21, rue d'Artois, F-75008 Paris
http://www.cigre.org

A2-205

Session 2004

PRACTICAL EXPERIENCE WITH THE DRYING OF POWER TRANSFORMERS IN THE FIELD, APPLYING THE LFH** TECHNOLOGY

**(LFH = LOW FREQUENCY HEATING)

PAUL KOESTINGER*, ERIK ARONSEN
ABB POWER TECHNOLOGIES DIVISION AS
(Norway)

PIERRE BOSS
ABB Sécheron SA (Switzerland)

GÜNTER RINDLISBACHER
Micafil AG (Switzerland)

Summary

Drying of a utilised power transformer is an object that has been worked on for many years. The main problem is to achieve an optimal drying of an aged power transformer without the displacement to a workshop, as this operation is very cost intensive and sometimes no longer possible. There is a wide range of possibilities known on the market. A new possibility is now offered with the so-called Low Frequency Heating System. This system and the process have developed over the time and are used in different countries. Over 40 power transformers with a power of up to 400 MVA were dried successfully on site. Long term measuring has been shown that much better drying effects could be achieved than with other known processes.

The latest development is the combination of the LFH process with other known processes such as the hot oil spray process. With such a combination the needed drying time could be again reduced and the achievable moisture values were considerably lower and are below 1% H_2O, coming into the range of the original values in the production. Thus the ageing velocity of the insulation material could be reduced massively and subsequently the lifetime prolonged.

Keywords:

Transformer, Drying, Onsite, Vacuum, Low-Frequency-Heating, Oil spray

Introduction

"Healthy" power transformers are one of the key components in a reliable electrical grid. Especially unplanned interruptions can disturb a large supply area, which can lead to enormous financial losses. On the other hand, the pressure to keep older units into operation for economical reasons is growing steadily. This leads to a situation, where the population of the transformers is getting older and at the same time running at a higher load, due to the steadily growing demand. Yet, transformers do not live forever. The life end of a transformer depends very much on the state of the solid insulation.

(*) paul.koestinger@no.abb.com

Due to 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 temperatures, oxygen concentration, acidity of the oil and the moisture content in the insulation. Especially water content and temperature play a major role (see Fig. 1). Temperature is mainly dependent on the transformer design, the loading, the cooling facilities, and the ambient temperature. Changing these parameters normally involves large investments. Water is accumulated in the paper insulation of the transformer and has different sources.

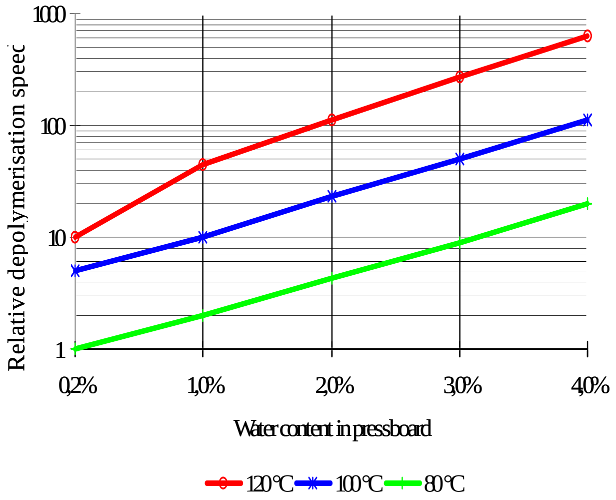


Fig. 1: Comparison of the relative depolymerisation velocity at different water content of a non oil-impregnated insulation paper [2] [6]

It can diffuse into the transformer on different paths. Not well maintained breathing apparatus on open breathing expansion tanks or broken sealing on the cover can be a source of water from outside. Examinations carried out by Sokolov, Griffin and Vanin [1] have shown, that in an open breathing system the moisture content in the insulation paper can increase by approx. 0.2 % per year. But also the depolymerisation (ageing) of the insulation paper and the ageing of the oil create water as a by-product inside the transformer. To extend the technical life and the reliability of the transformer the moisture level in the insulation should be kept as low as possible. Once the water has accumulated only an effective drying method can reduce the moisture level close to manufacturing values.
But not only the ageing of a transformer has to be considered because of the water content. There are other more direct risks with high water concentration in the insulation such as the formation of bubbles under heavy load conditions or free water formation when the transformer cools down [3].

