LIFE EXTENSION OF POWER TRANSFORMERS
OIL REGENERATION, ON SITE DRYING AND ONSITE REPAIR

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1. Abstract

Poorly maintained transformer oil will significantly reduce the life of a transformer. The oil in a transformer can have a very long technical life but only if it is cared for properly. Even though during the life of a transformer several things can happen to jeopardize the function of the oil and consequently the function of the transformer, this can in most cases be corrected by appropriate maintenance activities.

Poor dielectric strength due to particle content and/or high water content can be mitigated by reconditioning, i.e. filtering and degassing. This can be carried out on-line or off-line. Drying of not only the oil, but also the solid insulation by methods involving vacuum and low frequency heating, will ensure a longer lasting effect and therefore is a better long-term solution.

Some of the properties of transformer oil change as it ages, especially if by oxidative processes. If, as a consequence, acidifies and sludge’s form, the dielectric properties slowly deteriorate. However the oil can be restored to nearly as-new condition by on-line reclaiming. Today this is a very efficient and environmentally friendly form of treatment, with the absorbent being reactivated hundreds of times before disposal, keeping waste products to a minimum. Oil reclaiming should always be followed by the addition of an inhibitor, to ensure that the oil stays in good condition for many years. If carried out in time, both the proper drying and oil reclaiming activities will add a significant number of years to the transformer’s technical life. With originally inhibited oil it is advisable to add new inhibitor before the initial content has been consumed. This very simple measure will not really improve the actual condition of the oil but if carried out in time it will significantly retard the oxidation processes and therefore prolong the time before more costly actions are required.

The purpose of this paper is to put the complexity of degrading processes into context and to give guidance on the remedial actions that will significantly improve the reliability and life of a transformer.

If a transformer has to be repaired in a factory, the transportation time from the end-user site to factory and return plays a major influence on the duration of the project and putting transformer back in service to resume power. Also the cost and risks associated with heavy transport must be considered.

To date a total of more than 300 transformers including utility, industrial, HVDC transformers and reactors have been successfully repaired on site. In many cases transformer output power were also upgraded to provide an increased rating using present advanced design tools.

2. Introduction/ Background

A transformer has many components that require maintenance. The insulating system is a truly vital part, consisting of the oil and the solid insulation. The solid insulation may not be so readily accessible, but the oil certainly is. Oil can be kept in a good condition for a very long time and with proper care, probably for an indefinite period of time. However, poorly maintained oil will significantly reduce the technical life of the transformer.

It is sometimes stated that the end of life of a transformer is ultimately decided by the end of life of the solid insulation. Even though it is true that many transformers are taken out of service before the solid insulation is so severely degraded, it is still true that the condition of the cellulosic insulation sets a limit for how long a transformer can be safely and reliably operated. For this reason alone, it is wise to carry out preventive maintenance.

2.1 Ageing of Oil and Cellulosic Materials

Oil is both the coolant and part of the insulation together with oil-impregnated paper and board. Both types of material are affected by several different ageing processes, and both materials are affected by each other. They can not really be treated independently of each other. They function together; age together, a bit like Siamese twins. Nevertheless, this paper will discuss the main degradation mechanisms of each separately, as far as it is possible.

2.1.1 Oil

Transformer oil is at the same time both very simple and very complex. It consists mainly (>99%) of hydrocarbons, a mix that is not very different from diesel fuel. However, it has thousands of different components; however, some of the minor components have a major impact on its properties.

The main degradation mechanism is oxidation. This is a very complex process, especially since in real life the degradation of oil and of paper interacts with each other to a large degree. Some of the important features are listed below:

- The rate of degradation is dependant on temperature (as all chemical reactions are).
- It also depends on access to oxygen. This cannot however be eliminated unless the oxygen is completely excluded, which is unrealistic to achieve.
- It is a chain reaction. Free radicals and peroxides are the most important intermediates.
• The oxidation is catalyzed by metal ions. It should be noted that copper can be dissolved in oil by the action of some of the oxidation products.

• The presence of substances acting as radical scavengers, peroxide scavengers and metal deactivators will retard the process.

There are both “inhibited” and “uninhibited” oils. This refers to the use or non-use of synthetic peroxide scavenging antioxidants. When the use of such an additive is accepted, the oil can have a very high degree of refining and relies mainly on the ability of the phenolic antioxidant to suppress the oxidation process by halting the process at a very early stage. “Uninhibited” oils, on the other hand, must contain a certain amount of sulphur compounds to act as peroxide scavengers and some aromatic and polyaromatic hydrocarbons as natural precursors to radical scavengers formed by oxidation. A correctly formulated inhibited oil has a very long technical life, with very little production of detectable oxidation products as long as there is sufficient inhibitor left. The uninhibited oil will start to oxidize and produce acids early in its life but will age in a fairly predictable way.

