CONTINUOUS MOISTURE MANAGEMENT: EXTENDING TRANSFORMER SERVICE LIFE.

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SUMMARY

The Power transformer is a vital part of any distribution network and in the UK significant numbers are close to or indeed have exceeded their 40 Year design life.

Engineers are faced with the dichotomy of reducing capital and maintenance expenditure on such items whilst being asked to meet ever more stringent supply availability figures. If the transformers’ life could be extended without affecting reliability then this may be one way of helping them meet the above objective.

Ultimately it is the condition of the cellulose of the paper insulation that determines the life of the transformer. It is well documented that the rate of deterioration of the paper, and the breakdown strength of the insulating oil is significantly influenced by moisture contamination.

If transformers are to have service life extended it is imperative that moisture is removed from the oil AND the paper insulation. Traditional means of attempting to accomplish this have been either to carry out a vapour phase dry-out at the transformer manufacturers premises, or, to undertake on-site heat and vacuum treatment of the transformer oil. The former, whilst removing water from the paper, is expensive and inconvenient, the latter quickly dries the oil but, because of its short time on site has little effect on removal of water from the paper.

This paper examines the concept of employing new high temperature molecular sponge materials to continually remove moisture from the transformer oil. Overall the effect will be to slowly reduce moisture in the paper thereby reducing the rate of ageing of the paper.

The concept of ‘moisture management’ to control, within strict limits, the amount of water removed in order to prevent core-winding shrinkage will be explained.

Finally the service history details of continuous moisture removal systems operated by 24Seven Utility Services Ltd will be provided.
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INTRODUCTION

With the need to show increased return on assets, Engineers are faced with the dichotomy of reducing capital and maintenance expenditure whilst attempting to meet more demanding supply availability criteria.

Transformers are vital components within power distribution systems and it would be advantageous if their service life could be extended, without detracting from reliability. (1) (2)

This paper will examine how continuous moisture removal systems, utilising ceramic molecular sponge materials, effects service life, maintenance and reliability of transformers.

Experience of systems operating in 24Seven Utility Services Ltd (formerly London and Eastern REC’s) will be reported.

Ageing Processes of Power Transformers

Degeneration of the cellulose material within a transformer ultimately determines its’ service life and although numerous processes are involved, this paper will concentrate on ageing resulting from moisture contamination. (3)

Paper consists of a long chain Hydrocarbon glucose molecule identified as a linear condensation polymer consisting of D – anhydroglucopyranose units joined by β 1.4 - glucosidic bonds.

The condition of the paper is indicated by the Degree of Polymerisation or ‘DP’. The higher the DP, the longer the length of the cellulose Hydrocarbon chain and the better the condition of the paper. New paper typically has a DP value of around 1800.

As the cellulose ages, (3) it breaks down into smaller lengths i.e. the DP value falls. Critical DP values are around 200-300 and the breakdown process generates CO, CO₂ and H₂O.

The water generated by cellulose breakdown remains in the transformer insulation and the vast majority (> 99%) is contained within the paper. As paper moisture content rises’ the rate of ageing increases and Dielectric Strength falls (4). Ultimately the paper becomes brittle and fails.

Whilst operating temperature is undoubtedly a significant factor in ageing, once moisture has been produced and is held in the winding papers this acts as a catalyst and increases the rate of ageing.

Recent work undertaken by Weidemann (5) and sponsored by Rotek Engineering of South Africa has shown that the fastest ageing can occur at the oil/paper interface: not adjacent to the conductor.

This research demonstrated that when the outer paper DP value reaches 200-300 it rapidly deteriorates and, in a very short period of time, sheds large quantities of fibres into the oil. Having high water content the fibres are polarised and concentrate at high electrical stress points inside the transformer. This can initiate flashovers. Research is continuing but the results from transformers removed from service suggest that practical experience mirrors the research predictions. This may offer an explanation to flashovers categorised as “cause unknown”.

