Moisture-equilibrium charts

ABSTRACT

Green transformers, a sustainable and environmentally-friendly range of power transformers, are gaining in popularity. The growing interest in such transformers is linked to the introduction of innovative technologies, such as natural esters (biodegradable and renewable liquid offering higher fire safety) combined with a sealed design, to be used instead of classical mineral oil. For efficient and accurate moisture-condition monitoring, green transformers need moisture-equilibrium charts. In-depth experiments have been carried out to produce and validate such charts, similar to those existing for mineral-oil-filled transformers.

KEYWORDS

green transformer, natural ester, moisture-equilibrium charts, cellulose

Monitoring natural-ester green transformers

1. Green power transformers (from 10 to 500 MVA and up to 550 kV)

Today it is taken for granted that power transformers are robust pieces of equipment designed to ensure long lifetime, safety, low weight, compactness and cost-effectiveness. On top of that, it is expected that they will meet the requirements for high efficiency, noiselessness and environmental friendliness. This is the reason why green transformers [1], a sustainable and environmentally-friendly range of eco-efficient power transformers with innovative technical characteristics, have been developed (Figure 1). To enable this, modern technologies, such as biodegradable insulating liquids based on natural esters combined with a hermetically-sealed design, are available today. First successful operating experiences of power transformers have already been gained.

Natural esters, also called vegetable oils, are mainly extracted from soya, rapeseed and sunflower [2] and they offer several advantages: they less affect the groundwater; they are more biologically degradable, less-flammable and have a higher thermal class than mineral oil (130 °C compared to 105 °C). Thanks to the lower effect on the groundwater, additional oil pits under the transformers may be omitted. It is to be noted, however, that in case of a spill of natural ester, most national regulations will require the same clean-up procedures as for mineral oils. In addition, natural esters may have a protective effect on the insulation of a transformer [3] mainly for two reasons. Firstly, natural esters have a

higher water solubility, which means that they can absorb more water. Secondly, they may have this effect because of the transesterification, i.e. conversion of water into fatty acids (not aggressive), observed during laboratory tests [4], which may also occur in transformers in service. In order to benefit from these improvements, it was necessary to analyse several material properties. The thermal and electrical characteristics of this alternative insulating liquid were evaluated in detail and the ageing behaviour was studied. In addition, it was necessary to examine the material compatibility and the influence on the transformer manufacturing process.

Controlling the fans using electronically commutated technology (DC motors with AC supply) also allows the optimization of noises and losses, as well as achieving a reduction in wiring expenditures. This concept can be linked intelligently to an on-line monitoring system. In this way, the advantages of the concept can be joined with those of an on-line management system. The monitoring system can preset the cooling performance required and control the fans intelligently.

A lot of investigations have been performed over the last years to optimise the design of a sustainable and environmentally-friendly range of power transformers, the so-called green transformers

Besides this, a new innovative concept of a common oil volume for the tap changer (vacuum-type), as well as the main transformer tank, is also available [1]. This advanced solution can be used to significantly improve the design of a power transformer and its add-on parts. The new principle can be applied to both free-breathing and hermetically-sealed transformers. The advantage: fewer components mean less time and lower expenses for maintenance, which rounds up the overall concept.

2. Moisture and cellulosic insulation

Transformer insulation is a composite system made of liquid and solid materials (impregnated with the liquid). The lifetime of a transformer is driven by the lifetime of the cellulosic (i.e. solid) insulation because solid insulation cannot be as easily replaced as the insulating liquid. Therefore, it is of great importance

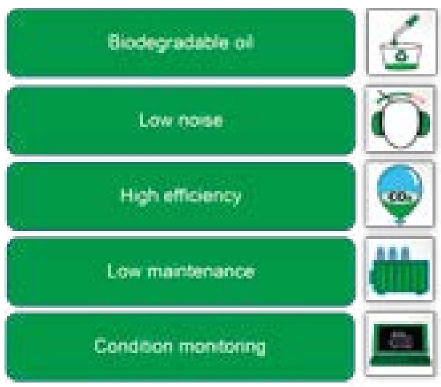

Figure 1. New and innovative green transformer generation: key areas of development to support eco-friendly solutions

For efficient and accurate moisture-condition monitoring, green transformers need moisture-equilibrium charts

Table 1. Description of tested materials

Materials	Type	Standard
Mineral oil	Naphtenic, non-inhibited	IEC 60296 Ed. 4 [15]
Natural ester	Triester	IEC 62770 Ed. 1 [16]
Kraft paper	Thickness 0.25 mm Density 1.2-1.3 g/cm^3	IEC 60641-3-1 Ed. 2 [17]
Pressboard	Thickness 1 mm Density 1-1.2 g/cm^3	IEC 60641-3-1

The mechanical lifetime expectation of the transformer insulation is halved for each doubling in the water content

to check regularly the condition of the cellulosic insulation in order to timely apply mitigation techniques, such as oil treatment, new gaskets, expansion system maintenance, etc.

