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DRYING OF POWER TRANSFORMERS IN THE FIELD, APPLYING THE LFH-TECHNOLOGY IN COMBINATION WITH OIL RECLAMATION

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SUMMARY

Lifetime extension of power transformers has become very important as the bulk of the installed transformers in the western world is now coming into the final life phase. The main point of concern when it comes to life expectation is the condition of the insulation system that is based on organic products: Mineral oil and paper. They degrade over time and finally lose the capability to withstand the stresses a transformer might see in the daily life (short circuits, energizing, vibration…).
Main factors for the degradation processes of the organic materials are: Temperature, moisture, oxygen and acids. When a transformer leaves the factory, it is dry and almost free of acids. This will change over the time as water and acids are degradation products and will accumulate in the transformer. As a result, the degradation speed of paper and oil will increase and the "evil circle" with the self-accelerated degradation will start.
Removing moisture and acids from the transformer can slow down the ageing process and thus extend the lifetime of the insulation system. Preferably these removal processes will be executed on site, as it involves substantial amounts of time and money to move a large power transformer to the next transformer workshop equipped with a vapour phase drying plant. Onsite drying and online oil reclamation are two processes that will extend the remaining lifetime of the insulation system on site.

Onsite drying of power transformers is a process that has been developed in the past years. There is a wide range of possibilities known in the market. A new possibility is offered with the so-called Low Frequency Heating (LFH) system. With this technology a much better drying effect can be achieved, in much shorter time, than with other known processes. In addition to the efficient removal of water, substantial amounts of acids can be removed with the combination of heat and vacuum.
The latest development is the combination of the LFH process with other known processes like online oil reclamation. With such a combination, both the oil and the paper ageing can be delayed dramatically. Thus extending the technical lifetime of the transformer.

KEYWORDS

Drying – Moisture - Low molecular weight acids - Lifetime - Extension - Paper degradation - Oil reclamation - Acid removal - Practical experience - Acids

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1 Introduction

"Healthy" power transformers are among the most essential components in a reliable electrical grid. Unplanned interruptions can disturb a large supply area, which can lead to enormous financial losses. On the other hand is the pressure to keep older units in operation for economical reasons growing steadily. This leads to a situation, where the population of transformers is getting older and at the same time running at a higher load, due to the gradually growing demand. Yet, transformers do not live forever.
The end of the technical life of a transformer depends often on the state of the insulation system.
Due to a long and positive experience, the combination of mineral oil and pressboard is widely used in transformer manufacturing. The lifetime of this combination is very much dependent on the operating temperature, oxygen content, acidity of the oil and the moisture content in the insulation.
Temperature is mainly dependent on the transformer design, the loading, the cooling facilities, and the ambient temperature. Changing these parameters is not easy and normally involves large investments.
Moisture is accumulated in the paper insulation of the transformer and has different sources.
It can diffuse into the transformer along different paths. Not well maintained breathing apparatus on open breathing expansion tanks or damaged gaskets on the cover can be a source of water from outside as well as an exposure of the insulation material to air under a repair [1]. But also the depolymerisation (ageing, degradation) of the insulation paper and the ageing of the oil create water as a by-product inside the transformer [2,3].
New research [10] is showing that also the acid content plays a major role in the degradation processes. Of which the low molecular acids are of main concern. The acids are produced as by-product of the oil and paper degradation.
To extend the technical life and to increase the reliability of the transformer, the moisture and acid level in the insulation should be kept as low as possible. Once the water and acid have been accumulated in the solid insulation, only effective drying and washing methods can remove them in an efficient way. The combination of the low frequency heating technique (LFH) with online oil reclamation gives now the possibility to remove these degradation accelerators also on site. An on site process has the large advantage of the reduced transportation cost and risk as well as a shorter total process time.
With the removal of moisture and acids can the degradation speed of the paper insulation be reduced and is thus leading to an extended technical lifetime.

