Power Transformer Condition Monitoring and Life-Cycle Management

Experience from a Detailed Case Study

By

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Abstract

This technical article addresses how we meet the challenges in a real case and introduce experience learnt from a detailed study in implementing various measurement and diagnostic approaches to “look after” a 750MVA power transformer. The story started from a low-voltage cable through fault and the online partial discharge (PD) monitoring on GIS showing PD activity. Subsequently, acoustic PD analysis identified that issue was not with the GIS but the 750MVA transformer. In the meanwhile, the dissolved gas analysis (DGA) results in main tank showed increasing acetylene. The decision was then made to carry out offline condition assessment, as this transformer has known a design weakness with loose clamping. Sweep frequency response analysis (SFRA) carried out confirmed no winding movement and therefore an internal inspection and re-tightening of clamping were carried out. After oil processing, a UHF PD survey was carried out to confirm that the unit was PD free and the final decision was then made to return the transformer back in service, accompanied with enhanced DGA as well as online GIS PD monitoring. This is a detailed case study that illustrates where online monitoring triggered further offline assessment which led to the transformer being repaired and further online monitoring applied to determine the effectiveness of the repair. Utilising these life-cycle maintenance experiences and techniques allows utility transformer asset engineers to manage the risk of unplanned failure and discount the need for replacement.

Introduction

Condition monitoring and life cycle management of power transformers have received considerable attention in recent years [1-6]. Many monitoring techniques have been developed for power transformers, especially for partial discharge fault detection and localization [7-12]. The driving force behind the effort to develop and implement advanced monitoring technologies has been the vital need in helping manage the risk of unplanned failures of power transformers. This is because the average age of the in-service power transformer fleet has been increasing and has exceeded their nominal design lives even though it is believed that many are in reasonably good working condition but their condition and ability to carry peak loads are usually unknown. On the other hand, there is an increasing need for utilities to take their power transformers to the limit while maintaining system reliability.

The successful utilities implement condition monitoring as part of a reliability driven maintenance strategy that maximizes the performance of large power transformers at the lowest life-cycle cost, optimising power transformer replacement strategy and eliminating or reducing catastrophic failures. From an engineering perspective, however, implementing condition monitoring is not straightforward but critical. Despite numerous studies and many publications on the subject, there have been difficult challenges on deciding ***when to*** utilise condition monitoring on a power transformer and ***how*** to use condition monitoring to its potential for early fault detection.

This technical article aims to address how we meet the challenges in a real case and introduce experience learnt from a detailed case study in implementing various measurement and diagnostic approaches to "look after" a fault-specific power transformer.

Experience from a Detailed Case Study

Background

In late 2008, a 28 year old 750MVA 400/275kV autotransformer experienced a LV cable through fault on the attached circuit. The same LV cable fault might well have contributed to the subsequent failure of the Quad Booster on the other side of the 275kV substation on the 25th of December 2008, too. Almost at the same time the online GIS PD monitoring system had seen an increase in PD activity on the GIS zone connected to this transformer. This raised considerable concern on the condition of the transformer and therefore enhanced oil sampling was first recommended to check if there was any indication of possibly developing fault inside the transformer.

Step 1: Enhanced DGA Sampling

The oil results in January 2009, as shown in the graphical form in Figure 1, showed a significant increase in acetylene to 26 ppm from trace (<1ppm), and the follow-up sample not only confirmed the high level of acetylene but also showed a further increase to 30 ppm within two weeks. The rise in acetylene was accompanied by an increase in hydrogen and rather more modest increases in levels of the other hydrocarbon gases. Such a DGA signature is typical of an arcing/sparking fault in the main tank of a power transformer. It was then decided to carry out a PD survey to confirm the critical transformer.

Step 2: Acoustic PD survey

Partial Discharges were seen across all three phases at the coupling point, located on the HV side of the transformer, as shown from Figure 2 (red), Figure 3 (yellow) and Figure 4 (blue). The highest activity appeared to be from the yellow phase. Note little PD activity was picked up from the 400kV GIS switchgear building, at the circuit breaker end, and no PD activity was seen on the other side of the circuit breaker (bus bar end). This strongly suggested that PD activity was not in the GIS but inside the 750MVA transformer.

PD activity was detected using the CT and chase on the transformer, too. Results are shown in Table 1. The results measured on the transformer were much higher than expected, and much higher than the measurements made on the sister transformer within the same substation on the same day, suggesting PD activity inside the transformer T6607, which agreed well with the results from the spectrum analyser.

Further investigation was made to localise where the PD was emanating from the transformer T6607. The PD source appeared to be coming from the yellow phase (middle phase) on the HV side of the main tank. It was then decided that further tests should be carried out on the transformer T6607 to identify and localise the problem. An internal visual inspection should also be carried out in order to identify the problem. The transformer should only be put back in service after the problem has been found and rectified.