The quantity of water inside the insulation in a large power transformer can reach several hundred litres (300 MVA Transformer, with 10’000 kg insulation with a moisture level of 3 % represents 300 litres water). The amount in the oil is normally negligible (300 MVA Transformer with 60’000 kg oil and 10 ppm H_2O at 30°C represents 0.6 litre water). There are well known drying techniques on the market that dry and degass the insulation oil either continuously or in intervals, but the fact that there is less than 1 % of the whole water in the oil, these processes failed to dry out large quantities of solid insulation within reasonable time. In the following, an approach is presented to dry the insulation out in the field, down to the range of factory production levels.

2. Physics of Drying

Three moisture-moving forces may be identified when drying a porous material as paper is considered:

1. Moisture gradient (isothermal diffusion)
2. Temperature gradient (thermo diffusion)
3. Pressure difference (convection diffusion)

According to the law of Fick the amount of moisture diffusing through a material is:

$$v = D * \frac{\delta C}{\delta x}$$

Whereby:

v = amount of moisture which vertically diffuses per unit of time through a defined surface
D = Diffusion coefficient [cm2/day]
C = Moisture concentration [%]
x = Distance
dc/dx = Moisture profile

The diffusion coefficient D exercises a linear influence on the speed of diffusion and is strongly dependent on:

- Temperature
- Moisture content
- Pressure difference over the diffusion path
- Material properties

The decisive influence of elevated temperatures and vacuum on the diffusion coefficient, respectively drying speed, is shown in figure 2 with the help of the relative diffusion coefficient. To optimise the drying process is even more important with oil impregnated pressboard, as the diffusion coefficient compared to dry pressboard is approximately in the range of 1/20-1/40 [4].

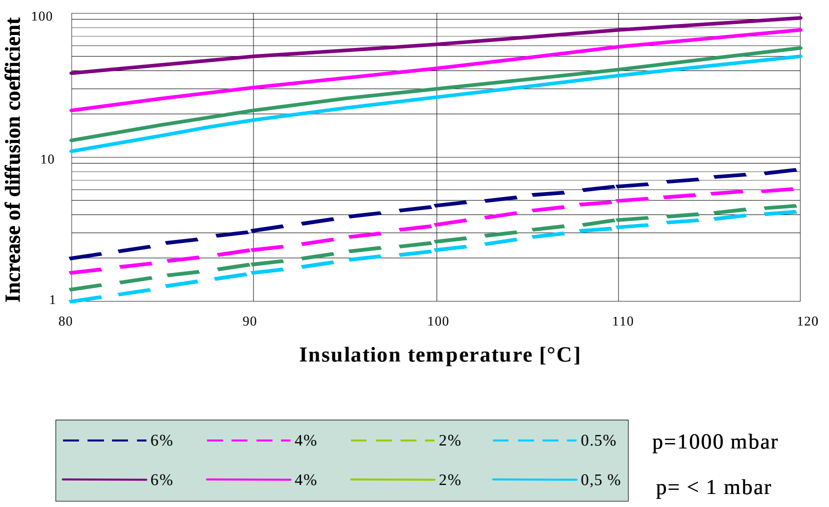


Fig. 2: Relative increase of the diffusion coefficient of a non-impregnated pressboard at different moisture levels, process pressure and temperatures [4] [6]

The practically achievable or better the economically justifiable moisture content is mainly determined by the achieved drying temperature and in minor extent through the reached final vacuum in the transformer vessel. As shown in figure 1, temperature and moisture content are two main criteria's for the depolymerisation. Therefore, the maximum admissible drying temperature must be determined for each process step in relation to the actual moisture content.