Water is a secondary degradation product of cellulosic insulation. It is formed by hydrolysis and is also an end product in the oxidation of insulation liquid, as well as that of paper [5]. Most of the water in transformers, however, comes from contamination by ambient moist atmosphere through leaking gaskets, membranes or air preservation systems. Since the cellulose insulation is more hygroscopic than the insulation liquid, it contains most of the water in paper/oil system and can constitute several percentages by weight of the total mass of solid insulation. As an example, for a 150 MVA/400 kV transformer having around 7 tonnes of cellulose and 80,000 litres of oil, 3 % of humidity in the cellulose and 20 ppm (parts per million) in the oil are equivalent to around 220 kg and 2 kg, respectively [6]. Water has a detrimental effect on the dielectric properties of the insulation system as well as its resistance to degradation. This may later influence the ability of the transformer to withstand short circuit stress. As an example, the mechanical lifetime expectation of the transformer insulation is halved for each doubling in the water content [7].

Laboratory moisture-equilibrium curves constitute a useful tool for indirect estimation of water content in cellulose in a green transformer in service

Figure 2. Material conditioning for the study

In order to avoid affecting these properties of the cellulosic insulation, the water must be kept to a minimum value. In a new transformer, the water content of the cellulose is about 0.5 % and is expected to gradually increase during the life of the transformer. As an example, in practice, moisture levels in paper insulation have been observed to increase from 0.5 % to, in extreme cases, 4-8 % over the lifetime [8]. IEC 60422 Ed.4 [9] provides some general guidelines for interpreting humidity in cellulose: everything below 2 % is considered dry insulation; 2 % to 5 % is moderately wet to wet, and values higher than 5 % are considered as extremely wet. It is not possible to remove paper samples from the active windings of a transformer under operation. Thus, indirect measurements were developed to assess the water content of the paper from moisture in oil (chemical method). This method is based on moisture-partitioning curves between oil and paper under equilibrium conditions. While there are large volumes of information for mineral oils [10, 11, 12], pertinent charts for natural ester are lacking. This missing data constitutes a limiting factor to the implementation of natural ester in high-voltage power transformers. In addition, it is generally not known from the existing charts whether the equilibrium curves were obtained from experiments using paper and pressboard insulation in mass ratios corresponding to actual ratios used in transformers, or how the water is distributed between the paper and pressboard insulation. To improve the relevance of these charts, new moisture-equilibrium curves have been developed for standard Kraft paper and pressboard immersed in natural ester. Experiments

