Methods for Increasing the Reliability, Availability and Life Duration of Power Transformers

By

H. Borsi, E. Gockenbach
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H. Borsi, E. Gockenbach
Institute of Electric Power Systems (Schering-Institute)
Leibniz Universität Hannover
Callinstr. 25 A, D-30167 Hannover, Germany

Abstract

Transformers are one of the most important and expensive components of electrical energy systems. Deregulation and liberalization of the energy market forces transformer operators to use their devices with maximum profit. Thus life extension of power transformers at high availability and reliability becomes more and more important.

For power transformers the combination of insulating liquid, normally mineral based transformer oil, and a solid insulation, normally cellulose, impregnated therewith is almost the only kind of utilized insulation. If the liquid is aged it can be treated or retro filled. If however the cellulose is damaged it can not be easily repaired and very often it causes a breakdown.

For life extension it is so necessary to reduce the aging velocity of the cellulose. The main parameters causing the aging of the cellulose are water content, hydrogen and temperature. For the life extension it is necessary to reduce the influence of the mentioned aging parameters specially the humidity because it is the main aging factor. A procedure for this purpose is the reduction of water in the liquid and solid insulation.

Most of the continuously operating desiccation devices act upon the insulating liquid and dry this liquid with vacuum. During this process also gases, that are dissolved in the fluid, are to some extent or completely extracted, thus for a transformer, where such a device is applied, the Dissolved Gas Analysis (DGA) is not valid any more. With a new system, based on a different principle of operation, this disadvantage is avoided and the insulating liquid is purified and desiccated without affecting the DGA.

In this contribution besides the explaining of the principle of operation and some experiences with this system different procedure for reducing the influence of oxygen and temperature on the aging of cellulose are presented.

1 Introduction

For power transformers the combination of an insulating liquid and a solid insulation impregnated therewith is almost the only kind of utilized insulation. Although long term experience has shown, that this kind of insulation is very reliable, the market demands for an extended efficiency and reliability of the equipment forces the utilities to increase the transformer load while avoiding malfunctions. This can cause an accelerated ageing of the insulation system of the transformers which generates gases, slugs acids and thus reduces the life expectation of the transformer. If the oil is aged it can be treated or even replaced. Much
more problems cause the ageing of cellulose solid insulation materials. Ageing causes a depolymerisation of the insulation paper and thus a reduction of the mechanical properties and generation of CO and CO$_2$. An ageing of the cellulose even only at a very small area of the insulation is normally irreparable and can cause a breakdown and total destruction of the transformer. Thus for a long life duration it is very important to reduce the insulation aging velocity.

2 Ageing Factors

Aging is an irreversible deleterious change of an insulation system. Transformers insulation is subjected to several types of stresses. Stresses that produce ageing are called ageing factors. Insulation aging is caused by different factors such as environmental, electrical, thermal and mechanic stresses (see Figure 1) which are highly depending on operational conditions. All these ageing processes lead to the formation of water, acids and other substances of partly polarisable and ionisable character.

![Figure 1: Transformer insulation ageing factors](image)

Paper ageing process, depends primarily on temperature and water content. The existence of oxygen will however markedly increase the rate by as much as 2.5 to 10 times. Previous studies of transformer insulation ageing show the influence of three main degradation agents, temperature, moisture, and oxygen, on the degree of ageing. Figure 2 depicts the relation between relative depolymerisation velocity as a function of water content and temperature. With the help of a thermal modelling of the transformer the temperature of the hot spots can be calculated from the measured temperatures at different points. So it is possible to control the load of the transformer to prevent the increasing of the hot spot temperature above the allowed level.
One of the most significant influences that decrease the insulation reliability and lifetime is water in the insulating system which reduces the breakdown strength of the insulating liquid and increases aging of the solid insulation. Water is not only absorbed from the environment as it happens especially for breathing transformers with a conservator, it also is generated inside the device due to the depolymerisation of cellulose as shown in Figure 3.