3. Basic technology of the low frequency drying

As shown previously temperature and vacuum are the main factors for the drying speed and 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). But under vacuum the breakdown voltage is much lower than under atmospheric pressure, also known as Paschen law.

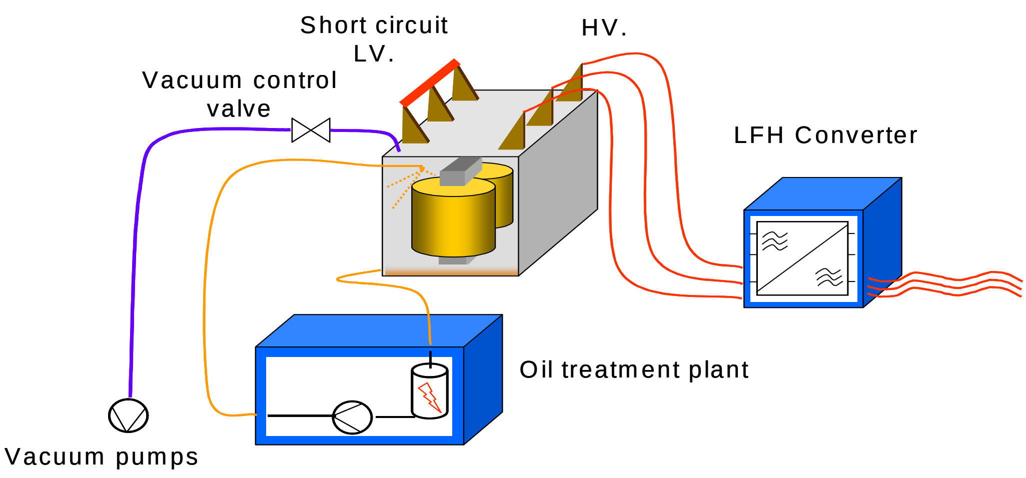
Thus it is not possible to apply normal short circuit voltages under vacuum without harming the transformer. By reducing the frequency, the short circuit impedance can be lowered so far, that at a low voltage a high current can flow through both windings. With the LFH technology the frequency is lowered so much, that the transformer effect is still working but the voltages applied are far below the critical level. Modern LFH plants are using the DTMH system (dual temperature measuring and heating system) to allow for the separate average temperature determination of the high and low voltage winding, as well as for separate heating of the high voltage winding. This is together with the so-called LF pulsation heating, a pre-condition for a uniform temperature distribution within the windings, which is very important for the on site drying of large power transformers. As a consequence, higher drying temperatures can be selected without the risk of local overheating due to hot spots. The LFH technology has been used for many years in the production of distribution transformers, but the development of the DTMH system allowed it to be used also on large power transformers.

3.1 Plant concept

The LFH plant includes:

- Frequency converter: supply 3*400 Volts 50/60 Hz, output: 3 phase max 650 A / 1000V, 0,001 – 5 Hz, rectifier, converter, transformer and measuring units for current and voltage.
- Control panel: Visualisation, process control, reporting
- Vacuum control valve, pressure and temperature probes for process control
- Moisture meter: for measuring water extraction rates
- Supply cables

To heat up both phases, a frequency of approx. 0.5 - 1 Hz is applied to the transformer. The corresponding current and voltage are measured continuously for the calculation of the actual resistances. The plant control checks the heat up speed and controls the applied current within the set limits. In addition an oil treatment plant heats the oil and the vacuum pumps are connected to the vacuum control valve.



4. On site drying by oil circulation or hot oil spray

The drying in the field with the hot oil spray or the hot oil circulation method in conjunction with vacuum applied to the transformer is very well known and had been practised for many years.

