Abstract Although solid and gaseous insulations have become increasingly popular during the last decades the application of insulating liquids together with a solid insulant immersed therein is still essential for some kinds of applications like power transformers. A significant risk, reducing the strength of such insulations, is water, thus drying procedures are required to extend lifetime and operation reliability. As actually used systems for this purpose comprise several imponderabilities new systems are required. Actually transformer drying is in most cases performed as a maintenance action where it is tried to remove water by vacuum and heat. Such a procedure has to be performed offline and thus is time consuming and expensive.

In this contribution an innovative procedure for the dehydration of the transformer insulating system is presented, working online during transformer operation. Thus it is well-priced and ideally suited for transformers with a moderate water strain, where an immediate drying is not yet indispensable. The procedure not only performs a complete desiccation, it also purifies the liquid without influencing the dissolved gas analysis (DGA) or any other physical property. The application of the system on power transformers has shown, that the procedure is beneficial for insulating liquids as well as for solid insulation immersed therein.

As the insulating liquid operates as a “water transport medium”, disposing the water out of the transformer insulating system, the efficiency of this system can be increased by a hygroscopic insulating liquid like ester liquid, that is capable to comprise more than 30 times the rate of water compared to mineral oils. Beside the acceleration of the drying process together with the presented system they also have a beneficial effect on the aging of cellulose impregnated therewith. As ester liquids and mineral insulating oils are completely miscible also blends of esters and insulating oils are advantageous.

The contribution presents these beneficial effects by means of some examples gained during aging tests in laboratory and also discusses the applicability of the test results for transformers in operation.

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 decreases 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 [1]. Water is not only absorbed from the environment as it happens especially for breathing transformers, it also is generated inside the device due to the depolymerisation of cellulose as it is schematically illustrated by Figure 1.

![Figure 1: Water generation by the scission of cellulose molecules.](image_url)
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 as well. 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 this combination.

The water solubility of an insulating liquid can be expressed by the following formula [2]:

\[ W_S = K \ast e^{\frac{H}{T}} \]

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 * 10^7 and H = 3.807 * 10^3. The water solubility therefore increases exponentially with the temperature.

The insulating oil of a transformer in operation, which is, due to the different losses, of elevated temperature thus intends to collect water. 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, too. 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 2 [3].

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 inverse, 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 pressed through a cooled cellulosic filter in a bypass system.

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 potential 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].

The basic characteristic of online treatments is their profitableness over long time periods. Although power transformers contain several tons of liquid and solid insulating materials the drying of small volumes of insulating liquid is therefore sufficient.

To estimate the water inside a transformer the following example is given: Inside a 10 MVA transformer for voltages up to 123 kV 8600 kg of insulating oil are contained [5]. About between 1/8 and 1/7 of this weight is the mass of the solid insulation. For the appraisal presented here a weight of 1200 kg is therefore rated. With an oil humidity of 15 ppm and an operation temperature of 60 °C the oil dissolves 130 g of water while the solid insulation envelopes 2 % of its weight, thus being 24 kg (values gathered from Figure 2).

Therewith the vital problem of any short time treatment becomes obvious. 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 originating 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 depicted in Figure 3.

The insulating liquid removed from the transformer via the oil sample extraction tubes passes at first the pump that transports the fluid through the system. Afterwards the oil is injected into the 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 sample extraction 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**

For an application on power transformers it is essential to detect the saturation state of the filter as in the case of a saturated purifier the drying stops and the cartridge has to be replaced. For this purpose the water content of the insulating liquid entering and leaving the setup is continually monitored. With these parameters the transferred oil volume is controlled and in case of a filter saturation even set to zero. In this case an alarm is posted to the system operator via mobile or conventional phone lines, forcing him to change the filter cartridge. The maintenance of this system is thus condition based, thus being an additional benefit compared to time- based maintained systems.

With the help of the insulating liquids’ water content gathered from the oil in- and outlet together with the volume of the treated liquid also the amount of extracted water is continuously calculable. This value as well as many other operation parameters can on request be transmitted to the system operator via phone line.

