24th International Conference & Exhibition on Electricity Distribution (CIRED)

12-15 June 2017

Session 1: Network components

Teardown of a compact distribution transformer after 12 years of severe loading conditions

IET Journals
The Institution of Engineering and Technology

ISSN 2515-0855
doi: 10.1049/oap-cired.2017.1078
www.ietdl.org

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Abstract: In 2003, CPFL Energia, a Brazilian utility, initiated investigations for high temperature compact distribution transformer, using Natural Ester liquids. Based on a 45 kVA transformer, a final rated capacity of 88 kVA has been reached after modifications in the cooling ducts and radiators. Two prototypes were installed at a heavily loaded network point, replacing mineral oil filled transformers of 112.5 kVA. After 12 years of continuous operation, one of the prototypes was removed for the study, while the other remains in service. The transformer was still in perfect operational conditions, submitted to an average loading along the 12 years of 82 kVA and peak loading reaching 123 kVA (273.3% of the original 45 kVA rating). A complete teardown was performed and samples of main insulating materials were assessed by two different laboratories, one in Brazil and one in USA. The visible wearing of the external painting is the main indication of the years, while the core and coil, when untanked, gave the impression of handling a brand new transformer. Full details will be presented in this article. Based on this long term/real life test, the long-term performance of the materials at high temperature operating conditions has been confirmed.

1 Introduction

In early 2003 CPFL Energia was one of the first utility companies in Brazil to evaluate the use of natural ester filled transformers in their overhead distribution lines. The improved fire safety and the benefits of using an 'environmental-friendly' solution were key points for the company.

Among the several alternatives for developing a profitable business case, the initial choice was to explore the benefits of the higher temperature class of the cellulose-based materials [1] in order to downsize the transformers while keeping same capacity. This results in a significant drop of cost per kVA installed.

Based on a conventional three-phase mineral oil immersed distribution transformer rated 15 kV/45 kVA, which was built using conventional Kraft paper as solid insulation, the studies of the manufacturer indicated that it would be possible to reach more than 75 kVA when one extra radiator was added, and adjusting the cooling ducts and increasing limits of temperature rise to 85/80/100°C, respectively, average winding rise, top oil rise and hotpot rise. A heat run test confirmed a new rated capacity of 88 kVA.

As the distribution grid loading is driven by the end users, the only alternative to ensure heavy loading condition was to install the two transformers replacing larger mineral oil units. Units of 112.5 kVA were chosen. After a little more than 12 years of continuous operation, without any intervention, one of the two units was removed. The results of the assessment are presented in this report.

An important benefit expected by the utility was the reduction of the no-load losses. While the 112.5 kVA transformer had no-load losses of 390 W, the 45/88 kVA transformer had 195 W, a 50% reduction. The load losses would be higher during the peak loading conditions, driven by the effective applied load.

When the Brazilian programme of 'transformer efficiency labelling' limited the total transformer losses evaluated at nominal load, the initial approach was no longer acceptable. A new generation of natural ester 'green transformers' was developed, keeping the strategy of exploring the higher temperature rises allowed for Kraft paper immersed in natural ester liquids. For this second generation, the rated power of the transformer is defined at the current temperature rise limit for Kraft paper immersed in natural ester, which is 75/70/90°C (average winding, top liquid and hotspot, respectively). The winding optimisation allowed a reduction in core size, and consequently, of no-load losses up to 37% of the acceptable limit while total losses reaches the limit values required for the Brazilian standard, as the load losses are not limited individually, just the no-load and total losses.

In October 2013, CPFL Energia decided to switch 100% of the new purchased transformers to the 'green transformer' approach for the entire concession area (second largest in Brazil in number of customers). In total, more than 35,000 high-temperature green transformers are in service on the CPFL distribution grid, including South Region (utility RGE, a subsidiary of CPFL) and Southeast Region (CPFL) of Brazil.

2 Natural ester and cellulose

In the early 1990s, accelerated ageing test indicated that the rate of thermal degradation of cellulosic-based insulation material was significantly reduced when it was immersed in natural ester liquids. It was the starting point of several years of additional investigation and tests resulting in the development of new Arrhenius curves for natural ester immersed papers [2–4].

Currently, this improved behaviour is included in two international standards. Published in October 2012 [5] and September 2013 [6], their informative Annexes included a review of ageing studies and suggested higher thermal classes for

Table 1 Values of thermal classes for cellulose-based materials immersed in natural ester liquids compared with the traditional values of the same papers immersed in mineral oil [5, 6]

Insulation system	Temperature of nominal life, °C	Thermal class
mineral oil/TUK paper	110	120
natural ester/TUK paper	130.6	140
mineral oil/Kraft paper	95	105
natural ester/Kraft paper	110.8	120

conventional Kraft and thermally upgraded Kraft paper (TUK) immersed in natural ester liquids, as presented in Table 1.

