical strength (ability to withstand any through faults);
(3) Reduction in thermal integrity of the current carrying circuit (ability to withstand overloads);
(4) Reduction in electromagnetic integrity (ability to transfer electromagnetic energy at specified conditions including overloading).

A failure ultimately occurs when the withstand strength with respect to one of the above key properties is exceeded by operating stresses.

From our records and case historical data, failures are commonly associated with localised stress concentrations (faults), which can occur for several reasons including [8]:

(1) Design and manufacture weakness, e.g. poor design of conductor sizing and transpositions, poor joints, poor stress shield and shunts, poor design of clamping, inadequate local cooling, high leakage flux, poor workmanship, etc.;
(2) The microstructure of the material utilised may be defective right from the start, e.g. containing micro-voids, micro-cracks etc.;
(3) Corrosive attack of the material, e.g. sulphur corrosion on paper and conductor can also generate a local stress concentration.

Weakness in transformer design, construction and materials could be covered by low loading. Increasing loading and extended period of in-service will recover these weaknesses.

2.2 Common failure modes

Failure modes of transformers are not always straightforward. Most of the transformer failures could be classified into either one or a combination of more than one of the following three modes:

(1) Breakdown of insulation as a whole, due to severe solid insulation ageing;
(2) Breakdown of insulation by part, due to premature ageing via localised overheating;
(3) Mechanical failure of windings.

Common among many of the transformer failure modes is a shorted turn. The shorted turn was developed as a result of breakdown of the solid insulation which causes winding temperature shoot-up. The breakdown of solid insulation could be due to natural wear of insulation or repeated overloading or cooling system deficiency, which often result in severe ageing of winding insulation. This type of failure (shorted turns without any prior warning or obvious system cause) is a typical ‘end of life’ failure mode. If the transformer runs abnormally hot and/or develops less than its normal out voltage, one can safely assume the possibility of shorted turns.

Electrical breakdown is also a common failure mode for transformers. The electrical breakdown could be developed by a number of reasons such as ageing of insulation, excessive moisture, deformed windings etc. Moisture reduces the dielectric strength of insulation and can promote the occurrence of surface creeping discharges on the pressboard barriers and lead to a flashover. Deformed windings indicate not only a high level of force that may have broken or abraded the winding conductor insulation, but also a reduction in electrical clearance. This mechanical failure of windings will then manifest itself as an electrical breakdown to lead a failure of transformer.

Poor design and overheating are very much interrelated and make for high failure modes. In the bottom end, lack of cooling causes either general or localised high temperature overheating, resulting in rapid insulation deterioration and damage progression. Breakdown of insulation between the core and main tank may lead to circulating currents in the core/frame/tank and result in local overheating. Circulating current in the tank can produce hotspots in the tank and across gasket joints, resulting in partial discharges emanation from the ground potential surfaces of the tank and parts mounted on the tank.

Note local overheating in current carrying circuit, if not extremely severe, often will not itself cause direct failure of the transformer, but will reduce the mechanical strength of the insulation so that when the transformer is subjected to a system fault close to the terminals, it will then fail. Similar is true for that of winding movement.

Poor design and loose clamping are very much interrelated and make for high failure modes, too. The most known design problem with loose clamps is arcing/sparking fault at the loose clamping bolts, which compromises the mechanical strength of the transformer and makes diagnosis of dielectric faults using DGA difficult. The arcing/sparking discharges also lead to deterioration of the oil and the production of fine carbon, which compromises the dielectric integrity of the transformer.

3 WHY TRANSFORMER TEARDOWNS

Transformer teardowns provide a unique opportunity that enables the asset managers to [6]:

(1) Easily understand the transformer
(2) Easily see what’s inside
(3) Obtain specific information about the design and construction in details
(4) Observe the condition of every parts
(5) Uncover the weakness developed in service
(6) Identify the root cause if it is a failure

As part of the transformer Asset Health Review and life extension program, over the years Doble PowerTest in the UK have records of detailed teardown inspection of more than hundred large power transformers, and have developed a systematic approach to forensic examinations so that during a transformer teardown all the information available is gathered and that not only the point of failure is investigated [5]. Knowledge of the causes of transformer in service failures, together with condition assessments made during teardowns of transformers removed due to high risk exposures, have given significant insight into modes of deterioration/failure in particular design groups. This has been translated firstly into a diagnostic strategy for assessing the condition of power transformers nearing the end of their life and then integrated into asset health and asset risk reviews and finally utilized in aged transformer replacement planning [2-4, 9].