The most important products from the oxidation are acids and sludge, and to some extent water. Sludge is a mix of strongly polar compounds with poor solubility in oil, which causes it to precipitate, forming deposits. How the acids and water produced in the ageing process will influence the cellulosic material will be discussed later, though it should be mentioned here that the amount of water produced from the ageing of a well maintained oil system is probably insignificant compared to the contributions from water ingress and what is produced in the paper.

Besides oxidation, there are other possible reasons for the degradation of oil. Local overheating may produce small hydrocarbons and hydrogen. Electric discharges will give rise to similar products (though with more acetylene and hydrogen present). This is extremely important for the detection of incipient faults using DGA (dissolved gas in oil analysis). However, for the long-term stability of the oil, these mechanisms are of minor importance. If there is some fault condition that causes significant production of such gases, that is a bigger and much more urgent problem than the normal ageing of oil.

2.1.2 Paper.

Board and paper have three main components, cellulose, hemicellulose and lignin. All components influence the properties of the material. However, it is the degradation of the main component cellulose (and to some extent hemicellulose) that has the greatest effect on its mechanical properties.

The most important degradation mechanism of paper and board is the “specific acid-catalyzed hydrolysis” of the cellulose. “Hydrolysis” means decay under the influence of water and “specific acid-catalyzed” means that the process is accelerated by dissociated acids that provide free hydrogen ions. Laboratory ageing experiments with paper in oil indicate that the degradation rate is nearly proportional to the water content, at least within the range of water content that it is realistic to encounter in transformers windings. However, the rate-determining reactions depends more on the amount of dissociated acids than access to water. Hence, the effect of water content is to increase the availability of hydrogen ions, since the acids with most impact, small carboxylic acids like formic and acetic acids, are more dissociated the higher the water content is. The hydrolysis itself will consume some water but this process is followed by dehydration reactions that produce water. Oxidative processes also contribute, probably mainly by producing water and acids, and by activating the cellulose molecule, introducing functional groups making it more susceptible to hydrolysis. At very high temperatures pyrolysis will contribute but this should only be significant in case of a thermal fault.

The dielectric strength is not very much affected by the ageing process. With the paper it is mainly the changes in mechanical properties that is a cause for concern. When the paper is too degraded, the ability to withstand vibrations and short-circuit stresses reduces dramatically. High water content will of course influence the dielectric properties but this can be corrected. However, the changes in mechanical properties due to degradation of the cellulose chains are irreversible.

2.1.3 Other sources of water

The degradation of paper and board produces significant amounts of water. However, there are other contributing factors. There will always be some residual water in the solid insulation of a new transformer. Even though the active part is dried before oil impregnation, there may be in the region of 0.5 % residual water. Ingress of water by several different mechanisms may also be a major contribution and is considered to be the most important in many cases.

2.1.4 Distribution of Degradation Products between Oil and Paper

It is very important to understand that many polar compounds, including the most important degradation products, are distributed between oil and paper, sometimes very unevenly so. This is especially important for water but actually applies to many other substances as well.

Many studies have been made on the equilibrium between water in paper and water in oil. Fig. 1 below shows the results from a study carried out by ASEA in Ludvika in 1972. It serves well to illustrate the phenomenon.
The most important conclusion is that at all realistic temperatures, the bulk of the water will reside in the solid insulation. This has several important implications. Most importantly, it means that drying a transformer by drying the oil alone will be a very inefficient and time-consuming business. It also means that estimating total water content in a transformer from determining the amount of water in the oil is complicated and may be quite uncertain, as will be discussed later.

Let us consider an extremely simplified case, just to illustrate the difficulties of drying a large transformer by continuous drying of the oil by degassing. Let us assume we have a large transformer, with 10000 kg of cellulose and that we want to reduce the water content in the solid insulation from 3% down to 1%. This means that we want to remove 200 kg of water. Let us further assume that we have a constant average temperature of 40°C. We would then have a water content in the oil of 15 ppm. If we reach the desired end-point we would at equilibrium find approx. 2 ppm in the oil. If we have during the whole treatment an average water content of 7 ppm (very optimistic, considering the slow transport of water from thick structures!) and treat 3000 kg of oil per hour with a degasser removing all the water from the oil (also very optimistic), then we would remove 0.021 kg per hour, or 0.5 kg per day. It would then take 400 days of round-the-clock drying of oil to achieve the set goal, even with the very optimistic assumptions made in this example. In reality the time would surely take much longer. It is more likely to take few years, with a vacuum degasser tied up full-time and during that period there would be no possibility to do DGA with any accurate interpretation.

Water is not the only substance that is distributed between oil and paper. It is a similar situation with small carboxylic acids, furanic compounds and carbon oxides (CO and CO₂), to mention just a few. In all condition assessments it is important to know if anything has upset this balance. E.g. after reconditioning or reclaiming of oil, it may be months until equilibrium is re-established, and the apparent production rates of gases and furanes are near the true values.

3. Condition Monitoring
In order to be able to choose the correct maintenance activity and specific actions to be carried out, the true condition of the oil and solid insulation must be known. Regular DGA, though not the subject of this paper, is of course essential, however, tests more directly aimed at assessing the condition of the oil (and paper) are more valuable.