The main disadvantages of these methods are:

- Limited temperature
- No heating during vacuum phase with the oil circulation method
- Difficulty to get a uniform temperature distribution with the spray method
- Long drying times
- Limited drying quality

5. Combination with LFH method

With the combination of LFH drying and conventional methods, especially with "hot oil spray", drying results close in the range to factory levels were achieved within a short time. This has slowed down the effect on the depolymerisation of the insulation material and thus has a positive effect on the lifetime expectancy.

5.1 Process procedure for a combination with an oil circulation process

On the transformer to be treated, the low voltage winding is short-circuited and the high voltage winding is connected to the LFH unit. During the first heating phase, the oil will circulate over the oil treatment plant, where it is heated. In parallel, the windings are heated by means of the LFH heating. The combination of the hot oil and the current heating assures that all parts of the transformer is well heated up to a first temperature level. Once the temperature step is reached and the temperatures inside the transformer are stabilised, the oil is drained into a separate tank and vacuum is applied. For the next temperature step only LFH is used to heat the windings. During the electrical heating, the vacuum level is kept at approx. 30 mbar for safety reasons (Paschen law). If the temperature reaches the set point, the current heating is automatically stopped and only vacuum down to <1 mbar is applied. During this period most of the water will evaporate. The length of the heating break is dependent on the transformer size, humidity and insulation weight. After the break, the vacuum level is automatically brought up to 30 mbar again and the current heating is started again. This cycle is repeated as long as the moisture extraction rate is higher than a set point. The moisture extraction rate is automatically measured with a system (VZ 402), which is also used in the vapour phase process, to determine the end of the drying process. Finally the transformer is heated up to the final drying temperature where the same cycles run again. At the end of the process only fine vacuum is applied. Once the desired drying quality is reached, the transformer is filled again with oil.

5.2 Process procedure for a combination with a hot oil spray process

This process starts with the drainage of the oil so that only a small amount is left in the transformer. This oil is then circulated over the oil treatment plant, where it is heated and then sprayed over the transformer. Vacuum is applied from the beginning and the oil spray continues till the final temperature step is reached. Only then all the oil is drained from the transformer. The rest of the process control is the same as 5.1 This process has the advantage, that LF current heats the transformer coils from the inside, while the hot oil simultaneously heats the outside insulation which are not heated by the LF current.

6. Drying results

Over 40 power transformers have been dried on site with the LFH technology (see Fig. 3). The range varies from 6 MVA/12,5 kV to a 400 MVA/400 kV single-phase transformer. According to the actual requirements and the process control the average drying result could vary from 1,5 % down to 0,5 % residual humidity in the insulation. Such low values could so far only be achieved when the transformers were dried in a workshop with a vapour phase drying plant.

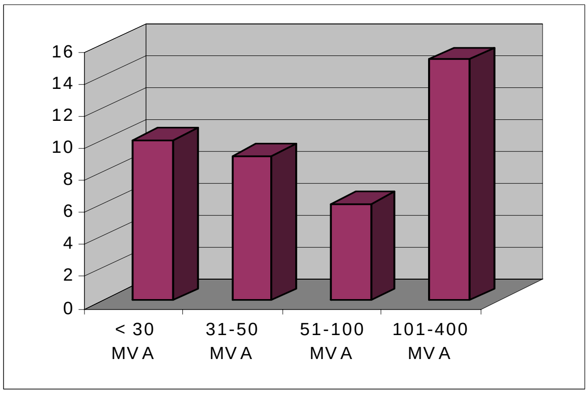


Fig. 3 : Quantity of power transformers dried in the field with LFH technology

The aimed moisture level is dependent on:

- Transformer voltage level
- Age
- Original moisture level
- Re-clamping possibilities of the windings after drying

The reclamping of the winding is a critical part in any drying process. Due to the water extraction the clamping pressure on the winding will be reduced [5]. The size of clamping pressure loss or the risk of even loose windings depends on:

- Amount of water extracted
- Pressing method of the winding during production
- depolymerisation value of the insulation material
- Max. winding temperature in service
- Temperature cycles in service

<u>General observations</u>:

With a total water extraction <1,5 % no loose windings were observed. Windings which were dried and pressed at the same time during the fabrication (pressing in the drying oven with an isostatic pressing equipment) show less shrinking during additional drying (experience from drying of aged transformers in vapour phase plants). Due to a possible felting of the insulation material with a lower DP value, the shrinking effect is reduced compared to new material.