4 LEARNING FROM FAILURES

4.1 Case study one

This case example concerns a 400/275kV 750MVA transformer. It tripped on Buchholz after 30 years in service. Analysis of a subsequent DGA sample clearly indicated a major fault in main tank. Electrical testing results confirmed fault in the middle series winding, which was unlikely to be economically repairable.

During the scrapping, the shorted turns in the 2nd and 3rd discs of series winding was found as shown in Figure 1. There was extensive loss of conductor and conductor insulation in the upper part of the series winding. The worst degree of polymerisation (DP) measurement obtained was approx 144 from the middle strand of top disc of the middle phase series winding. The next worst result was approx 156 from the middle strand of top disc of A/red phase series winding. The DP results on paper samples showed that apparently the insulation condition of the series winding had reached the end of its life.

The learning point from this case study is that the short turn was developed as a result of severe winding conductor insulation ageing which was partly a function of the age of the transformer and the loading to which it had been subjected. The poor thermal design of the series winding, however, led to localised overheating of certain areas, including the point of failure.

Figure 1 Failure of transformer by shorted turns

4.2 Case study two

This case concerns a 16/275kV 160MVA generator transformer, which was built in 1960 for the UK's first major pumped storage power facility. It was decommissioned after 44 years in-service.

During the scrapping, visual examination revealed severe paper ageing on the LV winding. As shown in Figure 2, some of the LV winding close to the top end had paper which was dark brown in colour and appeared to have experienced severe overheating. The worst DP result was approx 185 which confirmed that the insulation of the LV winding had reached the end of its life.

The learning point from this teardown investigation was the discovery of the well-developed winding hotspots which is typical end-of-life scenario. The transformer although did not fail when it was decommissioned would have been at increased risk of failure from switching impulses and short circuits if was returned back to service.

Figure 2 Developed hotspots on LV winding

4.3 Case study three

This case concerns a 275/132kV 180MVA transformer which had been scrapped after 34 years in service. It was believed to be significantly in risk of failure from thermal fault after having received two Buchholz alarms within one year.

The first Buchholz alarm was received at the end of April 1995 during an attempt to load the 13kV 60MVA tertiary. The transformer was switched out of service for investigation. The only indication of a problem from electrical tests was a slightly higher resistance for the C phase LV winding. The oil was then removed from the transformer and an internal inspection carried out, but no fault was found. The transformer was returned to service with additional online monitoring. The second Buchholz alarm was received in November 1995 when the tertiary was next loaded. This time electrical tests indicated not only a developed C phase LV winding fault but also a deteriorated main winding to tertiary insulation on the C phase. The transformer was returned to service with tertiary loading prohibited.

After the return to service this transformer subsequently survived high loading in January 1996 without obvious signs of fault deterioration. But in April/May there were signs of increased gassing in the main tank, and the transformer was removed from service permanently. The subsequent teardown inspection revealed the cause of the two incidents. As shown in Figure 3, the inter-strand insulation at a transposition joint at the midpoint of the innermost LV winding was badly damaged and it would have been impractical to repair the transformer at site.

So when did this thermal fault start? Figure 4 shows the abnormal DGA signature, indicating that the developing thermal fault should have been identified between 1991 and 1994 (i.e. years before the first Buchholz alarm at the end of April 1995) and unit put on a risk list for investigation and life management.

In summary, this case example illustrates that little paper ageing does not necessarily mean little risk of failure of a transformer. While no furans could be found, a developing thermal winding fault could be diagnosed by electrical tests, and the process of thermal fault development could be identified much earlier from an effective DGA analysis technique, and in such a way it becomes possible to differentiate normal and abnormal transformers for risk assignment and allow asset health to be identified and managed. This experience had led to development of a DGA scoring system for distinguishing abnormal from normal results [10].