When assessing the degree of ageing of the oil, the most relevant oil tests are acidity, colour, dielectric dissipation factor and interfacial tension. For inhibited oil it is very useful to monitor the inhibitor content, since very little degradation of oil will occur as long as there is sufficient inhibitor left. A useful parameter to assess the degree of degradation of oil is the “Oxidation Index” (not to be confused with DP of paper). The Oxidation Index is obtained by dividing the interfacial tension by the acidity. It has been suggested that oil should be reclaimed or replaced when this values is lower than 300.

The water content in the oil is strictly speaking just a reflection of the water content in the solid insulation, since that is where the bulk of the water resides. A rough estimate of water content in the solid insulation can be made if the temperature is known, and has been stable for some time. However, there is great uncertainty in the accuracy of such an estimate, for several reasons.

- It can rarely safely be assumed that equilibrium has been established. With a cyclic load it will never be attained.
- There is not a uniform temperature distribution in an operating transformer. The water content in different regions will therefore be different. The difference between the coldest and hottest areas can be large.
- Several water in oil versus water in paper curves exist. These will differ depending on type of paper and oil and the degree of ageing of both.

However, in spite of these difficulties, a rough estimate is better than just a “raw” value of water content, especially one without any reference to temperature. If water content values are converted into a corresponding value at a reference temperature or a water content of the solid insulation, it is more or less a matter of taste, since these two approaches really amount to the same thing.

It is possible to estimate the water content in the solid insulation in other ways. One approach is to use sensors...
that give readings of the degree of saturation with water ("relative humidity"). This will overcome some of the problems. An even more advanced method is dielectric frequency response (DFR). This requires special equipment and some knowledge of design and geometries to obtain a meaningful interpretation. On the other hand it will provide more accurate estimates, if the interpretation is done correctly. \(^4\) Even a test so seemingly straight-forward as the dielectric breakdown voltage of the oil, may in some cases be misleading. Many poor breakdown values are the result of improper sampling and handling of the samples, such values should always be confirmed before any remedial action is taken.

In spite of all the difficulties, and in order to end this section on a more optimistic note, it must be said the water content by Karl Fischer titration and the dielectric breakdown voltage will usually together give a fair idea of if a transformer is wet or not, at least if historical data for the unit in question is available.

### 3.1 Remedial actions

There is a whole range of maintenance actions at our disposal, depending on what conditions need to be corrected. Decisions should always to be made on a case-by-case basis and should use as much information as possible, including any data from oil tests, DGA, etc.

#### 3.1.1 Oil reconditioning

Reconditioning is “a process that eliminates or reduces physical contamination by means of physical processes (filtration, de-humidification, degasification, etc.)”. \(^6\) Typically this means a combination of mechanical filtration and vacuum degassing. It can be done both off-line and on-line. The effect is normally an efficient removal of particles larger than a certain size and removal of most of the dissolved water and gases in the oil. It is usually sufficient to correct a poor breakdown value of oil, due to a combination of particles and high water content, which is not a very unusual condition.

It will sometimes be necessary to carry out such a treatment. However, it is not a long-term solution for a wet transformer, since only a small fraction of the total water content is removed. To obtain a significant reduction of the water content in a transformer, a more powerful technique must be applied. This will be discussed in more detail later.

#### 3.1.2 Oil reclaiming

Oil reclaiming is, according to IEC, “a process that eliminates or reduces soluble and insoluble polar contaminants from the oil by chemical and physical processing”. \(^6\) This very wide definition covers many different treatments, but we will limit the discussion to the case when aged acidic oil is restored to nearly as new condition by state-of-the-art on-line treatment.

The essential elements of modern reclaiming technology are that relatively small amounts of sorbent packed in columns are used and that the sorbent is reactivated after each treatment cycle. In the simplest (but fully sufficient) execution no chemical pre-treatment is involved. The process is run in two alternating modes:

##### 3.1.2.1. A Treatment mode

Where the oil is:
1. Pumped from the bottom of the tank
2. Heated (if needed)
3. Run through the sorbent columns
4. Filtered and degassed
5. Returned to the transformer

After some time the sorbent will get saturated and ceases to remove very efficiently acids and other polar substances from the oil. Then the system is switched to reactivation mode.

##### 3.1.2.2. B Reactivation mode

In this stage, the sorbent columns are by-passed, and the oil led directly to the filter-degasser. The sorbent is reactivated by in situ incineration of the organic material collected on the columns. Meanwhile it is possible to continue to circulate the oil, in order to lower even further the water content and the amount of dissolved gases.

This sequence A-B is repeated until the desired oil quality is achieved. The sorbent can be reactivated several hundred times. This means that the amount of waste per ton of oil treated is very small. Furthermore, this minute
quantity of spent sorbent is problem-free from a disposal point of view, since the last reactivation leaves it free from oil.