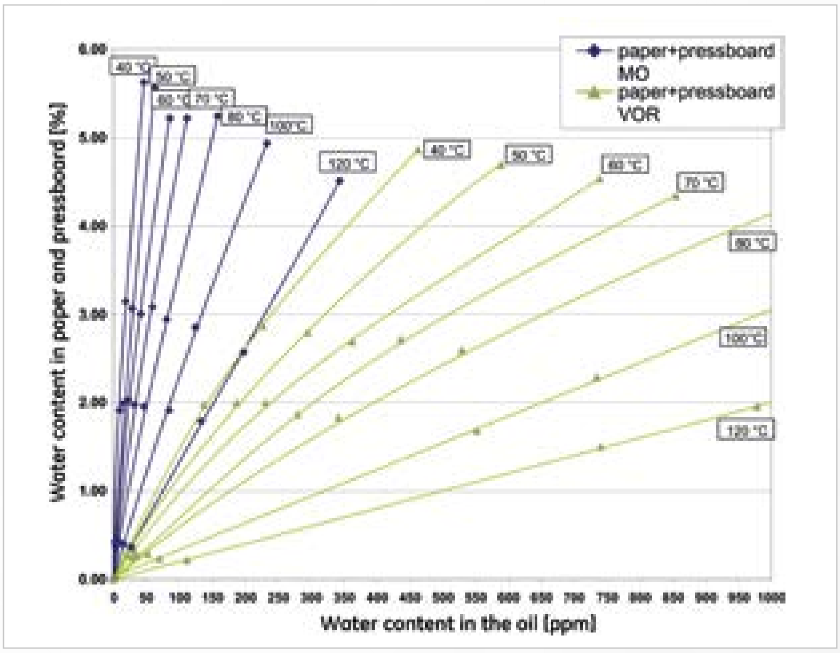

Figure 3. Perrier-Lukic moisture-equilibrium curves for paper and pressboard in mineral oil (MO) and natural ester (vegetable oil, VOR) [13]

were also carried out with mineral oil to compare and validate the results with regard to the existing data. [13].

3. New moisture-equilibrium charts with natural ester

3.1 Test conditions

Insulating liquids (mineral oil and natural ester), paper and pressboard (Table 1) were taken in specified insulation mass ratios (90 % of insulation liquid, 4 % of paper, 6 % of pressboard) corresponding to approximate ratios in actual power transformers (core-type). To achieve the initial low water content, the paper and pressboard samples were dried and filtered under vacuum. This procedure was followed by impregnation with dried and degassed insulation liquid, for 24 hours at 70 °C for mineral oil, and 90 °C for natural ester. The water content in the mineral oil and natural ester used for impregnation was up to 5 ppm and 30 ppm, respectively. The oxygen level in the insulation liquids was kept below 10,000 ppm. The moisture contents of solids and liquids were analysed in accordance with IEC 60814 Ed. 2 [14]. Initial water contents in the paper and pressboard at selected moisture levels of 0.5 % to 5.0 % were achieved by placing the impregnated specimens in a wet chamber. All materials were placed together in 50 mL vials crimped with butyl septa (Figure 2), leaving the air space above the insulation liquid level. Then, they were heated in an oven at specified temperatures between 40 °C and 120 °C and for an equilibration time, taking into consideration the material type and thickness. The moisture levels were considered as reached when last three measurements matched closely. All preparation procedures were made in a glove box with Argon atmosphere. For the same moisture level and the same temperature, equilibration time was longer with natural ester, taking into consideration higher viscosity. As an example at 40 °C and 2 % of humidity, equilibrium was reached after 74 hours with mineral oil, in comparison to 108 hours with natural ester [13].

3.2 Equilibrium curves for cellulosic insulation (paper and pressboard)

Due to the higher solubility of moisture in natural ester compared to mineral oil, the moisture-equilibrium curves are significantly moved to the right-hand side toward the natural-ester curves (Figure 3). Therefore, for the same moisture content in the cellulosic materials, the expected water content in natural ester is significantly higher than in mineral oil. For example, for an equilibrium of 60 °C and 3 % water in cellulosic insulation, water content in natural ester is around 10 times higher than in mineral oil.

3.3 Equilibrium curves for paper and pressboard separately

Separate equilibrium curves for paper and pressboard in both insulating liquid types are presented in Figures 4 and 5. Distribution of humidity in mineral oil between both types of cellulosic materials is relatively similar, whereas uneven distribution, i.e., lower water content in

The mechanisms involved in natural esters are different from those in mineral oil and need to be understood more deeply

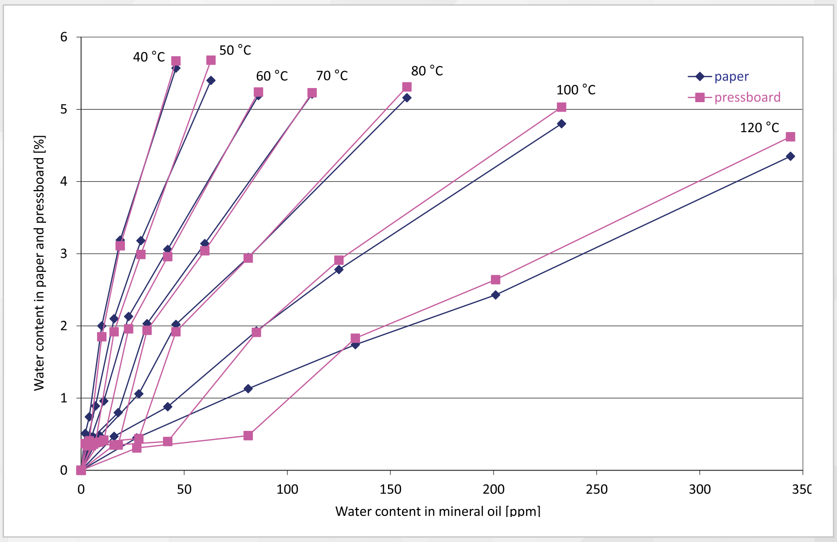

Figure 4. Perrier-Lukic moisture-equilibrium curves for paper and pressboard in mineral oil