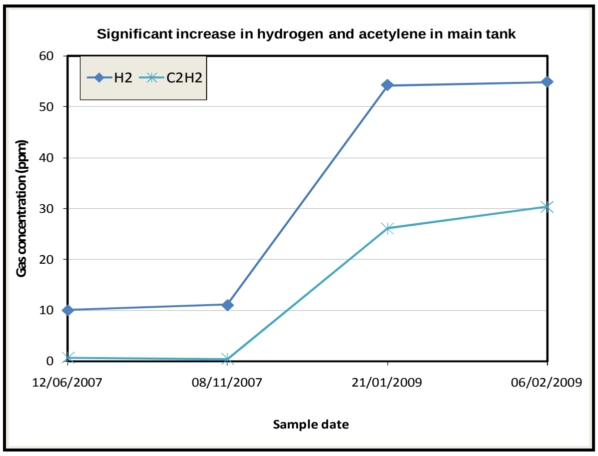
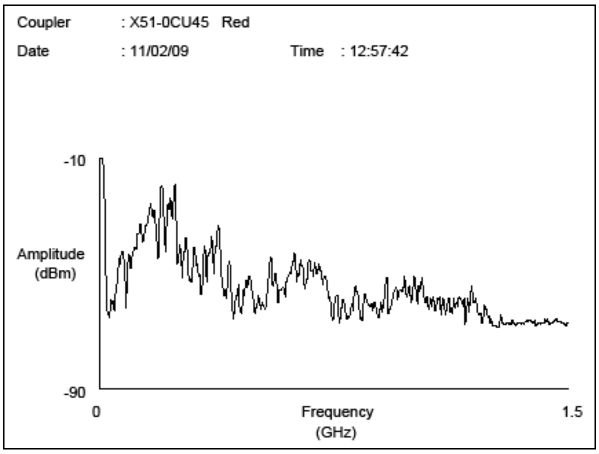


Figure 1
DGA increase in the main tank



Coupler : X51-0CU45 Red
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Figure 2
UHF PD survey, A/red phase

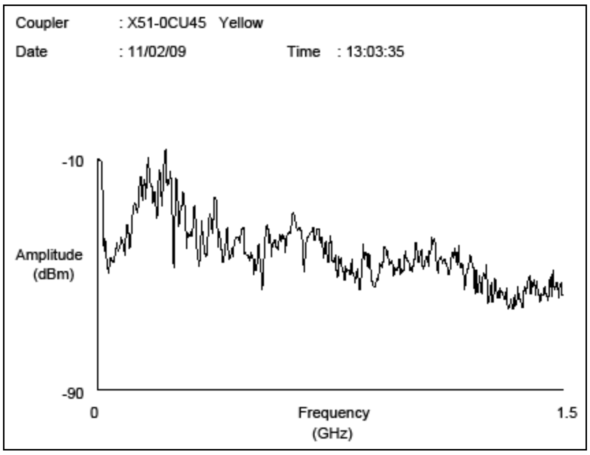


Figure 3
UHF PD survey, B/yellow phase

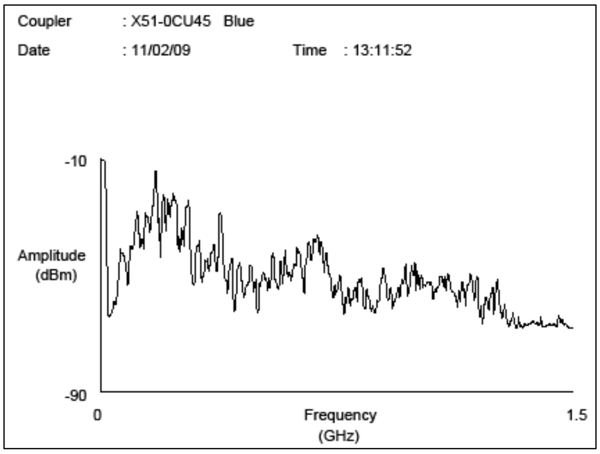


Figure 4
UHF PD survey, C/blue phase

Table 1
Measured PD activity on the critical transformer T6607

High Frequency CT on Neutral	Frequency	Transformer T6607
	15MHz	28db
	30MHz	34db
High Frequency CT on Tertiary	15MHz	28db
	30MHz	34db
Notes: Measurements above -10db is an indication of RFI activity		

Step 3: Review on Transformer Design, Maintenance and DGA History

The critical transformer T6607 identified is one of a family of four transformers built in 1980. The clamping system was designed with eight clamping bolts per phase on each side of the top yoke. These were arranged symmetrically, with four on each side separated by various leads exiting the winding assembly. Three of the four clamping bolts were attached directly to the top clamping frame and clamp the windings close to the top yoke. The fourth clamping bolt was attached to an outrigger and clamps the windings away from the top yoke.