During the reactivation phase the columns are by-passed (indicated by the dotted line) and the oil only circulates through the filter/degasser.

The final step is re-additivation. It is essential to restore the inhibitor content to the range 0.3-0.4 %, which is considered the optimal for inhibited oil. The appropriate amount is dissolved in a portion of the newly treated oil. This stock solution is introduced in the main oil flow and then circulated until it is well blended. Upon a customer’s request, metal passivator can also be added in the same manner, to further improve the oxidation stability.

During reclaiming of the oil in a transformer, samples are drawn regularly to monitor the progress. Changes of some properties of the oil during treatment are shown in Fig. 5. N.B That the drying effect is only temporary, since water will redistribute from the solid insulation into the oil.

Extensive oil tests are routinely carried out before and immediately after treatment. A follow-up sample is taken after a few months. Data from three mobile units in Scandinavia have been compiled in Table I.

Table I. Data from 247 transformers treated in Norway and Sweden. DDF is Dielectric Dissipation Factor, BDV is Breakdown Voltage, IFT is Interfacial Tension, DBPC is content of antioxidant di-t-butylparacresol. A comparison is included with the recommended limits for unused mineral insulating oil filled in new power transformers, before energisation (from IEC 60422).

<table>
<thead>
<tr>
<th></th>
<th>Acidity (mgKOH/g)</th>
<th>Colour</th>
<th>BDV (kV/2,5mm)</th>
<th>DDF at 90°C</th>
<th>IFT (mN/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before</td>
<td>0,157</td>
<td>4,1</td>
<td>68</td>
<td>0,081</td>
<td>23,5</td>
</tr>
<tr>
<td>After</td>
<td>0,009</td>
<td>1,5</td>
<td>80</td>
<td>0,003</td>
<td>46,0</td>
</tr>
<tr>
<td>Follow-up</td>
<td>0,014</td>
<td>1,6</td>
<td>74</td>
<td>0,006</td>
<td>42,3</td>
</tr>
<tr>
<td>IEC 60422</td>
<td>0,03</td>
<td>2,0</td>
<td>55-60</td>
<td>0,010</td>
<td>35</td>
</tr>
</tbody>
</table>

Figure 3: Mobile oil reclamation plant in action

Figure 4: Simplified Scheme for On-Line Reclaiming Of Transformer Oil.

Figure 5: Acidity, Colour And Water Content Measured During On-Line Reclaiming.

"No of circulations" is the treated volume expressed as an equivalent number of total oil volumes of the transformer in question.
The oxidation stability of reclaimed oil can not be expected to be quite as good as that of the highest quality inhibited oils produced today. After all, there have been advances in refining technology. However, it has been found that with re-inhibiting the oxidation stability of reclaimed oil is on par with oils fulfilling the requirements for inhibited oils in IEC 60296:1982, which is a fair comparison, considering what the vintages are of oil that are normally the subject of reclaiming.  

There are several attractive features of reclaiming, compared to exchange of the oil. Although for safety reasons sometimes it is necessary to de-energise the transformer when the reclaiming equipment is being connected and disconnected, the process can (and indeed should) be run when transformers are loaded. This may have a major impact on total costs, depending on how production losses are valued.

From a technical point of view, the repeated or continuous “washing” of the solid insulation represents a major advantage. First of all, in the case of oil exchange, there are several % of the old oil in the solid insulation that will contaminate the new oil. Furthermore, during aging of the oil and paper, significant amounts of acids, sludge and other degradation products are accumulated in the paper and board. They can later be partially re-dissolved by clean oil. In the case of reclaiming, this happens to a large extent already during the process, in which they are permanently removed shortly after being extracted from the cellulose. In the case of oil replacement without proper cleaning of the active part, residual degradation products in oil and paper can cause rapidly enhancing levels of contamination of the new oil as well.

To summarize the effects of on-line reclaiming with modern technology, we conclude:

- On-line reclaiming restores the oil’s properties to close to those of new oil.
- The oxidation stability of the reclaimed oil is good when the treatment is combined with re-inhibiting.
- The changes in properties (due to recontamination from degradation products in the solid insulation) during the first years in service after treatment are small.
- From an environmental point of view, the advantages compared to oil exchange or traditional reclaiming technologies are indisputable. The most important reasons are that oil is not a renewable resource and the new technology causes much less waste of oil and sorbent than traditional methods.
- More than 700 transformers successfully treated in the Scandinavian countries alone

### 3.2 Reinhbiting as stand-alone action

Reinhbiting is not only an indispensable part of the oil reclaiming process. With originally inhibited oils, it will sometimes be possible to replenish the phenolic inhibitor content before the on-set of oxidation at a significant rate.