2 Paper degradation

Ageing of the paper insulation in the windings is irreversible, and considered as one of the life limiting processes of a transformer. When the paper ages, its mechanical properties like tensile, bursting and folding strength is reduced. This was early described by Monzinger [4], who gave the rule that the rate of change of mechanical properties was accelerated with temperature and doubled/halved for every 6-8 degrees Celsius according to the formula:

$$\textit{Rate of ageing} = \textit{constant} \cdot e^{p\Theta}$$

Where Θ is a the temperature in Celsius and p a constant

Paper (and pressboard) consists mainly of cellulose and some percent of hemicellulose and lignine. The reduction in mechanical strength is due to chain scissions of the cellulose molecules, on average having a chain length of 1000-1200 polysaccharide rings in series – denoted degree of polymerisation (DP) - when the paper in the transformer is new. The tensile strength depends on the DP as shown in figure 1. Conventionally a DP value of 200 is used as an end of life criterion

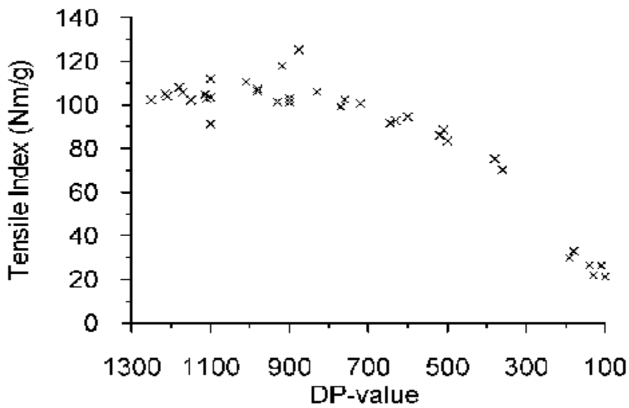


Figure 1: Tensile strength dependence of DP for Munksjø kraft paper

Instead of using tensile strength for ageing estimation one can use the scissoring of the cellulose molecules (η) reducing the DP value and Arrhenius dependence according to Ekenstam [5]:

$$\eta = DP_{new} \cdot A \cdot exp(-E/(RT)) \cdot t = DP_{new} \cdot k \cdot t$$

Here it is shown how the number of chain scissions (η) increases with time (t). The whole right hand expression in front of t describes the ageing rate k. *R* is the molar gas constant, *T* the absolute temperature and *E* - the activation energy- describes how temperature dependent the ageing is. The higher E is, the faster the ageing rate increases with temperature. *A* is a factor depending on the chemical environment of the cellulose.

It has long time been established that the ageing of cellulose can be divided in two processes: oxidation and hydrolyses [6,7]. For both processes the ageing rate increases with temperature. There are strong indications [8] that the temperature dependence is different for the two processes, and it may well be that oxidation dominates at lower and hydrolysis at higher temperatures.

The first mentioned mechanism of paper ageing is oxidation. The oxidizing agent in this environment is oxygen from air ingress. The ultimate end products of oxidation are the same as for combustion, i.e. water and carbon dioxide. The mechanism of low temperature oxidation is quite different from that of combustion, though. The oxygen concentration is of course an important parameter to determine the rate of oxidation. However, most experimental studies show that the ageing rate is not so strongly influenced by oxygen content. Typically, the overall degradation rate will no more than double in experiments with oxygen present, compared to when oxygen is totally excluded. We can therefore say that the importance of oxygen is limited.

The other major mechanism of paper ageing is hydrolysis. The significance of water content is paramount: a humidity of 3-4% may increase the degradation rate of paper by a factor of 10 or more, compared to dry paper. This underlines the importance on both assessing moisture and temperature. Bear in mind that the data are uncertain and not directly transferable to transformer life assessment.

Newer theories on hydrolyses proposes that this process is due to acid catalysis; H^+ (or rather H_2^+O) ions from carboxylic acids dissociated in water catalyses the chain scissoring of the cellulose molecules [9]. Since both hydrolysis (and also oxidation) produces carboxylic acids and water this makes the hydrolysis and auto-accelerating process.

Here one must be aware that the acids produced by the ageing of paper will predominately be lower molecular weight, hydrophilic acids like formic, acetic and levulinic acids, while oxidation of oils produces manly larger hydrophobic acids like stearic and naphtenic acids. That the various acids do influence ageing differently is demonstrated in an experiment where five different acids were added to the oil up to a neutralisation value of about 0,4 mg KOH/g [10].