Preventing moisture entering the transformer from external sources will not inhibit production of water from the cellulose breakdown (6), neither will it decrease the rate of ageing of the cellulose nor ultimately the rapid release of fibres into the oil. If a transformer is to have extended service life then internally generated moisture and free fibres must be continuously removed.

Existing moisture removal techniques

The best method of removing water from a power transformer is to undertake a full Vapour Phase dry-out at the transformer manufacturer using hot kerosene at 150-180°C to remove oil and water from the insulating papers.

The process is expensive, and when factors such as high transportation costs and protracted outage times are considered, these ensure that this process is rarely undertaken in practice.

On-site techniques, such as short-term heat/vacuuming of the oil utilising mobile equipment resolve the transportation and protracted outage issues. However the vacuum process generates low electrical strength gas bubbles, which can enter the transformer. It is preferred therefore; that this technique is undertaken with the
transformer de-energised and this, together with high daily operating costs generally limits the application time of these techniques to around 48 hours.

NB: There will be instances when network operational considerations decree that heating and vacuuming must be undertaken with the transformer energised and in such instances it is imperative that risk assessments are carried out and contingency plans put in place to cater for a ‘risk of trip’

At the end of a typical 48-hour processing period the water in the oil will have been reduced significantly. However there would be insufficient time for all the water in the paper to migrate into the oil and the overwhelming majority of moisture inside the paper insulation remains. Water will continue to migrate from the paper into the dry oil to re-establish the paper/oil water equilibrium and as soon as the processing equipment is disconnected the initial water in oil ppm value is quickly re-established.

CONTINUOUS MOISTURE REMOVAL

Continuous moisture removal relies on the principle that water will migrate from cellulose into dry oil to establish temperature dependent equilibrium. In this system oil is pumped from the transformer, passed over molecular sponges, through in-line particulate filters, and returned in a closed loop system.

The molecular sponges capture the water and the in-line filters remove fibres. Dry, fibre free oil is returned to the transformer. The molecular sponge dispenses with the need for heating and vacuuming and it can safely operate over a long time period with the transformer energised. Water slowly migrates from the cellulose into the dry oil and since the oil is regularly dried on subsequent passes over the sponges a continuous process is established and water is slowly removed from the cellulose. It is imperative that moisture captured by the sponges is never returned to the transformer and the correct choice of sponge material is vital if the benefits of continuous moisture removal are to be gained.

Early attempts at the technique were hampered by the choice of sponge materials. Dry reed and/or dry paper are efficient sponges at low temperatures but they release water back into the oil at temperatures below the max value allowable in transformers.

New high quality ceramic materials (4), that will not release captured moisture until they are removed from site and subjected to temperatures in excess of 180 deg C in a purpose built refurbishment facility are now available. These materials effectively transport the captured water off site ensuring it can never be returned back into the transformer. These new materials are the basis for the modern continuous moisture removal systems.

WINDING MECHANICAL PRESSURE

The windings of a transformer must be secure on the core if they are to withstand electro mechanical forces otherwise they will distort and fail catastrophically. To cater for this, following a vapour phase dry-out during manufacture, the windings are compressed or ‘jacked’.

Unfortunately paper expands as it absorbs moisture, conversely it shrinks when dried (4). The moisture content in transformer insulation paper increases with ageing and the increased volume places pressure on the jacking points. Although these distend, the winding will still be held tightly on the core.

If the ‘wet’ paper insulation is dried it will shrink and unless the jacking points can accommodate this dimensional change, the winding may become loose. It is vital therefore that paper shrinkage is considered when drying out transformers.

With vapour phase drying, since the transformer is already de-tank ed, re-jacking is easily achieved but care must be exercised with other dry out techniques.

The effects of winding shrinkage after short-term heating/vacuuming are rarely a problem since this method removes little water from the paper itself. Given sufficient time Continuous Moisture Removal would dry out transformers to levels similar to vapour phase techniques and shrinkage MUST be considered.

Unless automatic re-jacking compensates for dimensional changes, or the owner/operator undertakes manual re-jacking of the windings, ‘Moisture Management’ must be introduced to limit the amount of moisture removed so the ageing rate of the cellulose is reduced, but the winding remains compressed.