According to these standards, the suggested thermal class of conventional Kraft paper in natural ester would be 120. However, in 2003, the thermal class of conventional Kraft paper was assumed to be 140 (later reduced to 130) – still 10° higher than in international standards. A substantial number of investigations and studies in Brazil supported this definition [7].

A part of the scope of this investigation was to validate this lower degradation rate of the conventional Kraft paper. Another goal was to investigate the transesterification hypothesis. While the residual degree of polymerisation was high enough to validate the phenomena, the transesterified cellulose was not identified.

3 Application concept: downsizing the transformer

The typical loading profile of most of distribution utilities around the world includes one or two peak loading periods per day, having duration of 1 or 2 h, and a relatively low loading level for the rest of the 24 h cycle. In mineral oil transformers, the main limitation for transformer selection is exactly the peak load, since the overloading is limited by the top oil temperature, which should not be higher than 115°C (long- and short-term emergency loading limit, according to loading guides).

When the temperature goes beyond such limit, the thermal degradation of mineral oil is accelerated (called 'oil burning' effect), resulting in a quick darkening of the oil. In fact, paper degradation is a secondary aspect for the short term overloading, as there will be a compensation mechanism between the high and low loading periods. However the oil degradation is a non-reversible process (may require oil reclaiming), which reduces the dielectric capacity of the transformer permanently. Due to this, the standard practice for transformer selection by utilities takes into account the peak loading, resulting in a low level of average loading.

The higher temperature rise limits of natural ester filled transformers may allow reductions of transformer size, could be called a 'high-temperature optimisation'.

In a different direction, the extra degrees may also be exploited as a 'continuous over capacity', which may allow the use of smaller transformers as replacement of a larger one, due to this increased peak capacity. The final result is an increase of the average loading, meaning a higher utilisation factor of the assets.

The network point selected was known as a heavy loading region, requiring a mineral oil transformer of 112.5 kVA. Alternatively, the decision was to install the 88 kVA natural ester immersed transformer. The loading at this point is shown in Table 2. The column 'loading factor' indicates the percent average loading based on a nominal power of 112.5 kVA. The result is an average loading for the total 12 year period of 82 kVA (72.8% of 112.5 kVA). The column 'maximum winding temperature' shows the hotspot temperature during peak loading, not at the indicated loading factor (average). The location is a residential/commercial profile, having a loading peak daily between 5 pm and 8 pm, reaching up to 123 kVA, representing 140% of the 88 kVA rating and 273% of the original rating.

Table 2 Loading factor of the prototype transformer

Year	Loading factor, %	Maximum winding temperature (hotspot), °C
2003	0.68	115
2004	0.75	121
2005	0.71	118
2006	0.72	119
2007	0.72	119
2008	0.75	122
2009	0.73	120
2010	0.75	122
2011	0.76	126
2012	0.74	125
2013	0.72	119
2014	0.71	117
2015	0.72	118

4 Transformer teardown

Fig. 1 shows the transformer as removed from the pole, after 12 years of continuous loading. It can be seen the wearing of the painting, but no signals of any leakage.

Fig. 2 shows the inside of the transformer at the time of cover removal. As typical in distribution transformers in Brazil, the

Fig. 1 *Overview of the prototype transformer after 12 years of continuous service at overhead distribution lines in Brazil*

Fig. 2 *Transformer after cover removal*

Fig. 3 *View of tank bottom, after removal of active parts and fluid*

Table 3 Transformer natural ester properties after 12 years

	ASTM method	S/N 54309	New fluid specifications
water content, mg/kg	D1533B	219	≤200
dielectric breakdown, kV@2 mm	D1816	60	≥35
dissipation factor @ RT, %	D924	0.45	≤0.20
dissipation factor @ 100° C, %	D924	6.95	≤4.0
acid number, mg KOH/g	D974	0.174	≤0.06
flash/fire point, °C	D92	319/355	≥300
pour point, °C	D5950	−18	≤−10
viscosity @ 40°C, mm^2/s	D445	33.74	≤50
viscosity @ 100°C, mm^2/s	D445	8.20	≤15
oxidation inhibitor content, % initial value	D4768	92.5	—

transformer has a headspace for absorbing the volumetric expansion of the dielectric liquid due to temperature variation. This headspace is not filled with any inert gas, it was ambient air when the transformer was closed, kept confined along the years.

The natural ester liquid is clean and transparent, still holding its original green colour.