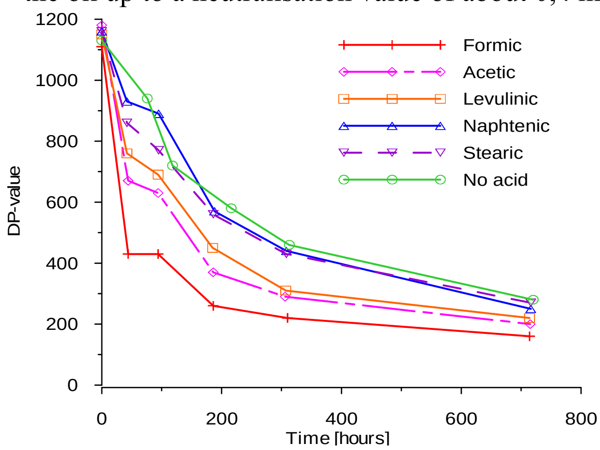


Figure 2: Ageing of paper at 130°C in oils with an acidity of 0,4 with x % water in

As can be seen from figure 2 do the high molecular weight acids not accelerate ageing, while for the other ones their impact increases with falling molecular weight. The reason for the different influence on the ageing rate is mainly to the hydrophilic nature of the lower molecular acids: The ones with lower molecular weight do dissolve easier in paper in the paper than the stearic and acetic acids [11].

The significance of these findings for maintenance is important. The ageing accelerating substances – water and low molecular acids will tend to dissolve better in paper than in oil. Removal of these substances from the cellulose is therefore what a

winding maintenance should aim for. Oil reclaiming will certainly remove some of these, but other methods will be more efficient.
It is in this context important to note that the measurement of the neutralisation value as is standardised in IEC 62021-1, do mainly detect acids formed by oil ageing. Detection of the dangerous hydrophilic acids do call for another measurment technique: Water washing of an oil sample will remove the low molecular acids from the oil sample, and taking the difference between a measurement on “pure” and a water washed oil sample may will yield a descriptor for these acids. Probably one can use reduction and the long-term stability of this value along with the water content as a quality test of a winding refurbishment.

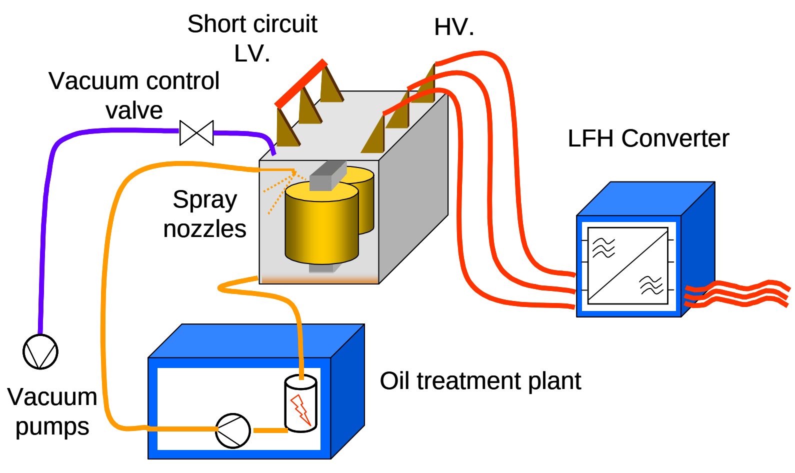
3 Onsite moisture and acid removal

An efficient moisture removal from the oil impregnated insulation material within a power transformer is only possible with the combination of heat and vacuum [12]. Typically temperatures above 100°C and vacuum below 1 mbar should be achieved. As parts of normal transformer oil will evaporate at these conditions, other means of heating are necessary. A well-proven technique is the heating by a low frequent current. The high temperature in combination with the low pressure has also the advantage that low molecular acids will evaporate.
An other acid removal technique is the online oil reclamation with Fullers earth. By circulation the hot oil several times over large amount of absorbent, acids and other oil degradation products can be removed from the oil as well as from the paper. The oil reclamation do also reduce the production of new acids as the oil degradation can be almost stopped.