The most serious known problem with this design family is loose clamping. It has been found and corrected in at least three of the four transformers. Loose clamping might also have played a part in the failure of one of them in 1991 by compromising short-circuit withstand capability.

Figure 5 shows acoustic emission traces from the sister transformer, which had the same issue in late 1990 and had been re-clamped to fix the problem. It clearly shows that the largest activity is coming from near the main tank flange, i.e. top of the windings where the clamping bolts would be located.

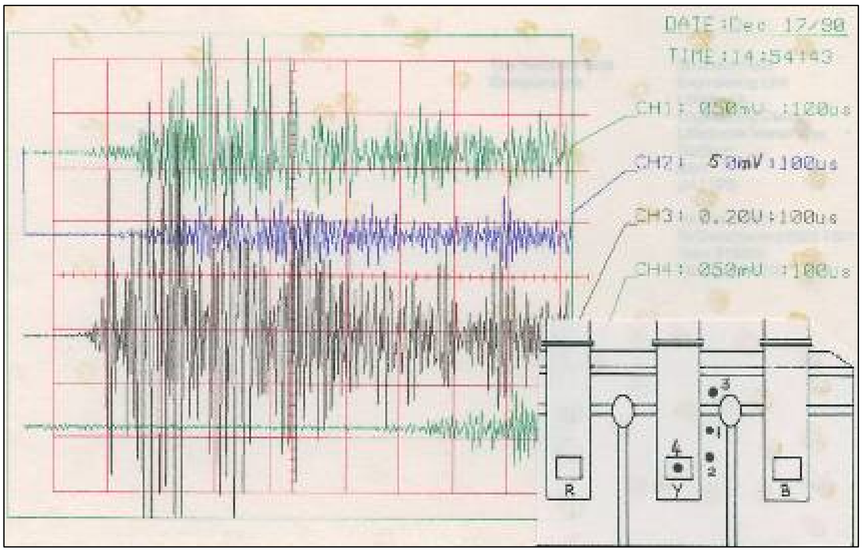


Figure 5
AE PD location in a sister transformer in December 1990

The maintenance records showed that the transformer T6607 had been re-clamped in March 2001, after serious PD activity was located around the top flange on the HV side. During the internal inspection in 2001, it was found that most of the coil clamping bolts were loose with evidence of discharge activity, as shown in Figure 6, and the two outer bolts on the HV side of the middle phase were the worst affected.

During major maintenance in July 2007, an internal inspection had been conducted to check the tightness of the winding clamping bolts on the transformer T6607. All clamping bolts were visibly inspected through panels on the A phase HV turret, the C phase HV turret and the C phase LV turret. They all seemed to be tight and there was no evidence of any arcing/sparking noted. Figure 7 shows a photo from 2007 internal inspection on B/yellow phase HV side clamping bolts.