WATER VOLUME CALCULATIONS

In order to utilise continuous moisture removal to reduce paper ageing, and extend transformer life the amount of water in the oil and in the paper is calculated (7) and an optimum dry out level determined.

The ideal solution would be to take a paper sample from the transformer and measure moisture content but Owner/operators are loath to open transformers for sampling. Taking oil is usually a simple procedure.

The Phiper chart, (8) relates water in the oil (in ppm) and corresponding % moisture content in the paper at various top oil temperatures. The derivation of the
original Phiper chart is unclear. However, the version in use today has been extensively modified and accurately correlates figures from many years of actual measurements of on site oil temperature, corresponding oil in water figures (in ppm) and volumes of water removed during subsequent vapour phase dry outs. Care must be exercised at oil temperatures below 50°C, but above this value the chart it is extremely accurate.

Similarly, practical readings obtained over many years give minimum allowable moisture content to ensure that re-jacking in not required.

The Phiper chart allows the volume of water in the paper and the optimum dry-out condition to be determined so as not to loosen the windings. An example of a ‘water in winding’ calculation is shown below.

**Transformer Details**

- **Location**: Power Station N
- **Name**: Generator TX
- **Rating**: 145MVA
- **Voltage**: 132/14kV
- **M’facturer**: Confidential
- **Date**: 1995
- **Oil Volume**: 34704 Litres
- **Water Content**: 23ppm
- **Top Oil Temp**: 50°C
- **Weight of paper**: 3019kg

**Water in Oil**: 34704 L x 23ppm = 0.80 litres

**From Phiper Chart**

23ppm @ 50°C equates to 2.8% Moisture Content

- **Water in insulation**: 3019 kg x 2.8% = 84.5 litres
- **Total Water in Transformer**: = 85.3 litres

**Dry out:**

- Min moisture for tx’s this type & age = 1.3%.
- 1.3% of 3019kg of water shall remain = 39.4 litres

∴ **Water to be removed** = 85.3 – 39.4 = 45.9 litres

For the regime to be applied accurately the amount of water removed must be closely monitored. This is best achieved if the molecular sponges with captured water are removed from site for re-processing when the ACTUAL volume removed can be measured. This allows the drying process to be closely monitored and prevents ‘over-drying’ and loosening the winding.

**NB** The above relates to transformers that have already aged and have water in the paper. Ideally continuous moisture removal equipment should be fitted at the time of manufacture. Concerns over paper shrinkage need not be considered since the system maintains the oil and papers at or very close to the levels following the Vapour Phase Dry-out.

**24Seven Utility Services Ltd perspective.**

24Seven Utility Services Ltd is currently the largest user of molecular sponge dry out systems within the UK and they have undertaken work to determine the effects of fitting such units to both existing and new transformers.

**What does the user want?**

The user wants transformers that give trouble free performance with a life in excess of 40 years with no premature failures. The maintenance regime should be relatively infrequent with the time out of service small to minimise costs.

**Moisture in transformers**

The problems of moisture content have been discussed earlier, but the users’ concerns are:

- The transformer is liable to premature failure.
- Increased maintenance to reduce moisture levels.
- Long term investment planning is made more difficult if unexpected failures occur.
- Operation of the Network is subject to uncertainties if the plant cannot be relied upon.
- In the event of the transformer emergency ratings being required, where the hot spot temperature is permitted to rise to 140°C, free water could form a vapour that might the Buchholz gas relay to operate.

On site analysis confirm that the water content of transformers rises with age and that the number of failures also increases. Degradation of the papers appears to be more rapid in transformers that have a history of higher moisture content.

**Other problems of high moisture content**

Measuring the level of furfuraldehyde (9) in the oil can indicate the paper DP and this is a relatively easy non-intrusive method. Usually there is good correlation between FFA levels and the paper DP. However if the moisture level is high, the level of FFA appears lower than expected. It is postulated that higher moisture levels mask FFA readings. We do not have sufficient data to provide a valid analysis but this work is continuing.