The solid insulation materials are commonly used as wrapping around the conductors and spacers, thus a refurbishment of these structures during a maintenance action would require an almost complete dismantling of the device. Due to the costs of such a treatment destroyed paper insulation therefore represents in most cases an unrecoverable failure which leads to the disposal of the transformer. Especially for aged transformers, that have already aggregated high amounts of water; a drying of the insulation therefore is an obligation to increase operation reliability and residual lifetime.

Moisture concentration in paper is typically expressed in % where as the moisture in oil is expressed by ppm. The amount of moisture in oil is about 1% of the amount of moisture in the cellulose. The amount of moisture in oil and cellulose depend on the whole amount of
moisture in transformer and the temperature. At higher temperature a part of the water migrates from cellulose into the oil and at lower temperature vice versa the water migrates from the oil back into cellulose. Water is particularly detrimental to both the dielectric properties of oil-paper insulation systems and to its resistance to ageing. Moisture in the oil may under fast decreasing temperature transients result in free water that can lead to electrical breakdown. The water in oil originates from air moisture in the case of “open-breather” or “oil-conservator” types, and the thermal decomposition of the solid insulating materials. The increase of the moisture content can also be the result of mishandling at transport, storage, with or without oil, at the installation, further on at small repairs with temporal and partial drainage of oil, or the result of defects in the breathing system filter etc.

Water affects the conductivity of the insulation, which in turn increases the dissipation factor. The oil in a transformer becomes increasingly contaminated as the transformer ages in service. Contaminants include particulate debris from thermal, oxidative, or electrical degradation of oil or solid insulation, fibers, gassing, moisture, etc. Water being a product of degradation, the moisture level in the paper insulation will acts as aging catalysts. The rate of degradation of paper increases in direct proportion to the water content.

For the extent ion of life duration of a transformer it is thus very important to dry the transformer and keep it dry during operation.

3 Drying of transformer insulation

For a drying of the solid insulation of a new transformer heat and vacuum have to be applied to remove the water. For aged transformers the solid insulation is already impregnated, thus the cellulose fibers are covered with insulating liquid which impedes the extraction of water from the cellulose. Occasionally failures have been reported after a conventional drying has been performed on an aged insulation. The reason for these hazards seems to be based on the fact, that the compression forces of the liquid immersed cellulose material is altered when water and insulating liquid are removed (Figure 4) With most of the actually available systems for drying transformers a desiccation is performed as a maintenance process during regular or abnormal transformer outage. Besides the expenses, that are caused by this action, the efficiency of such a treatment is equivocal as these procedures are suspected to endanger the solid insulation, because sporadically failures have been reported after such a cure has been performed.
An alternative thereto is the continuous extraction of the water covered by the insulating liquid. When the water saturation level of the fluid decreases due to the drying thereof water is extracted from the solid insulation. The insulating liquid acts as a “water transfer medium”. The advantages of such a cure are that it needs no transformer outage and that it does not endanger the solid insulation during drying.

Actual systems for this purpose either work with vacuum or with a desiccant and therefore influence the Dissolved Gas Analysis (DGA) which is the most useful tool for assessing the transformer insulation condition. The system presented in this contribution is based on a new technology and does neither afford modifications of the transformer design nor does it require long term transformer outages. Its basic principle is the sustainability of the water removal, thus to meet the requirements for the enhancement of the insulating system reliability and prolongation of the lifetime.

4 Principle of operation of continuous drying

4.1 Drying with cellulose

The basis of the conceived procedure is the water solubility in the insulating liquid and the equilibrium between the water content in the insulating liquid and the solid insulation immersed therein. As the combination of a cellulose paper and pressboard immersed in a mineral based insulating oil is the most common combination of materials the operating principle is illustrated for these materials. The water solubility of an insulating liquid can be expressed by the following formula \(^2\):

\[
W_s = K \cdot e^{-\frac{H}{T}}
\]
where $K$ and $H$ are constants specific for each insulating liquid and $T$ the temperature. For a very common mineral oil these constants are e.g. $K = 1.918 \times 10^7$ and $H = 3.807 \times 10^3$. The water solubility therefore increases exponentially with the temperature.