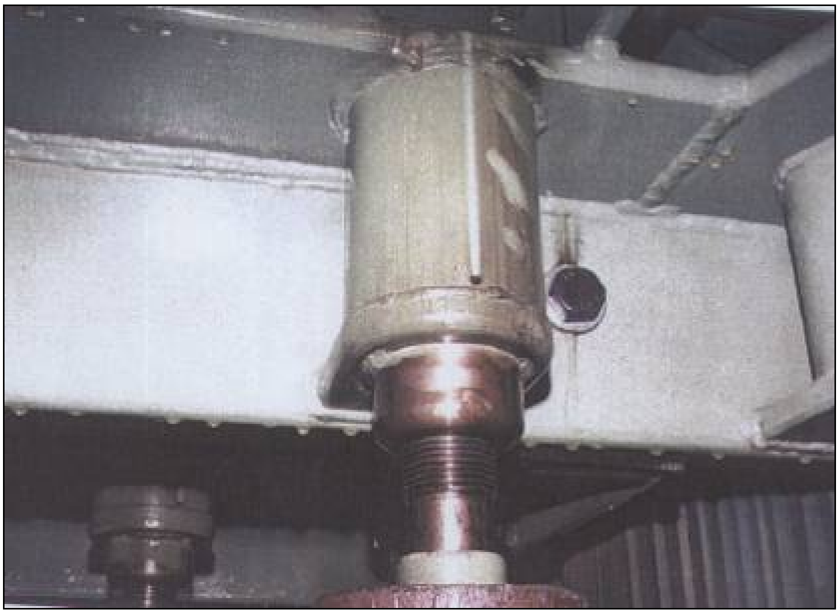


Figure 6
Photo from 2001 inspection of the transformer with carbon marks

Figure 7
Photo from 2007 inspection, B/yellow phase HV side clamping bolts

Dissolved gas results for this transformer are available from 1985. The diagnostic acetylene and hydrogen history is shown in graphical form in Figure 8. The dissolved gas signature is illustrated in Figure 9. Some unusual results were obtained early in the life of the transformer – 22 ppm of acetylene was found in one sample taken in June 1985. There followed a period of some years when hydrocarbon gas levels were low and steady. Traces of acetylene were found in the main tank from July 1993, with levels rising gradually to 3.3 ppm in April 2000. The acetylene level then rose rapidly to a peak of 116.3 ppm in March 2001. This signature is typical of an arcing/sparking fault. After the loose clamping bolts had been re-tightened in April 2001, the acetylene level had since fallen gradually from 12.9 ppm in October 2001 to less than 1.0 ppm in 2007. The significant increase in acetylene to 26 ppm in January 2001 was very much similar to that of March 2001 although the relatively lower acetylene level implies that most likely some of the clamping bolts were loosening again.