This may prolong by many years the time before more costly maintenance actions such as reclaiming are needed. However, it needs to be done in good time. The IEC insulating oil supervision and maintenance guide recommends that this is done when 40-60% of the original content has been consumed. 6

In absolute numbers this corresponds to the range 0.12% to 0.24%. However, it may be worthwhile to do this even at lower inhibitor contents, even below 0.10 %, provided that the oil is still in good condition. However, it should be stressed that reinhibiting will not restore the oils properties; it will only further retard the oxidation process.
3.2 Removal of Moisture from the Paper insulation

Oil analyses normally include also the measurement of the moisture in oil. As shown earlier in the paper, the amount of moisture in the oil is in relation to the amount of moisture in the paper. However, it is very important to remember that the moisture in oil is only an indicator of the total moisture content and not a moisture reservoir, as over 99% of the moisture is absorbed by the paper insulation. Thus any oil change or short time oil treatment will not be able to remove any considerable amount of water from the transformer.

A typical drying process for power transformers includes vacuum and heat (as it was earlier shown that the drying through the oil is not very efficient). Preferably, one should have both carried out at the same time. But as vacuum is thermally insulating the inner part of the transformer (like in a thermos bottle), the heat transfer to the windings is almost impossible with external heating. Conventional site drying processes normally include a heat cycle without vacuum followed by a vacuum cycle. These processes have different disadvantages:

- Limited drying temperature as the heat transfer media is oil.
- Substantial temperature drop during the vacuum cycles due to the energy needed to evaporate the moisture.
- Several heating cycles are needed were the insulation is exposed to heat as well as oxygen (potential stress for the insulation paper).
- Long drying processes are needed to achieve a substantial reduction of the moisture content in the insulation (typically several weeks).
- Oil spray processes cannot reach the inner part of the windings due to the covering of the winding blocks in the power transformers.

To overcome these disadvantages, ABB has developed a new on site transformer drying process equipment that is based on the heating of the windings with a low frequency current (LFH system). The goal was to heat up the whole transformer uniformly under a vacuum.

To achieve this, a mobile solid state low frequent current source was developed. In order to heat up the low and high voltage windings, a frequency of approx. 1 Hz is applied to the transformer. With the combination of LFH drying process and the conventional hot oil spray method, the whole transformer can be heated very uniformly. 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.

The LFH process combined with hot oil spray allows us to reduce the drying time substantially. It is possible to reach the same low levels of moisture in the whole insulation as with a factory process (applying vapour phase), within 1 to 2 weeks. Compared to “conventional” systems like hot oil circulation or hot oil spray, this is a time reduction by approximately a factor of 2-4.\(^7\)

![Figure 7 LFH Plant Concept](image)

3.2.1 Drying results.

Over 60 power transformers have been dried on site with the LFH technology. The range varies from 6 MVA/12,5 kV to 750 MVA/500 kV transformers. 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 only previously be achieved when the transformers were dried in a workshop with a vapour phase drying oven.

The target moisture level is dependent on:

- Transformer voltage level
- Age (degree of paper depolymerisation)
- Original moisture level
- Re-clamping possibilities of the windings after drying

Due to the water extraction the clamping pressure on the windings will be reduced.\(^8\) However, research carried out on large power transformers showed that this reduction effect is limited to approx. 5% of the original clamping pressure while staying above a moisture level of 1%. An additional 7% were “lost” when drying the transformer down to 0,5% residual moisture. Therefore, the drying on site is stopped at around 1%, whenever re-clamping is not a viable option.
3.2.2 Effect on low molecular weight acids.

Not only water is removed by the process. The low molecular weight acids have only a slightly higher boiling point than water. Thus heating the transformer over 100 °C with the combination of vacuum will also evaporate these acids. This can clearly be seen when analysing the extracted water during the LFH drying process. It contains large amounts of acids. The typical values for the neutralisation value in the condensed water are between 5 – 20 mgKOH/g (the typical content of low molecular acids in the oil 0.02 mgKOH/g).

3.2.3 Combination of LFH drying and reclaiming

Quite often transformers with acidic oil that needs to be reclaimed are also in need of drying, and vice versa. LFH and reclaiming can then be combined. There is already extensive experience of this practice. Since this combined treatment removes a large fraction of the main accelerating factors in the ageing of paper (water and low molecular weight acids) and also the acids in the oil, the long-term effect on paper ageing is even greater. The drying and reclaiming processes can in part run in parallel which reduces the total process time and cost.

3.3 Comparison of different drying technologies

As mentioned before, 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

The indirect drying through the oil is much slower as the oil contains only a very small part of the total water, <1% (see also the example under the paragraph Distribution of Degradation Products between Oil and Paper). On the other hand, it is not necessary to stop the transformer when drying it through the oil.

Continuous oil dryers are very convenient whenever a transformer needs to be kept dry or as an emergency measure when there is a risk of formation of water droplets when the transformer is cooled down. However, for the dry out of humid bulk insulation in an aged transformer these systems will hardly be able to remove sufficient moisture to change the speed of degradation and thus extend the remaining lifetime.

A quick drying reduces the ageing effect immediately, whereas with slower systems, the same effect can only be seen after several years. Whenever an online degassing system is used, it makes it nearly impossible to detect failures with DGA analyses. This will increase the risk of a major failure on the unit. This fact beside others needs to be considered when choosing a drying procedure.

