Increasing the Operation Reliability of Power Transformers by Continuous Desiccation without Affecting the DGA

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Abstract: Transformers are one of the most important and expensive components of electrical energy systems. Especially for transformers of prime importance always a liquid immersed solid insulation is used to insulate the device and to dispense thermal losses. Due to deregulation and liberalization of the energy market transformer operators’ have to use their devices with maximum profit. To nevertheless assure a reliable energy supply, systems, that limit transformer aging, have become of increasing importance. A procedure for this purpose is the reduction of water in the insulation.

With a new device, based on an innovative principle of operation, the disadvantage of influencing the DGA by insulation drying is avoided and the insulating liquid is purified and desiccated without affecting the DGA. In this contribution the principle of operation is explained and some experiences, which have been gathered on different transformers, are presented. By application experience and some additional experiments it could be shown, that the used filter cartridge is appropriate for extracting several liters of water from the transformer insulation before it has to be exchanged. With this desiccation the operation reliability of the transformer is enhanced and aging is reduced, thus both being a benefit to the user.

Key words: Transformer, DGA, water, drying, reliability, aging

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.

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 the aging of the solid insulation \cite{1}. 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. 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 a 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.

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 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.

PRINCIPLE OF OPERATION

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 cellulosic 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]

\[ W_s = K \cdot e^{H/T} \]

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 cellulosic paper is diverse for different temperatures. This effect, which has been reported by several authors [2], 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 1 [3].

![Figure 1: Relation between the water content in mineral oil and insulating paper immersed therein [3].](image)

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 behavior 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 cellulosic 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.

**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 [4].

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 cellulosic 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 2.

![Figure 2: Schematic view of the application of the presented system on a transformer in operation.](image)
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.

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 3.

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.

OPERATION EXPERIENCE

The desiccator, that has been assigned the commercial name “Puridryer”, is 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 4 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.

Figure 3 Drying setup applied to a transformer on site.

The drying setup has been enclosed in a waterproof housing to ensure resistance against weather conditions in summer and winter. The system operated reliable 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 (the water content at the outlet of the dryer has continuously between 1 and 2 ppm) the poor supply with water by the transformer insulating liquid limits the drying speed.

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.

** ADSORPTION CAPABILITIES **

To appraise the water adsorption of the filter cartridge of Figure 4 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 5. These particles mostly consist of cellulose fibers from the transformer insulation. In the electrical field inside of the transformer vessel these peakish cellulose needles may be the origin of Partial Discharges (PD) that also lead to insulation degradation.

After compression the weight of the ten samples was 0.850 kg, after vacuum drying 0.649 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 liters 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 sample 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 6.

![Figure 5: Sedimented particles from the squeezed out filter cartridge samples after 3 days of storage.](image1)

![Figure 6: Filter cartridge sample after squeezing out in the 4 ton press.](image2)

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.

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 heights.

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. The dryness attainable with this method is below 1 ppm. The insulating liquid is not stressed during this procedure,

- has proven its applicability and effectiveness on different transformers in the field.

REFERENCES