Thermal expansion and contraction is different for the materials used in a transformer. This leads to different clamping pressure according to the temperature. The clamping pressure on a 20 MVA transformer which was pressed with 5 N/mm^2 at 90 °C will be reduced down to 3 N/mm^2 at 0 °C [5]. This fact is especially critical for transformers that were out of service during wintertime and facing a short circuit right after energising.

7. Evaluation of the drying parameters

As described before, the drying temperature besides the vacuum, is the most important parameter concerning the drying result and time. The temperature also influences the depolymerisation of insulation material therefore an optimal temperature control is essential.

The drying process using LFH drying is controlled in three different temperature steps (see fig. 4):

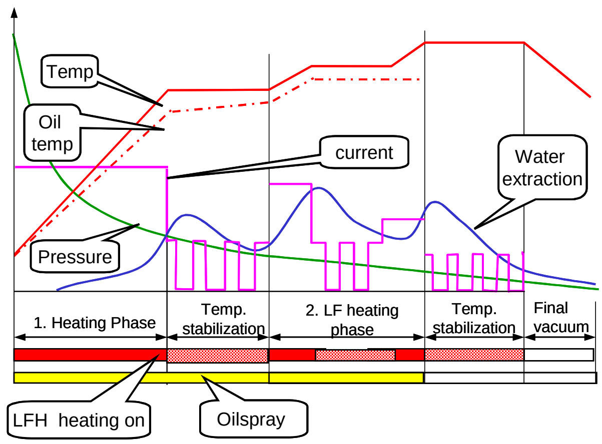


Fig. 4 : Process diagram of an LFH drying process with “hot oil spray”

Step 1 : at low temperature (70 – 80 °C) in order to extract as much water as possible in an early stage to limit the ageing effect.

Step 2 : at intermediate level. Normally the temperature is chosen according to the max. oil temperature (80 - 95°C).

Step 3 : step at the final drying temperature (90– 115°C). At this step, all the oil is drained from the transformer and only LFH heating is active.

During the last step, the thickest insulation parts are dried. The duration of the steps is dependent on the actual water extraction rate, measured with a VZ402. This instrument measures the partial water vapour pressure. As an alternative a cool trap installed after the vacuum pump can be used.

As the drying takes place under vacuum almost no oxygen is present. This technique reduces the ageing effect to a very low value. On several occasions, paper samples before and after the drying process had been tested, but no reduction of the depolymerisation value beyond the measuring accuracy could be measured. This shows, that even with higher drying temperatures no considerable ageing takes place. This due to the absence of oxygen, a correct selection of the temperature in relation to the moisture content in the insulation and the low water content at the final drying stage, as well as the short drying time.

8. Comparison of different drying technologies

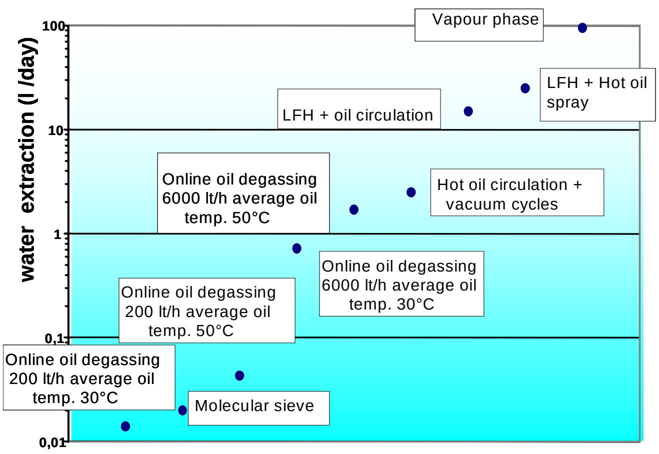


Fig. 5 : Drying velocity from 3% down to 1,5 % average humidity

As mentioned before many different procedures are available to dry out transformers on site or in a factory. Two major techniques are used:

- Drying the insulation by drying the oil
- Drying the insulation with heat and vacuum

Fig. 5 and 6 show a comparison of different techniques. In particular the fig. 5 shows the drying speed in terms of litre water/ per day extracted with the different techniques. All techniques are used on site, except the vapour phase drying process.

The indirect drying through the oil is much slower as the oil contains only a very small part of the total water (<1%). On the other hand it is not necessary to stop the transformer when drying it through the oil.

The time needed for the LFH drying is so short that it can fit in with most service shut downs of an installation. Not to be forgotten is

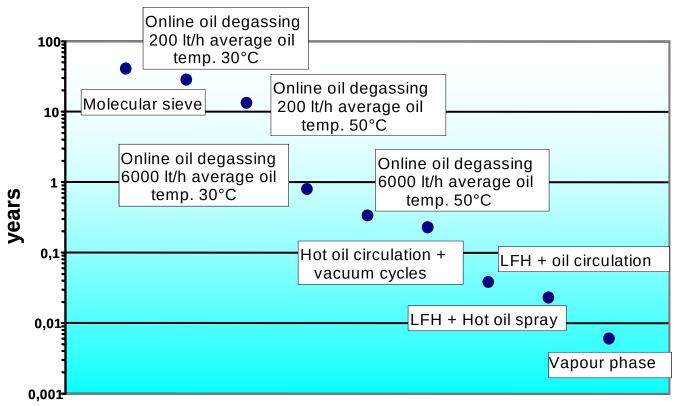


Fig. 6: Drying time to dry a 400 MVA transformer with 14 ton insulation from 3% down to 1,5 % average humidity

also the impact of the high water content on the paper ageing. A quick drying reduces the ageing effect immediately, where as with slower systems the same effect can only be seen in several years. The online degassing systems using it over a long time, make it nearly impossible, to detect failures with DGA analyses, which needs to be considered when choosing a drying procedure.

9. Conclusion

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

Recent studies in Norway showed that over 20 % of the power transformers >20 MVA have a humidity level above 2.2 %, urging the need of appropriate drying procedures.

The LFH technique, combined with the right procedures, now presents a strong tool to dry out even the largest power transformers on site in a 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 to much longer down times. Compared to the online degassing systems, an LFH drying does not influence the DGA analyses, that are used to detect failures in the transformer in an early stage. The collected experience from the drying of over 40 transformers in the field shows that the moisture level is reduced to very low levels and is stable over years, which indicates that also inner parts of the insulation are dried.

10. Bibliography

[1] V. Sokolov, P. Griffin, B. Vanin , Moisture equilibrium and moisture migration within transformer insulation systems, CIGRE

[2] B. Bouvier, Nouveaux critères pour caractériser la dégradation thermique d'une isolation à base de papier R.G.E. Tome 79 Juni 1970

[3] T.V. Oommen, Bubble evolution from Transformer Overload, IEEE Insulation life subcommittee Oct. 2000

[4] W. Lampe, Beitrag zur Berechnung der notwendigen Trocknungszeit von Grosstransformatoren, Archiv für Elektrotechnik, Band 53 (1969) Heft 3

[5] Ch. Krause, M. Prevost, D. Woodcock, The effects on winding clamping pressure due to changes in moisture, temperature and insulation age, sixty-seventh Annual International Conf. of Doble Clients, March 2000

[6] P. K. Gmeiner, Combi LFH-Trocknung von Leistungstransformatoren im Felde, Micafil Symposium, Zürich