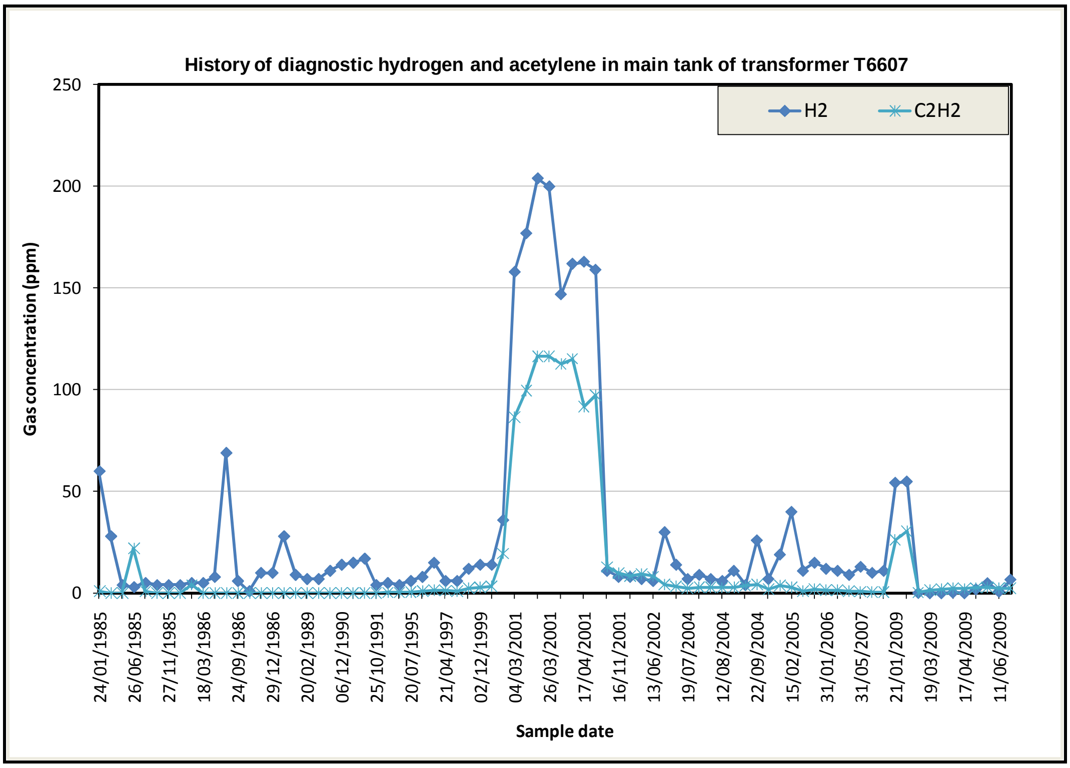


Figure 8
Acetylene and hydrogen history in main tank of the transformer T6607

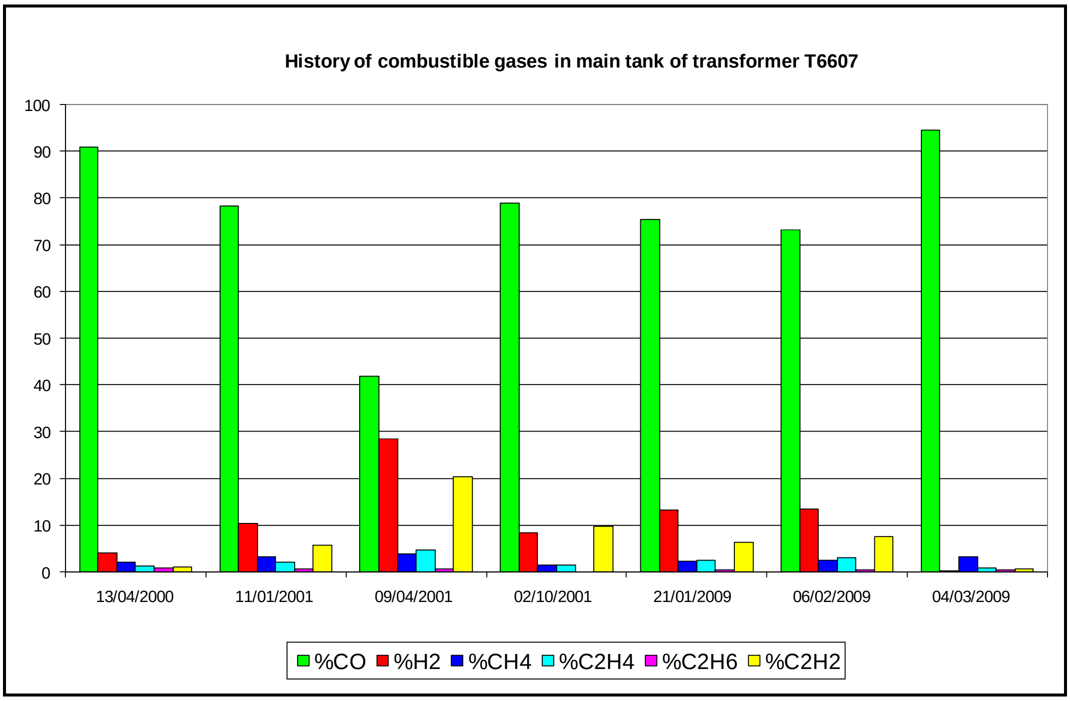


Figure 9
Combustible gases history in main tank of the transformer T6607

Step 4: Winding SFRA Assessment

Taking into account the age and maintenance history of the critical transformer T6607, it was decided to proceed with more in-depth investigation. It was then decided to carry out SFRA measurements to assess the mechanical condition of the windings before any action was taken to retighten the loosening clamping bolts.

Measured winding frequency responses, as partly illustrated in Figure 10 and Figure 11, were in very good agreement between phases and with previous 2001 results, with no indication of any significant winding movement. It was safe to say that the increase in acetylene in the main tank as well as the picked up discharge activity is most likely due to the winding clamping becoming loose again, possibly as a result of the LV cable fault on the attached circuit in late 2008.

It was therefore decided that an internal investigation of the transformer T6607 should be carried out to check the winding clamping arrangements and retighten any loose clamping bolts.

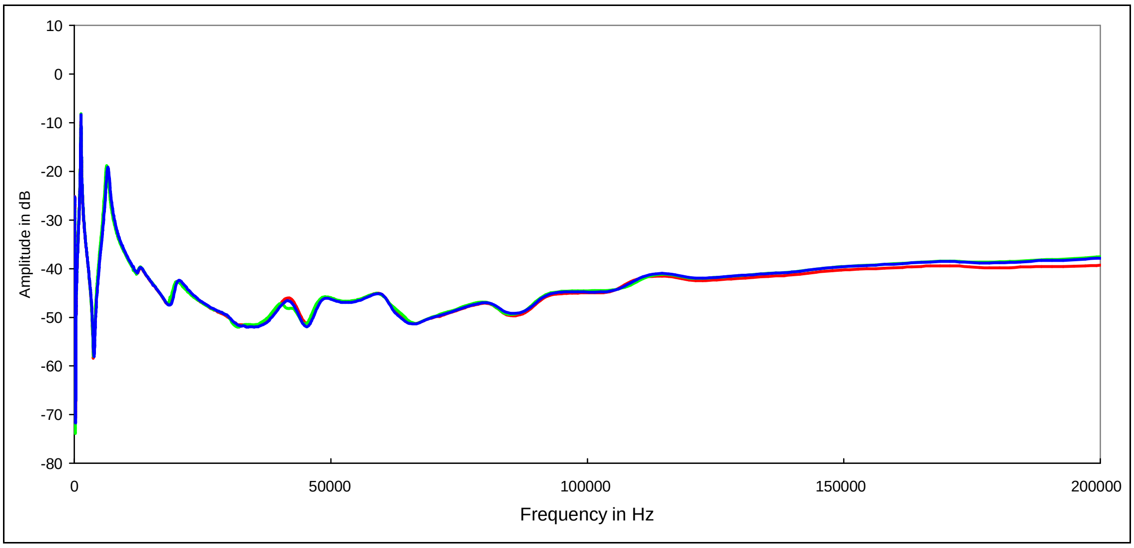


Figure 10
Transformer T6607 winding frequency responses (HV to LV)