3.3.1 Life time extension of the insulation system

With the appropriate measures one can extend the technical lifetime of the organic insulation system substantially. The removal of the ageing accelerators like moisture and acid will slow down the degradation process. In addition the formation of further ageing accelerators will be reduced. All this is leading to an extension of the time it takes for the insulation to reach a state where it is no longer withstanding the stresses applied to it.

However, by keeping the insulation system in a good shape, one has also a larger margin when it comes to daily stresses upon the system (stronger paper, better insulation capability of the oil...). This is results in a higher reliability of the whole system. It is also important to understand that the degradation of the paper is accelerated by the by-products formed from it. Conditions are thus gradually getting worse as the transformer ages.

Exactly how much the removal of water will slow down the ageing is difficult to predict. However, recent research results suggest that within the range of water contents that can reasonably be expected in real transformer windings, a halving of the water content (e.g. from 2% to 1%) should lead to at least a halving of the ageing rate. The effects of acids are even more difficult to predict, since different acids have different activities. However, oil reclaiming as well as the removal of acids that takes place during LFH drying will certainly have significant effects.

It is thus not possible to give a simple figure for all transformers, however, one can make some estimates for single units if the:

- Actual state of the degradation is known (how far has it come)
• Actual amount of degradation accelerators is known (moisture, acids)

• Future load pattern is resembling the historical transformer load

From this information one can simulate the estimated life time extension by applying the different counter actions. Of course such a simulation will always be a rough estimation. In the very simplified example in Fig. 9 the kinetic parameters suggested by Lundgaard (for initially dry paper under oxygen-poor conditions) have been applied. Arrows indicate the time to reach an end-of life criterion of DP 200, without and with removal of half the water content after a certain time. In real life, water ingress would contribute to build-up of water and the effect of oxidation would also make conditions in the windings progressively worse. Models can of course be made that take also this into account.

![Figure 9. DP versus time curve based on kinetic data from laboratory ageing experiments. Drying with 50% reduction of water content after 15 years.](image)

The main points for an optimal result are:

• Don’t wait too long. When less of the original lifetime is left, there is less to gain.

• Effective removal of moisture and acids is a must for the life time extension of an already aged system (if the moisture removal takes several years it might be already too late)

• Act before large amounts of moisture and acids are formed inside the transformer

**Conclusions**

Proper oil maintenance coupled with the removal of water from the solid insulation, when required, will improve the long-term reliability of the insulating system and thus help prolong the technical life of the transformer.

It is important to know that oil and paper interact and what is carried out for one will influence the future of the other. The distribution of degradation products, such as water, between the two will influence strongly what maintenance actions that are beneficial, especially in the longer term.

A proper condition assessment, based mainly (but not exclusively) on oil tests, is the basis for sound decisions about what maintenance activities should be carried out on the insulating system.

Today all the necessary maintenance actions and procedures are available, ranging from simply adding more oxidation inhibitor before oil starts to deteriorate, to combining oil reclaiming and LFH drying in the cases where there is both strongly aged acidic oil and a high water content.

### 4.0 On-Site Repair Process

Power transformer factories and workshops are characterized by their orderliness, cleanliness and well controlled atmospheres which are important conditions required for manufacturing and repair of high voltage equipment. They are also equipped with heavy lifting equipment, special tools and fixtures, high voltage test laboratories and highly skilled operators for each step of the process.

To perform a site repair of a transformer, the same capabilities have to be set up on site in order to meet the individual circumstances of each case. The concept requires the following:

- In order to perform a site repair a controlled environment facility will be required, where cleanliness and orderliness can be achieved. The facility should meet all the criteria’s required to perform the necessary repairs. If the customer does not have a repair area a temporary workshop can be set up on site.

- Heavy lifting equipment will be required on the site. The largest transformers may require a capacity of up to 400 metric tons and above for un-tanking and tanking of the core and coil assembly.
Windings and insulation components are manufactured at a transformer factory and are dried and oil impregnated prior to shipment. They are then specially packed to maintain the low moisture content during shipment and are stored on site in a controlled environment.

After assembly of core and coils the active part is placed in the transformer tank and prepared for final drying. The On-Site Drying processes used can reduce the moisture levels to below 1%. There are several methods available for On-Site drying to reduce the total time required for drying a large power transformer.

High voltage test of the assembled transformer is carried out on-site according to the agreed test plan. To meet the requirement of portability and flexibility an On-Site High Voltage test system has been developed together with a test equipment supplier.

4.1 Facilities for Temporary Workshops

Based on the experience gained globally within the Service centers that have performed site repair projects it was noted that a maintenance shop owned by the customer is available for approximately 50% of the repair projects completed.

The available shop may also be equipped with an overhead crane for lifting of core and coil assembly and winding blocks. For the remaining 50% of the projects it was necessary to set up a temporary facility. When a permanent facility is available at site for transformer repair it should be separated from the rest of the facility to maintain the cleanliness required.