Figure 3 LV winding fault caused by overheating

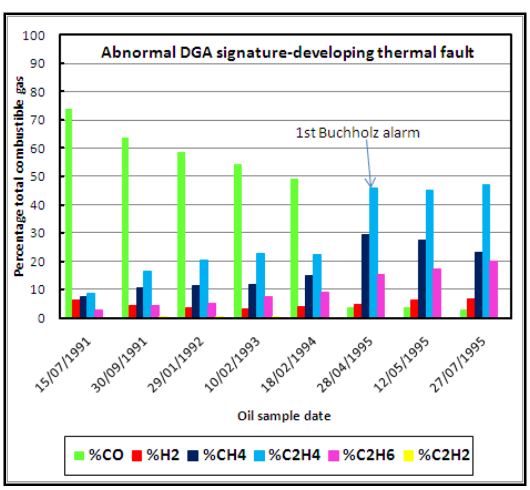

Figure 4 Abnormal DGA signatures

4.4 Case study four

This is a particular population of ten 275/33kV transformers, which were manufactured between 1968 and 1975 and were intended to supply heavy industry, especially steel works. Looking historically, two members of this family failed early in their lives. Details of the failures are limited but suggest winding movement owing to a through-fault in at least one case. Both failed transformers were rebuilt to the original design.

In 2001 a member of this population which was used to supply a steel works with arc melting furnaces failed suddenly. Electrical testing after failure showed signs of short-circuited turns. It is believed that the repeated impact loading from supplying the arc furnaces caused the winding clamping to loosen, allowing localised LV winding movement, fretting, loss of conductor insulation and eventually turn-to-turn failure. The failed transformer was replaced by another of the same design, which failed itself after approximately one years' service at its new location. Investigations showed that the second failure was very similar to the first, as shown in Figure 5 (up).

The two recent failures, and the two earlier failures, highlighted both weakness with the design of this population of transformers and weaknesses with the asset management of the population.

In 2005 winding frequency response (FRA) measurements in two sister units clearly indicated winding movement to the LV windings. Family history and information from site staff suggested that the mechanical damage to the LV windings was sustained whilst supplying a steelworks with arc furnaces. Winding resistance measurements indicated that the mechanical damage had not resulted in localised conductor erosion in the LV windings. The two sister transformers were then classed as AHI 1 in 2005 in the transformer Asset Health Review.

When they were removed from service in 2010 as a planned replacement after 40 years in service and after they had suffered suspected LV winding movement for 5 years, a detailed teardown examination of the windings revealed evidence of mechanical damage to the LV windings, including broken conductor insulation in the upper part of R and B phases, as shown in Figure 5 (down). These findings confirmed that the condition assessment, in particular the interpretation of abnormal winding frequency response measurements in 2005, was correct and the transformer was indeed approaching the end of its life.

From the teardown inspection, it was noted that three design weaknesses that may have made the transformer more prone to mechanical damage to the LV windings. These were inadequate placing of vertical spacers, inadequate mechanical stability and undesirable clamping arrangement.

The learning point from this case study is that a transformer feeding a steel works and seeing many LV short-circuits would be at greater risk if known to be in a family with a poor mechanical strength. When the transformer asset health review is performed, consideration of the impact of the operational environment in driving failures at known weakness points is of vital importance.

Figure 5 Understanding the implication of increasing risk of failure: LV winding failure in 2002 (up) and LV winding mechanical damage found in sister unit in April 2010 (down)

5 MANAGING THE RISK OF FAILURE BY TRANSFORMER ASSET HEALTH REVIEW

Forensic teardown investigations have shown that transformers can fail in a variety of ways and for a variety of reasons, including design weakness, abnormal system conditions, aged conditions, pre-existing faults and timescales for fault development. There is little hope for statistical risk models that rely on historical failure data to capture such complicated effects. To come up with useful assessments of risk, then transformer asset managers must look at longer horizons and take a comprehensive view of their risks. This involves using information from a wide range of sources, including oil tests, on-line and off-line condition assessment tests and visual inspections; and knowledge of transformer designs and of their strengths and weaknesses is essential to understanding the other information [11, 12].