Alternatively to an exchange also 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. 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. The actually implanted cellulose filter cartridge is capable for covering up to 15 liters of water.
ENHANCING THE EXTRACTION RATE

The preferred transformers, for which this system is beneficial, are power transformers with moderate water strain, for which an immediate drying, which has advantageously to be performed as a maintenance procedure in a workshop, is not yet indispensable. Nevertheless also for these transformers the conceived bypass drying during operation can be accelerated.

As the insulating liquid operates as a “water transport medium”, disposing the water out of the transformer insulating system, the efficiency can be increased by a hygroscopic insulating liquid like ester liquid, that is capable to comprise more than 30 times the rate of water compared to mineral oils. Beside the acceleration of the drying process together with the presented system they also have a beneficial effect on the aging of cellulose impregnated therewith. As ester liquids and mineral insulating oils are completely miscible also blends of esters and insulating oils are advantageous. Even the addition of 20 % ester increases the water solubility of the liquid by a factor of 10.

Since many years ester liquids are in use in distribution transformers as an alternative insulating liquid. The major advantage, forcing the application of these fluids, is their improved environmental compatibility. Almost all electrical properties of the esters are comparable to mineral oils, only two aspects obstructed the general use of these liquids. At first this is the price, which has primarily been higher than the costs of mineral oil. The other topic has been the high hygroscopicity of these liquids. According to the relevant international standards like IEC 60296 and IEC 61099 an unused ester liquid is allowed to contain 200 ppm of water while mineral oil is only accepted up to 10 or 20 ppm. Nevertheless ester liquids may hold much higher contents of water. Their saturation limit at room temperature is above 2500 ppm while their electrical strength is still high up to 500 ppm [6].

The high hygroscopicity, usually seen as a disadvantage, may be a benefit when a solid insulation is in contact with the insulating liquid where water, assimilated by the solid insulation, can be extracted. When in a second step the water is removed from the liquid the rate of water extraction from the cellulose of the solid insulation is equally higher compared to mineral oil.

Experiments in laboratory have shown [6], that also with the mixtures a significant increase of the water extraction from moist cellulosic insulation material occurs. Beside this enhanced water extraction also the breakdown voltage at low temperatures increases, thus being an additional benefit especially for transformers operating in cold climate regions. Especially for these transformers the switch on at cold temperatures and after a long term outage comprises the risk of breakdowns due to the high relative water content of the insulating liquid at these temperatures [7].

Several experiments have shown, that the aging of a cellulose material in ester liquid and blends of ester liquid and mineral insulating oil is significantly lower compared to the aging in pure mineral oil. This effect especially becomes significant for free breathing transformers, where the insulating materials are in contact with the environmental air and thus with oxygen. Although such systems have shown to be disadvantageous and thus should be avoided for new constructions [8], several older, free breathing systems are still in use. Especially for these systems the addition of ester liquids can reduce subsequent aging, especially, if systems for the exclusion of the oxygen like [9] are not applied.

Beside the different measured values like breakdown voltage or dissipation factor tan δ a simple look on paper samples aged with different blends of mineral oil and ester liquid like they are depicted in Figure 4 makes the beneficial effect of esters obvious with the glimpse of an eye. While the filter papers aged in mineral oil become black and brittle the samples simultaneously aged with different amounts of ester liquid keep brownish up to almost unaffected for the aging in pure ester liquid.

Figure 4: Photo of cellulosic filter papers filled with catalyst metals (iron, copper, aluminium, zinc as fine chips) and aged for 1000 hours at 105 °C with environmental air present. The samples have been immersed in different blends of mineral insulating oil (Shell Diala D) and ester liquid (Midel 7131).
CONCLUSIONS

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.
- can be optimized with the use of ester liquids or ester liquid / mineral oil blends.

With the application of the ester liquid additionally the rate of subsequent aging is significantly reduced. Already occurred aging can not be revised without the replacement of insulating materials which especially for the solid insulating components is expensive, time consuming and only in special cases reasonable. Nevertheless the reduction of subsequent aging after a qualified treatment can extend transformer lifetime without the need for replacement.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the Karberg & Hennemann CJC Feinfilter corporation, Hamburg, Germany (info@kh-filter.de) for their interest in the performed work and the support of a technical realization.

REFERENCES