No film is seen on top of the liquid or on the tank walls or internal portions of the bushings. It is also remarkable the absence of any indication of corrosion commonly seen when removing the cover of distribution transformers. The dry-out effect of natural ester, responsible by keeping the insulating paper dry, has also kept the air cushion free of moisture, preventing the formation of corrosion spots. No visible signs of degradation can be identified to the transformer or its components in this top view.

Fig. 3 shows the internal part of the tank after removal of core and coils and drained of dielectric liquid. At the bottom a small volume of natural ester may be identified, as the draining was performed by a suction system (no drain valve available). Also remarkable is the absence of sludge at the bottom. A mineral oil transformer loaded similarly would be expected to have a relevant amount of solid material at tank bottom. The absence of any type of wax or gel at tank bottom also confirms the oxidation stability natural ester liquid.

Fig. 4 shows the core/coil assembly, having the appearance of a brand new unit.

5 Laboratory analysis

The laboratory analysis of the material samples confirmed the findings from the visual inspection.

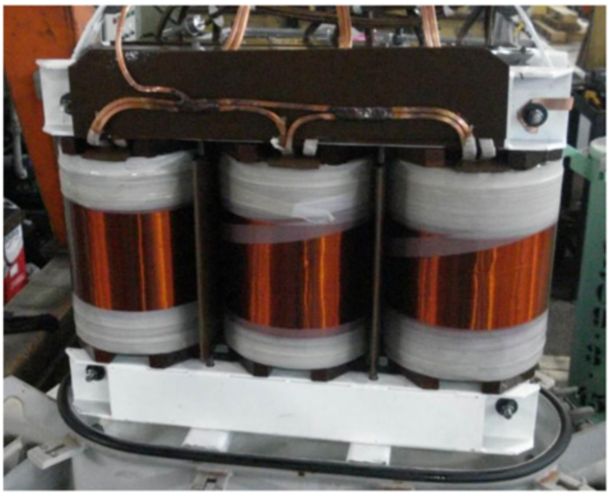

Fig. 4 *Core and coil assembly immediately after untanking*

Table 3 shows the natural ester liquid properties. The main change was the increased water content. The liquid sample was taken some time after the cover removal, which is at least a partial contributor to the water content. As expected after such severe service, the dissipation factor and acid number were above the allowable limits for new natural ester fluid.

The increased values of both acid number and dissipation factor can be attributed to the reaction of natural esters and water, the hydrolysis. The natural ester scavenges the water from the solid insulation and consumes it by the hydrolysis reaction, forming free fatty acids (FFA). The formed FFAs are long chain acids having 18 carbons. The high molecular weight is key for their classification as mild acids, not particularly aggressive to any of transformer materials even at temperatures much higher than operational range. The higher value of dissipation factor is a consequence of the polar nature of the FFAs.

This trend of increasing acid number and dissipation factor has also being seen in several power transformers where natural ester liquid was applied, always increasing at a very low rate. The production of acids is driven by the water extracted from the cellulosic materials, both the residual after the oven drying and the generated by the paper ageing. The acid number of the new fluid was 0.03 mg KOH/g, increasing to 0.174 in 12 years – an increase of 0.012 mg KOH/g per year. For a distribution transformer life expectancy of 25 years, the value at the end of life would be 0.33 mg KOH/g, very close to the suggested limit of continuous operation of standards [8].

It was also a target of this investigation to search for evidences of transesterification. The main indication of the process would be a modification in the structure of the Kraft paper, indicated by the appearance of a weak band at the 1717/cm [9]. However, this carbonyl band has not been identified in the FTIR results.

All six paper samples were extracted for approximately 4 h in a soxhlet extractor with a 10% acetone in heptane solvent to remove all traces of the dielectric fluid. The FTIR spectra of all samples were very similar. Representative spectra are shown in Fig. 5.

The non-identification of the transesterified cellulose does not mean the hypothesis is not valid. The high values of DP of the paper shows the process of degradation was still at the beginning, in comparison to the accelerated ageing tests performed with the sealed vessels. Apparently, the process was not long enough to reach a significant level of transesterification.

The measurement of the residual degree of polymerisation was performed according to IEC 60450.

Two different laboratories performed the measurements, for comparison. A new sample of Kraft paper is expected to have a degree of polymerisation (DP) of ∼1200.

During the transformer manufacturing process, this value is reduced by about 100 in each coil drying cycle. A typically accepted value for Kraft paper in new transformers is in the 1000–1100 range. According to Brazilian standard [10], a value as low as 800 is still sufficient for classifying the transformer as new. A very good process could result in initial DP in the range of 1100.