Over the years Doble PowerTest and National Grid have together created a framework of transformer asset health/risk review to streamline and improve the evaluation of the condition of transformers in order to support transformer asset management and risk-based resource allocation. The purpose of transformer asset health review is to [9]:

(1) Consolidate all sources of transformer asset information into an integrated view of asset health
(2) Assess the condition and performance of each individual transformer
(3) Identify issues, risks and opportunities
(4) Identify short to medium term priorities for transformer replacement planning
(5) Predict long-term transformer replacement volumes
(6) Trend evolution in transformer condition and replacement volumes
(7) Generate timely report for ongoing management attention
(8) Determine effectiveness of maintenance activities and optimise where appropriate
(9) Carry out gap analysis between strategic spares holding and requirements

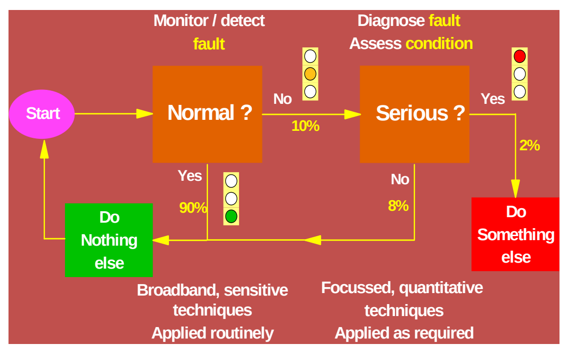

Figure 6 Transformer asset health review methodology

There is no standard procedure but the main philosophy in developing the transformer asset health review methodology is to utilise accurate and sufficiently detailed asset information to identify when and where risks and opportunities exist through a dynamic process of asset health reviews, as illustrated in Figure 6.

The ongoing transformer asset health review and asset risk review practice allows a scoring of the aged transformer population in terms of technical condition and presence of fault. Using evidence from teardowns and a knowledge of past and future operating regimes it should be possible to estimate transformer life expectancy and opportunities to overload. It will also indicate faulted transformers and these need to be life-managed and early replaced. The useful lives of ageing power transformers can therefore be extended with manageable reliability risk through a dynamic process of transformer asset health review, if effective diagnostic techniques can be combined with a comprehensive database to build up a capability to detect faults and differentiate normal and abnormal assets much earlier before failure. The results of the asset health review enable the asset manager to make more informed judgements in balancing the requirements of an investment plan.

6 CONCLUSION

The key to achieving a successful risk assessment and management relies upon having a in-depth understanding of the performance of the design groups, past and future operating conditions, an effective analysis process and the use of effective instrumentation capable of giving accurate and repeatable results independent of operators and electrical interference levels on different sites.

Forensic teardown investigations of failed or redundant transformers have enabled the condition assessment of critical components that would not normally be addressed during routine maintenance because of their inaccessibility.

Experience of Doble PowerTest is that so far learnt, most transformer failures are not old age, but localised damage or ageing due to some limitations in design and manufacture, application and maintenance. Sometimes a power transformer does fail without any warning notice. In most cases, however, the symptoms of developing fault and failure can be detected, prevented or eliminated. When transformer design error and/or weakness developed over time in service are uncovered, enhanced monitoring/investigation on sister units built by same manufacturer will help in preventing future failures and therefore managing the risk of unexpected failure.

There is a need to create a culture in which transformer tear down should be every utility's policy and to develop an effective learning strategy to verify, validate and enhance transformer asset risk assessments based on learning from any experienced incidents and failures which would help in-depth understanding of transformer end-of-life scenarios and therefore preventing or minimising unexpected incidents and failures.

7 ACKNOWLEDGMENTS

The authors wish to acknowledge and thank the support of National Grid. This paper is published with the permission of Doble PowerTest Ltd.

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