**Treatment of moisture in Transformers**

As described above, there are various methods of treating moisture in transformers but transporting to a manufacturer for vapour phase drying is not a
practicable solution in the London area. The costs and logistics are impracticable for the benefit gained.

On site heat/vacuum treatment has been used but the theory described earlier is borne out in practice. The oil is dried quickly, but after 4 weeks its moisture level increases substantially confirming that moisture in the solid insulation material has not been removed.

Other considerations of heat/vacuum processing are, can a vacuum be applied to older tanks and could vigorous pumping and vacuum treatment cause damage to the already fragile paper insulation?

**Consideration of installation of on-line dryers**

With any new process there are always challenges to be met and fitting on-line dryers no exception with both technical and human considerations.

**Technical Aspects**

A transformer contains large volumes of oil that must be kept inside the tank any drier system comprising pipes, valves, pumps etc. could give rise to leaks. It is vital to examine the type and quality of the fitting and the standard of installation. Modifications have been made to ensure that the systems are as leak-proof as possible especially in this new era of strict environmental controls of pollution. They have been examined to ensure they will continue to give reliable service for the life of the transformer.

On-line dryers require some maintenance and their advantages must be weighed against the periodic drying out of the transformers and repair after a possible failure.

**Human Aspects**

With all new processes there are always some resistance to change – from the maintenance fitter and the inspection teams who take additional oil samples to the designers and senior management team who have to justify the cost of installation of this equipment. It is vitally important that operatives are trained in all aspects the new equipment.

**Costs**

Costs are of ever increasing importance to the operation of an electrical supply network. Maintenance cost must be balanced against the capital cost of equipment. The cost of replacement of main plant is high and often many years away. It can be difficult to justify expenditure to extend transformer life when this cost is borne now and seen on this years’ balance sheet. It is important that the cost of dryers is kept low and that short term savings can be shown. It can however be demonstrated that fitting of on line dryers make savings by eliminating costly heat/vacuum treatments.

It is also important that operating costs of dryers are low so that the maintenance burden is not increased. One distinct advantage is the transformer does not need to be removed from service to change the molecular sponge material.

**Dryers in current use**

The two types of dryers currently in use have basically similar modes of operation but the maintenance of the two types differs.

**Type 1.** This uses a molecular sponge desiccant in a container that holds 50Kg of material. When the active life of this is exhausted, the 50kg of desiccant are removed and destroyed and replaced with a new 50kg load. It is therefore necessary that the 50kg of material can be removed from the unit, removed from site and disposed of easily.

**Type 2**

This uses desiccant cylinders that are removed for re-cycling when exhausted. It is therefore necessary that there is sufficient access space on site to enable these cylinders to be lifted out safely. It is important to consider site conditions when making the decision as to which type to fit.

**Assessment of performance**

It is of immense interest to assess the ongoing performance of the drying processes. The easiest non-intrusive method is to take samples of oil and measure the moisture content using the Karl Fisher method.

The most effective method devised so far is to take an oil sample from the inlet to the dryer and another from the outlet of the dryer over a period. The moisture values can then be plotted to discover:

- The effectiveness of moisture removal
- Determination of the condition of the molecular sponge material
- The actual moisture level in the transformer

These tests were carried out on a number of dryers fitted on older transformers and an example is shown graphically below in figure 1.

It is vital to take the temperature of the oil when the sample is taken so that an accurate assessment can be determined. The results show that moisture is steadily removed from the transformers and the performance of the dryer is dropping off towards the right hand side of the graphs as the sponge material saturates. This is the expected performance.

As the molecular sponge material is exhausted and requires re-cycling the inlet and outlet moisture levels close together.
CONCLUSION

Continuous moisture management systems utilising molecular sponge materials appear to offer the prospect of extending the life of the transformer insulation by slowing down the ageing effects that are associated with moisture contamination. Work is continuing on this topic but results obtained to date from transformers in service indicate that the theory is matched in practice. Continuous moisture management could herald a new era in Transformer maintenance and life extension methods.

References