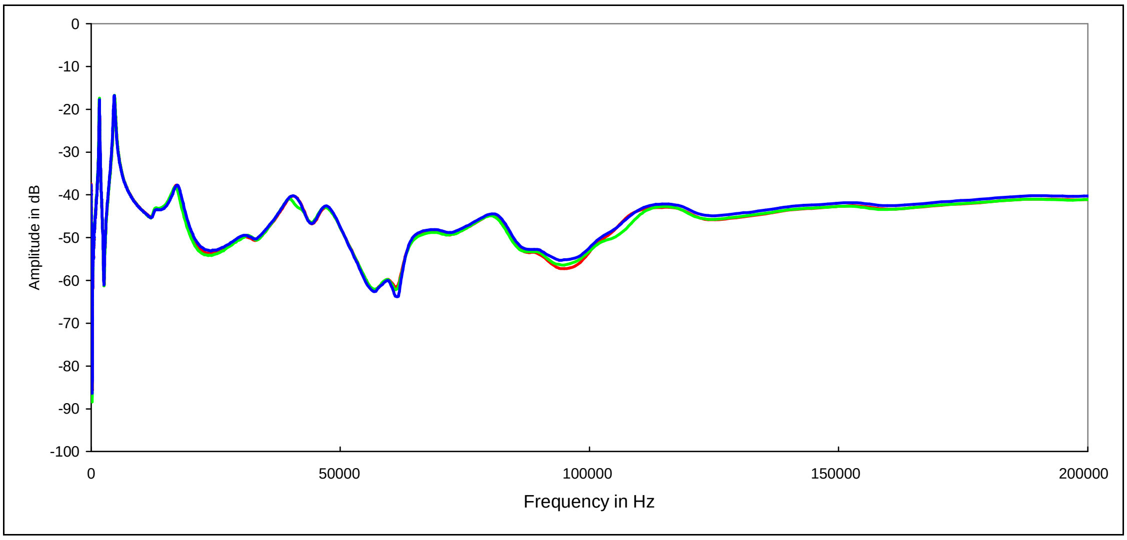


Figure 11
Transformer T6607 winding frequency responses (LV to neutral)

Step 5: Internal inspection and Repair

During the internal inspection of the transformer T6607 in late February 2009, it was found that some of the winding clamping bolts in the HV side were loosening with evidence of discharge activity, as shown in Figure 12 and Figure 13. The transformer was therefore re-clamped by retightening the loosened clamping bolts. The oil was also reprocessed before the transformer was returned back in service.

In order to confirm the effectiveness of the repair, it was then decided that a full UHF PD survey should be carried out when the transformer was returned to service to ensure that the transformer was discharge free.

Figure 12
HV red phase inside corner

Figure 13
HV yellow phase left hand side

Step 6: UHF PD survey

The UHF PD survey was carried out with Doble LDIC's PD Measuring System LDS-6/UHF. The main parts of this PD measurement system are the UHF probe DN50, a pre-amplifier and the measuring instrument LDS-6/UHF. The measuring system as a whole is illustrated in Figure 14. A close up of the applied UHF drain valve sensor and LDS-6/UHF measuring system are shown in Figure 15. The measuring frequency of the UHF Processing Unit in this system is adjustable in the frequency range from 110 MHz to 1700 MHz with a frequency bandwidth of 8 MHz. For the measurements at the transformer T6607, the measuring frequencies had been chosen according to spectrum analysis during performance check.