4 Basic technology of the low frequency heating (LFH) drying technique

Temperature and vacuum are the main factors for the drying speed and the drying quality. For an optimised drying, the transformer should be heated at the same time as vacuum is applied (as done in the vapour phase process). With the combination of the LFH technique with hot oil spray or hot oil circulation, this can also be achieved on site.
The low frequency is necessary in order to reduce the applied voltage on the transformer when it is under vacuum, as the breakdown voltage is much lower than under atmospheric pressure, also known as the Paschen law.
In order to prevent hotspots during the drying (due to reduced cooling), is the heating current for power transformers normally not exceeding 50% of the nominal current. Thus the copper losses will be max. ¼ of the nominal losses and the risk of potential hot spots at points with higher resistance is negligible.

4.1 Plant and process concept



In order heat up both low and high voltage windings, a frequency of approx. 1 Hz is applied to the transformer. With the combination of LFH drying and the conventional hot oil spray method the whole transformer can be heated very uniform. The LFH system is heating the windings from the inside and the hot oil spray supports the heating process by heating outer parts of the insulation system.

Figure 3: Plant concept for a mobile LFH drying process in combination with hot oil spray.

5 Online oil reclaiming technology [13]

The essential elements of the online reclamation technology are that the absorbent is automatically reactivated after each cycle and that the transformer is in operation. The reactivation allows for using much more active absorbent than with the classical type of reclaiming plants, where the Fullers earth needed to be replaced after short time and thereafter had to be dumped. To achieve a long lasting effect, the complete oil volume is typically circulated 8-12 times over the Fullers earth. The final step is to restore the inhibitor content.

5.1 Comparison with oil change

There are several attractive features of online reclaiming compared to an oil exchange. Although it for safety reasons sometimes may be necessary to shut down the transformer when the equipment is being connected and disconnected, the process can be run when transformers are energized. This can have a large impact on total costs in some cases.

From a technical point of view, the repeated, or rather continuous washing of the solid insulation represents a large advantage. During aging of the oil, large amounts of acids, sludge and other degradation products are absorbed by the paper and other cellulose material. They can later be redissolved into the new clean oil. In the case of reclaiming, this happens largely already during the process, in which they are permanently removed shortly after being dissolved from the cellulose. In the case of oil replacement without proper cleaning of the active part, these residual degradation products will cause a substantial shortening of the life of the new oil. Without an appropriate washing procedure, the oil will typically be degraded again after only a few years. See also fig. 4.

5.2 Long- term stability

The long-term stability and oxidation stability of reclaimed oil has been questioned. One reason for this is that the conventional reclaiming process (without reactivation of the absorbent) with the daily Fullers earth exchange was often executed with limited amount of absorbent. As a result of this, the aging by-products were not removed from the cellulose material and as they act as promoters for oxidation, the oil was again degraded in a very short time.

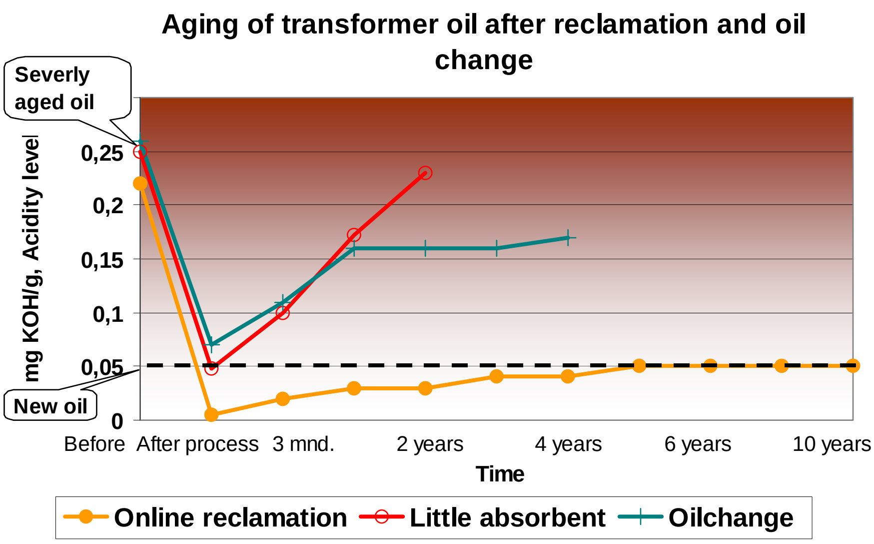


Figure 4: Evolution of total acidity in oil after online reclamation, oil change and reclamation with little absorbent