The insulating oil of a transformer in operation, which, due to the different losses inside the vessel, is of elevated temperature, intends to collect water. As the transformer is a sealed system the preferred source for water is the paper and pressboard insulation. As the water solubility of the insulating liquid depends on the temperature the equilibrium between the water content in the mineral oil and the cellulose paper is diverse for different temperatures. This effect, which has been reported by several authors, can be used to dry the insulation of liquid and paper insulated HV apparatuses. The equilibrium between the moisture contained in the paper and the moisture content in the surrounding mineral oil is depicted in Figure 5.

![Figure 5](image.png)

**Figure 5**
Relation between the water content in mineral oil and insulating paper immersed therein

This diagram shows that for high temperatures the water content of the mineral oil is relatively high while the water content of the paper insulation is low. For low temperatures this relation is reverse, the water content in the paper is high while the water in the oil is low.

This behaviour can be used for a continuous drying of the paper insulation in a liquid immersed insulation system. The warm and "wet" oil inside the transformer vessel is slowly drained from the transformer and pressed through a cooled cellulose filter.

In this filter a very porous cartridge offers a large surface for the oil to transfer its water to the cellulose fibers. The mineral oil has previously been cooled down to a temperature of about 3°C when it enters the cartridge, thus it is in almost any cases supersaturated with water and therefore dispenses it easily. Additionally to the drying the filter purifies the oil and removes particles of dirt out of the liquid. As such particles are possible sources for partial discharges or even breakdowns of the liquid insulation the operation reliability is additionally enhanced. The described procedure is actually protected by German and international patents.

**4.1.1 Technical realization** Basic investigations on mineral oil as well as on ester liquid have shown that the innovative procedure is applicable for drying transformer insulating liquids and therewith impregnated solid insulations. A vital problem of any short time
treatment is that the water covered by the solid insulation is captured all over the material. If the insulating liquid is removed and vacuum is applied the water to be removed from the inner layers of the insulation has to pass the surrounding cellulose material, thus still being impregnated with the insulating liquid. The speed of the water transfer out of the core of the solid insulation is thus limited by the transfer speed through the impregnated material. As this speed is quite low short term procedures can only be effective for the outer insulation layers close to the surface as long as the material is still impregnated.

The new system is directly applied to the transformer in operation as schematically depicted in Figure 6.

The insulating liquid drained from the transformer via the oil sampling tubes passes at first the pump that transports the fluid through the desiccator. Afterwards the oil is injected into a cycle stream through the filter vessel and the cooling unit where it is cooled down to 3 °C before it enters the filter cartridge. As the filter cartridge is a flow resistance this part of the system is continuously under a pressure of about 1 bar plus the hydrostatic pressure originating from oil level of the transformer.

After passing the filter cartridge the dried and purified mineral oil is refilled into the transformer vessel via another oil sampling tube or directly into the conservator. The attainable water content of the oil leaving the setup is depending on the operation parameters and can be set to values below 1 ppm.

4.1.2 Application on site After the technical realization has been completed an evaluation of the capabilities and limits of the new system has been performed. For this purpose the desiccator has been applied to a 110 / 12 kV, 33.5 MVA transformer as it is depicted in Figure 7.
The drying setup has been enclosed in a waterproof housing to ensure resistance against weather conditions in summer and winter. The system operated reliably for more than a year and gave hints for improvements in pump and cooling control.

The water content of the transformer had been reduced by 300 g although the efficiency of the drying has been limited by the relatively low temperature of the transformer. The transformer is used as a backup, which is connected to the high voltage net but transmits energy only if the consumer needs extra power. Therefore only the losses during idle operation led to a warming of the transformer. The ordinary transformer operation temperature has been around 30 °C while usual power transformers operate at temperatures above 60 °C. Due to the lower temperature the equilibrium between the water in the cellulose insulation and the water dissolved in the oil moves to the cellulose side (see Figure 1) and the insulating oil contains relatively small amounts of water. Even if this water is almost completely removed from the liquid during desiccation and the water content at the outlet of the dryer was continuously between 1 and 2 ppm. The poor supply with water by the transformer insulating liquid limits the drying speed.

With a subsequent system including all improvements out of the experiences from this on site evaluation several transformers have been dried. In all cases both a desiccation and a purification of the insulating liquid could be proved. The following results show the application on a transformer in a casting works where the reliable operation of the oven transformer directly influences factory operation.