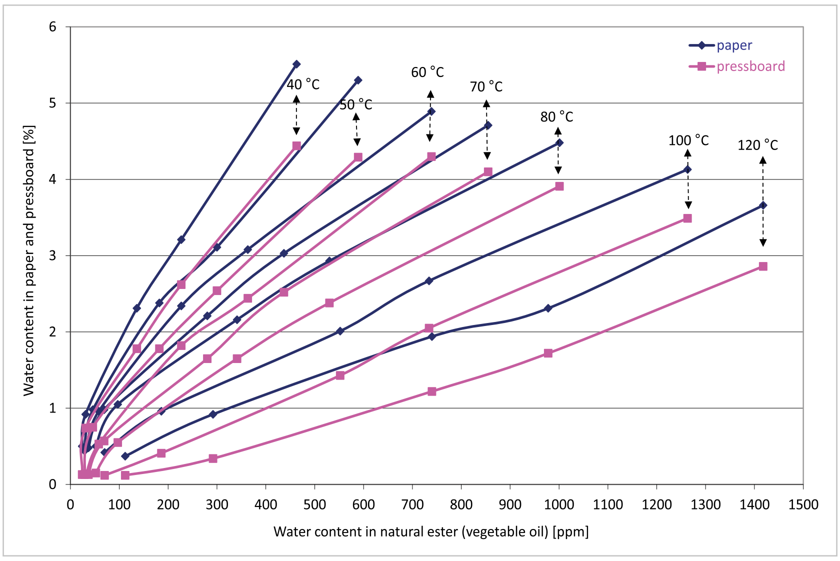

Figure 5. Perrier-Lukic moisture-equilibrium curves for paper and pressboard in natural ester

Users must keep in mind that the correlation between the amount of water in the oil and in the cellulose is always changing as a function of transformer loading

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Christophe Perrier obtained his Ph.D. in insulating materials in 2005 from the Ecole Centrale de Lyon, France. He started his career in the R&D centre of Areva T&D (Villeurbanne) working on insulating liquids to optimize power transformers reliability. In 2006, he moved to the R&D Centre on Power Transformers (Massy) where he developed a laboratory and activities dedicated to insulating materials with special focus on environmentally-friendly liquids. Since 2012 he has been in charge of the R&D projects on materials at GE Grid Solutions (formerly Alstom Grid), acting also as a technical expert on insulating liquids. He is member of CIGRE (A2, D1) & IEC (TC 10) as well as A2 French member.

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pressboard and higher water content in paper, was obtained in natural ester. The contributing factors for such behaviour in pressboard impregnated with natural ester are undergoing further investigations. They suggest that different mechanisms are involved in mineral oil and natural ester, and curves in Figure 5 should be used with caution to predict water content in paper in transformers in service.

It can be noted that obtained results matched well with the literature data [13] for equilibrium between paper and mineral oil [11] and between paper and natural ester [18].

Conclusion

A lot of investigations have been performed over the last years to optimise the transformer design with respect to eco-friendly solutions. The establishment of these moisture-equilibrium charts for natural-ester liquid is a new contribution giving the possibility to control transformer insulation and increase its lifetime. These curves underline that for the same moisture in the cellulose, the water content in natural ester is significantly higher than in mineral oil (curves are moved to the right due to the higher water solubility). It can also be noted that humidity distribution in mineral oil is relatively similar between paper and pressboard, whereas distribution is uneven in natural ester. This suggests that different mechanisms are involved and need to be understood more deeply. Nevertheless, these laboratory moisture-equilibrium curves constitute a useful tool for indirect estimation of water content in cellulose in a green transformer in service. As a conclusion, users must keep in mind that the correlation between the amount of water in the oil and in the cellulose is always changing as a function of transformer loading (temperature).

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