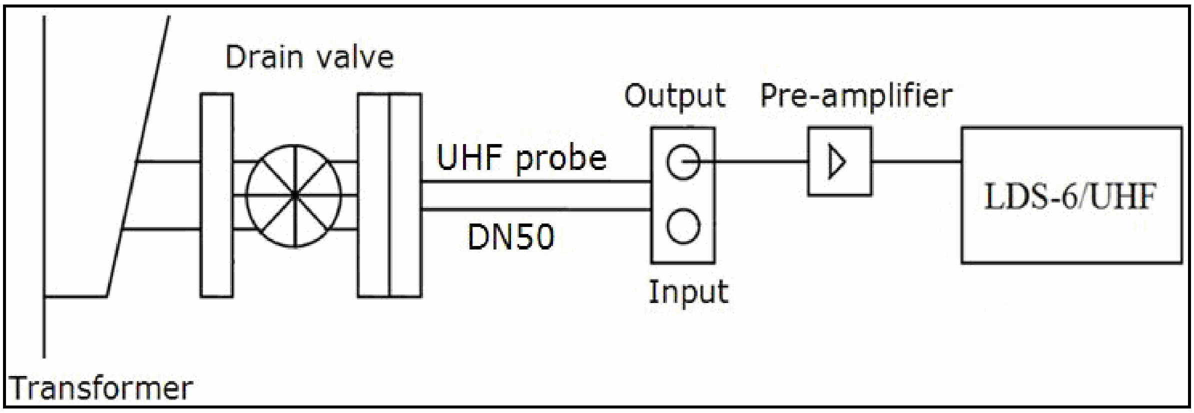
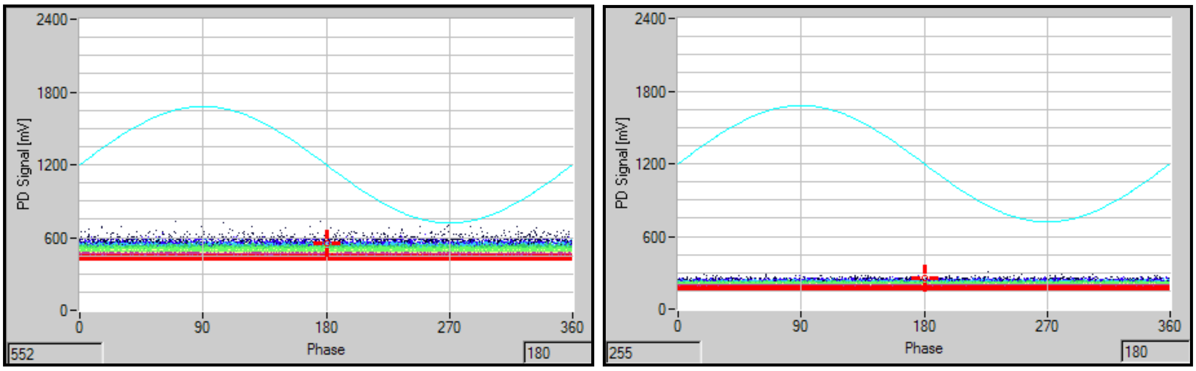


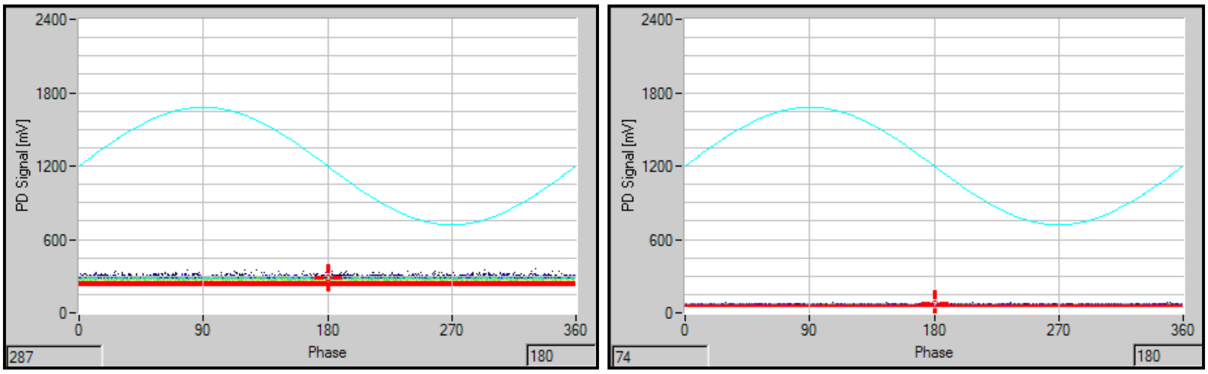
Figure 14
Schematic diagram of the PD measuring setup on the power transformer

Figure 15
UHF drain valve sensor (left) and LDS-6/UHF measuring system (right)



300 MHz- Recording

350 MHz- Recording



370 MHz- Recording

535 MHz- Recording

Figure 16
Results of the frequency selective measurements

Results of the frequency selective measurements at 300 MHz; 350 MHz; 370 MHz and 535 MHz are shown in Figure 16. No PD levels above the detection sensitivity had been measured. Based on the UHF PD survey results the investigated transformer T6607 was assessed PD-free under operation voltage considering the recorded background noise level.

It was then decided that the transformer should be returned to service with online GIS PD monitoring plus enhanced oil sampling for further assessment.

Step 8: Online GIS PD Monitoring Plus DGA while the Transformer is in Service

As shown in Figure 8, the acetylene level in main tank of the investigated transformer T6607 had fallen to trace levels (less than 3.0 ppm) since the return to service, which confirmed the success of retightening the loose clamping bolts.

It was then assessed that the transformer T6607 should remain a Condition Category 4 (normal) in the Transformer Asset Health Review, with online GIS PD monitoring plus routine oil DGA sampling to monitor.

Key Learning Points

Some key learning points could be summarized as the following:

- **Every power transformer is unique and needs to be treated uniquely.** Condition monitoring and life-cycle management of power transformer can only succeed if it is implemented and managed efficiently, with an in-depth knowledge of how a power transformer fails before making the decision to implement any type of condition monitoring techniques. Most power transformer failures are not of old age, but have localised damage or ageing due to some limitations in design and manufacture, application and maintenance [13-16]. Failure to correctly understand the failure mode of the specific transformer can result in the application of condition monitoring that has little impact on improving overall reliability of the critical transformer.