The modern reclaiming technology with the reactivation of the absorbent makes it economically feasible to use much more active absorbent material. Typically 5-10 times more absorbent is used compared with the old conventional systems. This leads to a much better cleaning effect of the paper and to an excellent long-term stability of the reclaimed oil.

For some transformers, there are data available from 10 years back. We find that after more than 10 years there are still only small changes in acidity and colour.

For a successful reclamation process with excellent long-term stability approx. 700 kg of active absorbent is necessary to treat 1000kg oil.

To prevent excessive production of acids due to oil degradation, it is recommended to reclaim the oil before it is severely degraded. Low molecular acids do migrate into the paper insulation from where they are much harder to remove then from the oil. A limit of 0,1 mgKOH/g for the acid level in the oil seems to be reasonable. Besides the acidity level are dielectric dissipation factor (tan d), inhibitor, colour and interfacial tension valuable indication

6 Practical experience with onsite rehabilitation of the insulation system

6.1 Start condition

Two 200 MVA net-transformers were showing severe rust damage on the cover and on different flanges. Oil and gas analyses showed also that the oil was degraded and that the moisture level in the insulation was higher then desired. The costumer decided to treat the damaged surfaces and at the same time to rehabilitate the insulation system by removing ageing accelerators like moisture and acids from the insulation material and the oil. The goal was to get rid of all the oil leaks, to stop the rust attack and to extend the technical lifetime of the transformer.
Due to the difficult transportation to the next transformer repair workshop was it preferably to execute all the work on site. A different aspect was also the expected total process time. As the two transformers were located at a central point in the net work, the process time should be limited as much as possible. By choosing the on site option, the total switch off time could be reduced considerably.

6.2 Summary of the moisture measurements (FDS: Dielectric response measurement)

Measuring method	Before repair	After repair (exposure to air)	After drying
Moisture in oil analyses*	15 ppm H_2O at 37 °C average temperature → 2,6% average moisture in paper		5,9 ppm H_2O at 34°C average temperature → 1,8 % moisture in paper
FDS	2,2 %		1,6 %
Paper samples	1,3 %,	4,4 %	1 %

Table 1. Summary of moisture measurements on transformer 1

*) For the calculation of the moisture in paper the moisture in oil was corrected with the acidity level.

The goal of the drying process was to reach a moisture level of approx 1,5 %. This level was chosen to make sure that all the moisture that enter during the repair (exposure to air) was removed without "over drying" of the thinner insulation parts.
The extracted water from the transformers was measured with a dew point measurement and was also collected in a water-cooled condenser. The measurements varied between 40-60 liters per transformer.