CIRED, Open Access Proc. J., 2017, Vol. 2017, Iss. 1, pp. 464–467

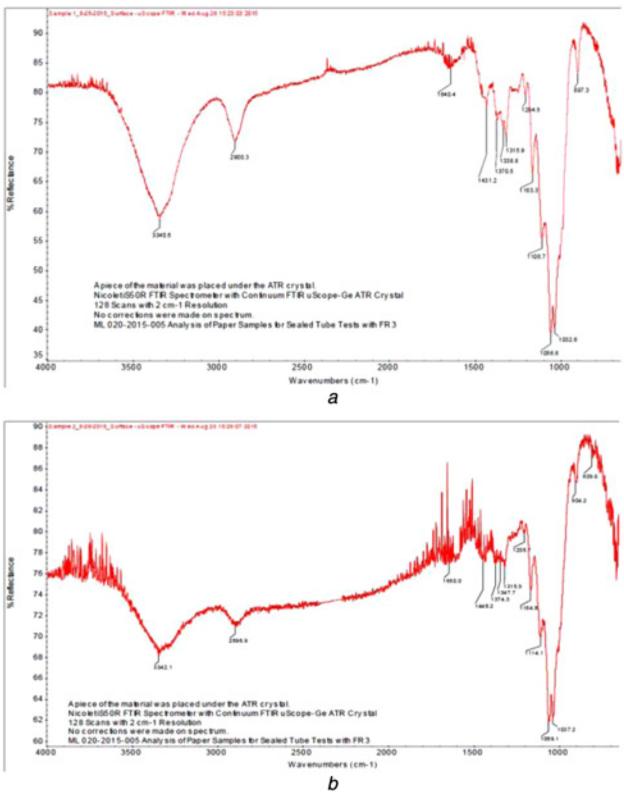

Fig. 5 *FTIR spectra:*

***(a)** Sample 5, average measured value of residual DP, **(b)** Sample 3, lowest measured DP*

Table 4 Degree of polymerisation of Kraft paper samples

Id.	Paper sample location	DP
1	HV1 layer 1 (near LV)	949.1
2	HV1 last layer	915.1
3	HV2 layer 1 (near LV)	832.6
4	HV2 last layer	946.8
5	HV3 layer 1 (near LV)	941.1
6	HV3 last layer	908.8
	average	915.6

During the regular loading of a transformer, there will be thermal degradation of the solid insulation, resulting in reduction of the DP. This is mainly accelerated by the factors:

- oxygen: an oxygen rich liquid increases paper degradation rate by a factor between 2.5 [11] and 10 [12], and is prevented by the use of oil preservation system;
- water: after oxygen, this is the main factor for paper degradation [10];
- acid number: depends on the corrosiveness of the acids (short chain versus long chain).

In a mineral oil transformer it would be expected a reduction of the DP around 50% after 12 years in service (half-life). Assuming an initial value of 1100 and 200 as end of life, the expected range of DP for a regular loaded transformer would around 650. As the transformer of this test has been severely loaded, reaching hotspot temperatures higher than the currently accepted values of nominal life for the Kraft paper immersed in natural ester, it would be reasonable to find valued closer to the 650 or even lower.

All paper samples taken from the transformer were analysed in Brazil and in United States, two independent and qualified laboratories. The average value of all measurements, taking the lowest measured values of each sample as valid, showed an average residual DP of 915.6. Values for each sample are presented in Table 4.

6 Conclusion

Tests performed by 'real-life conditions' are very often less accurate than laboratorial ones. In this study, some important information was lost due to the decision of keeping the process as close as possible to that of a regular transformer. This 'real life' transformer test as installed on the grid at high loading/overloading conditions for 12 years shows favorable results. The results of the materials analysis show that the materials remained in very good condition.

The 25 years life expectation for mineral oil immersed transformers is often not achieved due to the high incidence of lightning impulses in the region and the common loading peaks beyond nameplate rating, which result in overloading and overstressing the transformer. For natural ester immersed transformers, designed to the higher temperature rise limits as per [7], the national regulation agency (ANEEL) has already increase the life to 27 years, based on the performance of the installed transformers.

The concept applied for this test is not corresponding to the current 'green transformers' of this customer, but it may represent a new paradigm for distribution transformers selection. The capacity of holding much higher values of overloading improves the range of application of the transformers, potentially allowing an increase in average loading to better use the capability of the asset. It appears that higher peak loads will not affect the reliability of the network for natural ester immersed transformers, allowing the transformer selection to consider average loading instead of the peak.

A significant reduction in cellulose ageing of insulating paper impregnated with natural ester is confirmed in a real world application. The behaviour of all applied materials surpassed expectations. As a result, this may represent effective opportunities for the utilities to achieve real financial savings in their distribution and power grids.

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