4.1.3 Operation experience

The commercial name of the desiccator is “Puridryer”, and now in use for more than eight months and has reduced the humidity of the insulating oil of this oven transformer from ≈ 80 to about 25 ppm. Figure 8 shows one of the filter cartridges used in this transformer in a cross sectional cut. It becomes obvious out of this picture, that the particles of the insulating oil have been caught by the surface of the filter. The oil, which flows in radial direction to the central canal of the filter cartridge, is purified by the filter cellulose fibers that additionally desiccate the liquid. The upgraded insulating liquid enters the central canal with a water content of approximately 2 ppm and is then refilled into the transformer.
The basic attribute, that describes the adsorption capabilities of the filter cartridge, is the adsorption limit of the filter. Alternatively to an exchange a drying of the filter cartridge inside the filter vessel is possible but comprises several disadvantages. The particles, removed from the insulating liquid, remain on the surface of the filter and hamper the subsequent drying by vacuum (see Figure 4). The drying of the impregnated cellulose of the filter cartridge is a time consuming process during which the continuous drying has to stop. Each drying cycle worsens the condition of the filter due to the material burden. And finally the transformer gas balance and therewith also the DGA may be influenced by the application of vacuum. For these reasons the filter cartridge used in the presented system has been specified for single use only.

To nevertheless assimilate large amounts of water until a replacement is necessary the filter dimensions have been enlarged. Contrary to this the filter size can be limited, when the available space is limited (e.g. at indoor use). The appropriate size can be chosen fitting to each application.

4.1.4 Adsorption capabilities

To appraise the water adsorption of the filter cartridge of Figure 8 segments from 10 different locations of the filter staple have been taken. These samples have at first been squeezed by a press with a weight of 4 tons, thus to remove any free liquid out of the labyrinth of filter cellulose fibers. With the removed liquid also some of the particles from the surface of the filter material have been washed out. After 3 days the particles of the squeezed out liquid settle down as it can be seen in Figure 9. These particles mostly consist of cellulose fibers from the transformer insulation. In the electrical field inside of the transformer vessel these sharp cellulose needles may be the origin of Partial Discharges (PD) that also lead to insulation degradation.

After the free insulating liquid has been mostly removed from the samples by compression they have been dried in a vacuum cabinet for 24 hours at 105 °C to remove the water adsorbed by the cellulose fibers of the filter material. Both the weight of the samples before and after this drying has been recorded. As the density of water is 1 kg/l the weight before and after drying can be directly seen as the adsorbed water. To avoid any asymmetry in the different samples from the bottom and the top of the filter cartridge stack here only the sum of all weights is given.
After compression the weight of the ten samples was 0.8495 kg, after vacuum drying the weight was 0.6485 kg, thus the adsorption of the cartridge can be calculated to 31 %. This is the water adsorption of the filter cartridge, when it had been exchanged. This water adsorption does not need to be the maximum water adsorption. Before this limit is checked at first the results of this test method have been verified with the data recorded by the Puridryer.

The desiccation device continuously records several data like the temperature and water content of the incoming and outgoing insulating liquid as well as the flow rate of processed liquid. From this data it can be derived, that the whole cartridge had collected 3.545 l of water. With an average weight of the whole filter cartridge stack of not more than 15 kg an adsorption rate of 23.6 % can be calculated. Unfortunately the cartridge has not been weighted before application, thus only the specified weight for this type of filter cartridge can be used. As the adsorption rate is of similar magnitude compared to the results of the previously described tests, these test results can be taken for plausible.

For the assessment of the maximum adsorption capacity a new filter cartridge of similar material has been used. Out of this cartridge also 10 samples have been made and afterwards humidified in a cabinet under controlled conditions. The samples have been stored for seven days in water and at a relative air humidity of 100 % before they have been squeezed out using the 4 ton press. A photograph of a sample after compression is given in Figure 10.