6.3 Acid removal during drying process:

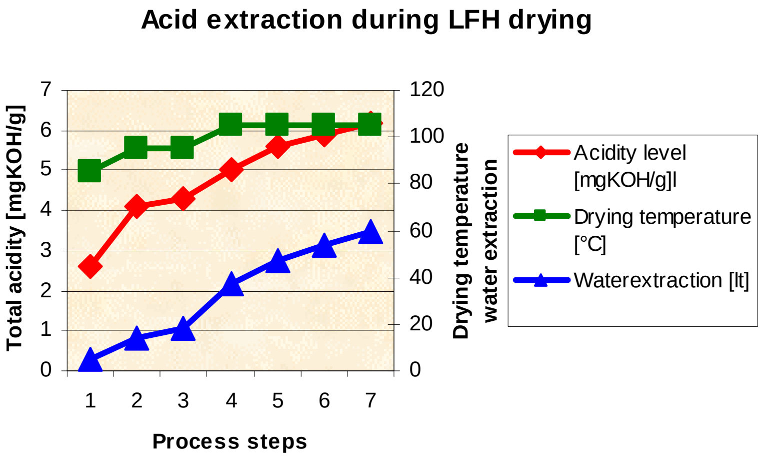


Figure 5: Acid and moisture extraction during the LFH drying process

The condensed water from the transformer was analysed for low molecular acids.
The water showed to be very acidic. It was reported form other cases [17] that vacuum pumps and condensers got damaged because of the high acidity of the condensed water. The boiling point of the low molecular acids is slightly higher then for water. The combination of heat and vacuum does evaporate them. Paper samples were taken before and after the drying process. After the drying was the acidity level in the paper reduced by approx. 20-30%.

6.4 Summary of the reclamation process

In parallel to the drying process was the oil reclaimed via a Fullers earth treatment. The Fullers earth does remove polar products from the oil as for example acids. Once the transformer was in operation again, the Fullers earth treatment (reclamation) was continued until the whole amount of oil was circulated 7-8 times over the Fullers earth. In order to check the reclamation process were the total acidity as well as the amount of low molecular acids measured before, after and 3-5 months after the reclamation process (table 2). It can be seen that almost all the acids, including low molecular acids, were removed from the oil and that acidity level was still very low after 3-5 months.

Table 2: Oil test results for the two treated transformers (DDF is Dielectric Dissipation Factor, IFT is Interfacial Tension)

	Before		After		Follow up	
	T1	T2	T1	T2	T1	T2
Total acidity [mgKOH/g]	0,08	0,16	0,004 *	0,001 *	0,005 *	0,005 *
Water soluble acids (LMA) [mgKOH/g]	0,013	0,03	<0,001 *	<0,001 *	<0,003 *	<0,003 *
Colour	3,0	4,0	1,0	1,5	1,0	1,5
DDF at 90°C (%)	2,1	5,4	0,07	0,11	0,26	0,28
IFT (mN/m)	26,9	18,7	49,3	49,1	46,8	46,7

*) The measured acidity values were very close to the detection levels of the instrument and with that including some uncertainty

7 Residual technical lifetime

By removing moisture and low molecular acids from the insulation paper, the paper degradation can be reduced and the expected residual lifetime could be increased to from 15-20 years to approx. 35-40 years.
These estimations are only valid when the operation conditions (temperature, load) are the same as in the last 30 years.

8 Conclusion

A high moisture and acid content speeds up the ageing of the insulation and leads to a shorter lifetime of the whole transformer. But high moisture content can also lead to the immediate failure of a transformer by causing the formation of bubbles or free water. Therefore, keeping the transformer dry is a major factor when looking at high reliability and extension of lifetime.

The LFH technique, combined with hot oil spray, now presents a strong tool to dry out even the largest power transformers on site in relatively short time. This has the advantage that the ageing process of the paper is reduced immediately and the transformers do not need to be transported to a repair shop, which would lead too much longer down times. The collected experience from the drying of over 50 transformers in the field shows that the moisture is reduced to very low levels and remains stable over years, which indicates that also inner parts of the insulation are dried.

Another ageing agent that needs to be considered are low molecular weight acids. They have a similar effect as water when it comes to degradation processes of the insulation. A drying process with temperatures above 100 °C will remove a part of the acids from the paper insulation, but to remove even more acids and to prevent the new formation of them, the transformer oil needs to be reclaimed with large amounts of Fullers earth.

The on-site reclaiming of oil on energized power transformers restores the oil's properties to very near those of new oil. This holds for all parameters that are routinely measured. The changes in properties during the first years in service after treatment are insignificant.

From an environmental point of view, the advantages of oil reclaiming compared to oil exchange are indisputable. Online oil reclamation technology with the reactivation of the Fullers earth causes close to none waste of oil and adsorbent, compared to traditional methods.

The combination of the LFH drying process with online oil reclamation creates the best possible environment for the insulation system at a power transformer without the risk and cost of transportation to a workshop with a vapour phase drying plant. This will lead to a substantial extension of the technical lifetime of transformers, and thus to an increase of the asset value.

9 Acknowledegments

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