A temporary workshop may be set up based on a steel structure with a cladding of corrugated sheets of steel. This type of building is primarily used when more than one transformer will be repaired at the same site or when there is a desire to keep the building for any future repair or maintenance work by the owner.

Another very flexible and economical solution is to use a large tent consisting of a steel structure and claddings. This structure could achieve and maintain clean and dry environment for the repair work to be performed on the active part of the transformer. These types of tents can be set up in very short time, normally less than a week and are designed to withstand severe weather conditions such strong winds and snow load.
4.3 Heavy Lifting At Site

One of the major heavy lifting required during repair of a core type transformer is the lifting of the core and coil assembly for un-tanking and tanking of the transformer. The core and coil assembly of the largest transformers may weigh up to 400 metric tons and above. To handle this weight, mobile compact lifting systems are available from global suppliers. For smaller transformers, the lifting of the active part may be performed with mobile cranes which are also used for lifting of windings and other components for disassembly and reassembly of the active part and the transformer.

Figure 13: Tanking of large power transformer using mobile lifting equipment

4.4. The Factory Is Brought To Site

For achieving the same quality standards of repair at site as repair in factory “Bring the factory to site”.

That means that the repairs are performed in the same way on site as in the factory. The same processes, tools, fixtures and equipment are applied as far as possible.

One of the processes used in factory which is not presently used on site is the drying of the core and coil assembly using the vapor-phase process. However based on the experience and detailed investigations of the result from a large number of projects, the drying result of the alternative processes used on site meets the required maximum level of moisture content. These alternative processes are described below.

5.0 On-Site Drying

Initially, all new windings and insulating components internal to the transformer are dried and impregnated while still in the factory using standard vapor phase drying process. The oil impregnation of the windings and insulation components minimizes the moisture absorption when handling the parts. In addition all parts are then specially packed and transported in special containers that are filled with dry transformer oil or positive dry air pressure. On site the new parts and the transformer are stored under controlled climatic conditions. Air drying units guarantee the best possible condition to prevent moisture ingress during the repair.

Once the repair on the core and coil is completed, an on site drying process is initiated after the assembly and tanking of the transformer’s active part. The on site drying includes a heating of the whole transformer succeeded by vacuum cycles.

Typical processes used:

5.1 Hot oil circulation:

Hot oil is circulated through the transformer and once the desired temperature is reached the oil is drained into a tank and vacuum is applied to the transformer tank. Based on the kV class of the transformer and moisture content vacuum cycles are maintained till the necessary drying criteria’s are met. Also the maximum allowed oil temperature may limit the maximum drying temperature.

5.2. Hot oil spray:

Spray nozzles are installed at the available flanges and hot oil is sprayed over the active part at the same time as vacuum is applied. This allows limiting the temperature reduction during the vacuum cycles. But due to design of the core type transformers with press plates and shielding, it might be difficult to heat up the core and coil assembly uniformly. For shell type transformer this method is more often used as the main insulation can be easily reached by the hot oil spray.

5.3 Low Frequency current Heating (LFH)

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

The LFH process combined with hot oil spray reduces the total drying time of the transformer on site. It is also possible to meet the same low levels of moisture in the insulation as compared to factory repair within short period of time. The savings in time compared to conventional hot oil spray method and LFH method could be between 3 to 4 weeks.
Using the most advanced techniques, the repair process including on-site drying, ensures low final moisture and high-quality insulation of the transformer, compatible with advanced on-factory drying processes.

6.0 On-Site High Voltage Testing

For most of the projects the quality and dielectric of the repair has been verified by high voltage tests including applied voltage test and induced voltage test with measurement of partial discharge. These tests are in addition to all other type of quality control tests which are normally performed when manufacturing new transformers or repairing transformers in a factory.

The performance of the projects repaired and tested after site repairs has been excellent. This confirms that the quality of the process performed on site meets the standards of a factory repair.

On-site high voltage testing can also be used for verifying the quality of a refurbishment projects for:

- As a part of a diagnostic procedure to confirm that the dielectric strength of the main insulation is free from defects and or provide reference values for future tests or to confirm results from earlier test
- As a commissioning test to confirm the condition of the transformer after shipment and the installation on site

In order to perform on-site high voltage tests, a test system that can be easily transported to any remote site and set up in short time is required. The test system should also be flexible and be able to test at different voltage levels as required for different transformers. So far the mobile high voltage test equipment has been built based on motor generator sets completed with adaptation transformers, components for reactive compensation and measurement and recording equipment. To improve the portability and flexibility of such equipment we have developed a new concept for on-site high voltage test based on high power electronics as a variable frequency power source.

The new mobile high voltage system is equipped to perform Applied Voltage test and Induced voltage test with measurement of Partial discharge. In addition, measurement of Load Losses and No-Load losses can be performed at reduced levels. The test system is designed and is capable of testing most of the HV transformers installed globally.