Afterwards the samples have been equally dried in a vacuum cabinet for 24 hours at 105 °C and a pressure below 10 mbar. The weight of the samples before this process had been 0.345 kg while the weight of the new samples (before humidification) was 0.233 kg, thus the mass of adsorbed water was 0.112 kg. In relation to the weight of the cellulose this gives a maximum adsorption of 48 %. The filter cartridge of 15 kg could thus adsorb up to more than 7 kg of water. As nevertheless with increasing adsorbed water the uptake velocity of the filter cartridge and thus also of the drying process decreases an exchange of the filter cartridge before this saturation would have been reached is advisable.
4.2 Drying with Zeolite

An alternative to short time drying is the continuous extraction of water covered by the insulating liquid. With a Zeolite drying unit as it is described hereafter by Figure 11, a continuous and sustainable drying can be performed while the transformer is in service.

When, due to the drying, the water saturation level of the fluid decreases, water is extracted from the solid insulation. During this process every water molecule, which has been removed from the cellulose fiber, is instantaneously replaced by a hydrocarbon molecule of the insulating liquid. From this point of view the insulating liquid acts as a “water transfer medium”. The advantages of such a treatment are, that it needs no transformer outage and that it does not endanger the solid insulation during drying. Regarded over the time of its application such a procedure is also more efficient than a short time treatment.

![Figure 10](image)

Filter cartridge sample after squeezing out in the 4 ton press.

**Figure 11**

Online drying procedure for liquid immersed transformer with zeolite as drying element
The operating transformer is connected to a Zeolite bed via a pump and a first fine filter for filtering insoluble particles out of the liquid. After the Zeolite bed, that performs the drying, the insulating liquid is returned into the tank through a second filter. The first filter is expected to prevent fine particles accessing to the Zeolite bed, avoiding thus the obstruction of their pores, while the second filter is required for preventing eventual particles from the Zeolite bed to contaminate the upgraded liquid. The only moving part in such a system would be the pump while a regular exchange of the filter cartridge would ensure constant drying capabilities.

In an operating transformer, paper can contain much more water than oil. For example, a 150 MVA, 400 kV transformer with about 7 tons of paper contains e.g. 223 kg of water. The oil volume being of about 80,000 litres, assuming a 20 ppm moisture concentration, the total mass is only 2 kg, much less than in paper. In order to appreciate the capability of the proposed drying procedure, a laboratory based-model has been investigated.

The model consisted of a vessel filled with 3.2 l insulating liquid. To keep close to reality 280 g of cellulose paper were impregnated and immersed in the transformer model. The model set-up, connected to a Zeolite bed (an amount of 1g/l was respected) via a pump, was then continually heated to a temperature of 60°C to simulate an operating transformer. Using a time relay, the pump was discontinuously activated in order to reach slow pumping velocities.

Altogether the experiments confirmed the feasibility of the method particularly in connection to the conductivity measurement. More research is needed to refine these methods and to collect more data on real transformers. Indeed, non-uniform distribution of moisture or other aging products can make the evaluation of measurements more difficult. Moreover, it is also known, that as material age, their permittivity and conductivity may change too. These difficulties can generally be mastered, however, with accumulating experiences and a knowledge of the test object’s service history.
5 Conclusions

With the presented new system for continuous transformer insulation drying an effective and sustainable device for insulation improvement during transformer operation is given. The application on different transformers showed, that the continuous insulation desiccation without influencing the DGA gives a continuous reduction in the water content of the insulating liquid and therewith also in the solid insulation, which is the most important part of the transformer insulation. With decreased water insulation aging declines and operation reliability heightens.

The innovative method for drying the solid and liquid insulation of high voltage apparatuses like power transformers

- allows a continuous, gentle and efficient drying of the insulating system and thereby increases the operation reliability and residual lifetime
- purifies the insulating liquid by filtering out solid contaminants and increases therewith the breakdown and partial discharge inception voltage of the liquid
- does not influence the gas balance of the transformer, thus the Dissolved Gas Analysis (DGA) is not affected
- is efficient over long time periods and can be applied on new and aged apparatus without the need for long time outages
- allows an almost complete desiccation of mineral insulating oils with an attainable dryness below 1 ppm without stressing the insulating liquid during the procedure
- has proven its applicability and effectiveness on different transformers in the field

6 References