- **Transformer design review is vital in understanding the condition monitoring results correctly.** Integration of the transformer design strength and weakness knowledge as well as historic operation and maintenance information with the selected condition monitoring model(s) is the key to improving the effectiveness and efficiency of power transformer asset health assessments. It is extremely important to realise that results which might be considered acceptable or normal for one design might indicate a serious fault with another design.

- **Don't stop with condition monitoring of power transformers**. Utility transformer asset managers and engineers must become proactive – always taking the next step when identifying problems with condition monitoring technologies to determine the root cause and to apply the subsequent solution and learning throughout the utility to mitigate the risk of unplanned failure.

Conclusions

This case study illustrates in steps how we meet difficult challenges to utilise power transformer condition monitoring to its potential for early fault detection and to apply life-cycle management techniques to manage the risk of developing failure and discount the need for replacement.

The detailed case study also shows the extra benefits of always taking the condition-monitoring program to the next level. By becoming more proactive and taking the next step when identifying problems with condition monitoring technologies, the power transformer asset managers and engineers can determine the latent cause and apply the subsequent solution and/or learning throughout the utility and finally help in preventing an unplanned outage or catastrophic failure.

References

[1] P. J. Burton, J. Graham, A. C. Hall, J. A. Laver and A. J. Oliver, “Recent development by CEGB to improve the prediction and monitoring of transformer performance”, CIGRE 1984 Session, Paris, Paper 12-09.

[2] C. Bengtsson, “Status and trends in transformer monitoring”, IEEE Transactions on Power Delivery, Vol. 11 (3), pp.1379-1384, 1996.

[3] B. Richardson, “Diagnostics and monitoring of power transformers**”,** IEE Colloquium on Condition Monitoring of Large Machines and Power Transformers (1997/086), London, UK, 19 June 1997.

[4] J. C. Steed, “Condition monitoring applied to power transformers - an REC experience”, IEE Colloquium on Condition Monitoring of Large Machines and Power Transformers (1997/086), London, UK, 19 June 1997.

[5] T. Liebfried, W. Knorr, K. Viereck, “Online Monitoring of Power Transformers – Trends, New Developments and First Experiences”, CIGRE Session 1998, paper 12-211.

[6] V. Sokolov, “Considerations on power transformer condition-based maintenance”, EPRI Substation Equipment Diagnostic Conference VIII, New Orleans, 20-23 February 2000.

[7] M. Wang, A. J. Vandermaar and K. D. Srivastava, “Review of condition assessment of power transformers in service”, IEEE Electrical Insulation Magazine, pp. 12-25, Nov/Dec 2002.

[8] A. Santosh Kumar, R. P. Gupta, K. Udayakumar and A. Venkatasami, “Online partial discharge detection and location techniques for condition monitoring of power transformers: A review”, International Conference on Condition Monitoring and Diagnosis, 21-24 August 2008, Beijing China, pp. 927-931.

[9] S. Coenen, S. Tenbohlen, S.M. Markalous, T. Strehl, “Sensitivity of UHF PD measurements in power transformers”, IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 15(6): 1553-1558, 2008.

[10] S. M. Strachan, S. Rudd, S. D. J. McArthur, M. D. Judd, S. Meijer and E. Gulski, “Knowledge-Based Diagnosis of Partial Discharges in Power Transformers”, IEEE Transactions on Dielectrics and Electrical Insulation Vol. 15, No. 1; pp. 259-268, February 2008.

[11] S. M. Markalous, M. Boltze, A. Bolliger and A. Wilson, “On-line partial discharge at power transformers”, Proceedings of 76th Annual International Doble Client Conference, Boston, 2009.

[12] S. M. Markalous and A. Wilson, “Techniques for detection and location of partial discharges in power transformers”, INSUCON2009, 26-28 May 2009, Birmingham, UK.

[13] R. Heywood, J. Lapworth, L. Hall, and Z. Richardson, “Transformer lifetime performance: Managing the risks”, 3rd IEE International Conference on Reliability of Transmission and Distribution Networks, London; February 2005.

[14] R. Heywood and A. Wilson, “Managing reliability risks-Ongoing use of ageing system power transformers”, Doble Israel Conference 2007.

[15] A. Wilson, R. Heywood and Z. Richardson, “The life time of power transformers”, INSUCON2006, 24-26 May 2006, Birmingham, UK.

[16] H. Ding and S. Ryder, “When to replace aged transformers? Experiences from forensic tear downs and research”, Euro TechCon 2008, 18-20 November 2008, Liverpool, UK.