For performing applied voltage test a resonance circuit is set up between the capacitance of the test object and the resonance reactor supplied with the test set up as shown in Fig. 16. The resonance circuit is fed by the frequency converter through the adaptation transformer. The block diagram below show schematically the test set up for a standard applied voltage test.

For performing an induced voltage test the advantage of the variable frequency converter is used to find the frequency of self compensation of the test object.

This frequency of a power transformer is normally between 50 and 150 Hz. By performing the test at the self compensation frequency the power consumption of the test circuit will be limited to the active losses of the transformer and the size of the converter can be reduced. The adaptation transformer is designed to match the normal voltage range applied for tertiary voltage windings of power transformers.
The block diagram Figure 17: below show schematically the test set up for Induced voltage test.

![Diagram](image)

Figure 17: Mobile High Voltage Test System set up for Induced voltage test

The Mobile High Voltage Test System is designed and built in order to be transported in a standard 40 feet container for easy transportation by truck, by sea or by air. The Fig. 18 shows the test system set up at a substation for test of a large single phase transformer.

![Image](image)

Figure 18: High voltage testing performed of a power transformer after site repair. The temporary workshop can be seen in the background

7.0 Transformer Repaired On Site

A Generator Step Up Transformer (GSU) located in Limay Bataan, Philippines failed in service.

The power plant is owned by the National Power Corporation (NPC) in the Philippines and operated by Alstom Power. The power plant did not have any spare transformers and required the quickest option to repair and return the existing GSU to service.

Initial electrical diagnostics testing and oil analysis indicated that the windings of the transformer were damaged and needed to be replaced.

The original transformer design data significantly reduced the design time for the replacement windings.

The manufacturing of the new windings and preassembling of the winding blocks were completed in Thailand, in accordance with the guidelines for new transformers. The winding blocks were dried and assembled in the transportation tank sealed with positive dry air pressure. The winding tanks were shipped to site in Philippines.
One of the key and most important challenges was to create factory environment on site. This was achieved by erecting a temporary workshop equipped with an air conditioner and dehumidifier.

After delivery of the windings from the factory in Thailand to site, the skilled team successfully replaced the windings and repaired the transformer to new condition.

After tanking of the core and coil assembly, a vacuum drying process along with hot oil circulation method was applied. The quality of the drying process was monitored by Frequency-Domain-Spectroscopy (FDS) measurements.

One of the most important scope of the project successfully performed was the High voltage testing on site after repair.

A Mobile High Voltage test system was brought to site in order to perform dielectric tests including Applied Voltage test, Induced Voltage test and Partial Discharge measurement. All tests were performed according to the international standards.

After the successful completion of all tests and acceptance by the customer the transformer was successfully put back into service.

8.0 Project References

In total more than 300 transformers have been repaired on-site. The largest transformer repaired on site is rated at 750 MVA, 800 kV ac. More than 60 transformers above 200 MVA including several HVDC transformers rated up to 600 kV dc have been repaired successfully on-site.

As it relates to transportation costs and risks, the large power transformers are the likely candidates to be considered for on site repair. The total repair time in most of the cases were reduced by 12 to 14 weeks depending on the geographical condition of the transformer and site. However several transformers below 50 MVA and 30 MVA were also repaired or refurbished on site.

9.0 Conclusions

Proper oil maintenance coupled with the removal of water from the solid insulation, when required, will improve the long-term reliability of the insulating system and thus help prolong the technical life of the transformer.

It is important to know that oil and paper interact and what is carried out for one will influence the future of the other. The distribution of degradation products, such as water, between the two will influence strongly what maintenance actions that are beneficial, especially in the longer term.

A proper condition assessment, based mainly (but not exclusively) on oil tests, is the basis for sound decisions about what maintenance activities should be carried out on the insulating system.
The electrical market in most of the countries, not to say all, value more and more the quality of the energy supplied to the end-users. One of the important challenges for industries and utilities is therefore to ensure no interruption in the delivery which means a high availability and reliability of the different equipment installed in the networks. After several years of experience in many countries the condition assessment survey and on site repair helps transformer owners to reduce the downtime of their equipment.

Condition Assessment provide relevant information to support informed decisions needed to implement condition based maintenance and reduce repair time by better planning the repair tasks and ordering of material.

On site repair based on a proven process and strong project management combined with state-of-the-art technology and strict quality control allows reducing repair time by several weeks or even months while ensuring a highly reliable repair.

Condition Assessment and on site repair help industries and utilities keeping a high standard of energy delivery through improved availability of transformers.

Today all the necessary maintenance actions and procedures are available, ranging from simply adding more oxidation inhibitor before oil starts to deteriorate, to combining oil reclaiming and LFH drying in the cases where there is both strongly aged acidic oil and a high water content.


10.0 References

[1] "Ageing Of Cellulose In Mineral-Oil Insulated Transformers", CIGRE Brochure # 323, Task Force D1.01.10


