

THERMAL  
PERFORMANCE  
AND MOISTURE  
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# Dynamic Thermal and Moisture Distribution in Transformers

by Ali Al-Abadi  
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**THE RATE OF MOISTURE MIGRATION BETWEEN DIFFERENT INSULATION SYSTEMS DEPENDS ON THE DIFFUSION COEFFICIENT OF THE LIQUID AND THE PRESSBOARD AND IS THEREFORE A FUNCTION OF TEMPERATURE, INSULATION GEOMETRY AND PROPERTIES.**



**Ali Al-Abadi** is a transformer expert in the fields of thermal performance, electrical insulation systems, moisture dynamics, sound and vibrations, electromagnetics, magnetic shielding, losses, and dynamic loading. Over the past years, he has been involved in the development of dynamic thermal and moisture distribution models in the insulation system of liquid-filled transformers, and the development of thermal performance models, development of analytical and numerical-based models to calculate sound levels for transformers and shunt reactors. Ali received his Ph.D. from Friedrich-Alexander University, Erlangen, Germany, in 2014. Following his doctorate, he worked as a research associate at the same university from 2014 to 2015, where he was managing collaborative industrial projects on wind energy, thermodynamics, fluid mechanics, aerodynamics, sound, and vibration. Ali started his career in the transformer field since 2015. In 2022, he joined Hitachi Power, Germany as a Business R&D expert and global team leader. Ali is an active member of standardization bodies and participates in several CIGRE working groups. He has authored and co-authored more than 50 articles on various topics related to transformers and power applications and reviewed numerous scientific and technical papers for international conferences and peer-reviewed journals. In 2024, Ali received the Best Technical Paper Award at the IEEE EIC Conference in the Transformers and Reactors session.

## Introduction

The reliable and efficient operation of distribution transformers is essential to ensure the quality and continuity of power supply to consumers. One of the critical factors affecting the performance and lifetime of transformers is the thermal performance, which is determined by the cooling design. The cooling mechanism of a transformer passes through the insulation system (solid and liquid) through which the heat is dissipated to the environment. The change in heat generated by the transformer during dynamic operation causes a change in temperature and therefore moisture migration between the liquid and solid insulators. The thermal dynamic behaviour depends on the load profile of the transformer and the environmental conditions, which cannot be easily estimated when evaluating power transformers in the field.

The rate of moisture migration between different insulation systems depends on the diffusion coefficient of the liquid and the pressboard and is therefore a function of temperature, insulation geometry and properties. When moisture exceeds acceptable limits in cellulose insulation, it affects the performance of pressboard liquid insulation systems in transformers by accelerating the ageing rate and reducing their dielectric and mechanical strength. Determining the moisture content over time in liquid and solid insulation supports the decision for liquid reconditioning and unit shutdown in time before paper insulation degradation causes failure.

Accurate determination of moisture in transformers during operation is an ongoing challenge due to the complicated mechanism of the moisture migration process and its dependence on many design and thermal parameters. Although drying procedures are usually applied at the manufacturing stage, the level of dryness must be maintained during operation to ensure a high level of dryness to delay deterioration of insulation strength and reductions in both dielectric strength and partial discharge susceptibility.

## Moisture saturation of insulating liquids

One of the main concerns and determining factors in transformer life is the rate of increase of moisture content during transformer operation. There are two main sources of moisture entering the liquid: the solid insulation and the atmosphere. The liquid can absorb moisture from the atmosphere through weak seals, pressure differentials between the environment and the liquid, or during maintenance or repair. These sources are manageable and can be controlled by quality measures. The challenge lies in the ageing of solid insulation, which inevitably forms water as it degrades. In addition, the drying process of the windings and active part could leave some moisture in thick wooden parts, which would migrate to the liquid during operation and spread to different solid insulation parts.

When dealing with different liquids, checking the water content in parts per million (ppm) does not provide consistent information because each type of liquid has its own moisture saturation (MS) curve, as shown in fig. 1.

Considering an operating point at 100°C with a water content of 20 ppm means relative saturations of about 0.4% for synthetic ester (SE), 0.64% for natural ester (NE) and 2.5% for mineral oil (MO). This difference in relative saturation shows that the water content limit for ester liquids can generally be higher than for mineral oil if safe dielectric operation is to be ensured.

In terms of temperature distribution inside a transformer, the relative saturation is expected to be different from one location to another in the whole tank volume. Assuming a 10 K difference between winding top liquid and tank top liquid with the same amount of water content results in a reduction of relative saturation at the hotspot area by about 15-20% at an operating point of 100°C. As

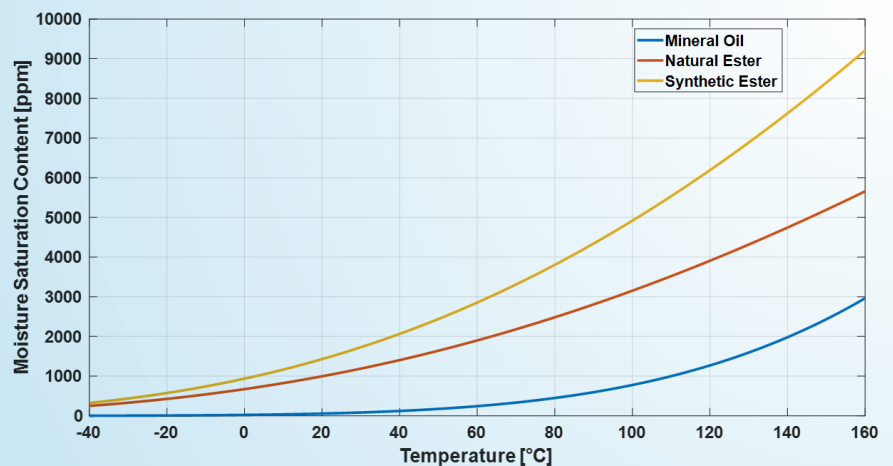


Figure 1. Comparison of the moisture saturation of different liquids versus temperature including the extreme cold range.



the synthetic ester has more space to absorb moisture, this deviation would be balanced by the moisture transfer from the solid insulation to liquid assuming that the transformer is hermetically sealed and the probability to exchange moisture with the ambient is low in the long term.

**Relative saturation ratio for transformer**

From relative moisture saturation at the top liquid  $RS_L$  one can calculate the relative saturation of the liquid at the hotspot region  $RS_h$  by using reference temperatures of both. Similar calculation can be done for liquid in contact with pressboard barrier.

The moisture transfer between the ambient and the liquid could be ignored as this transfer needs longer time than the time required during testing the transformer in the test field. That means any change in water content in liquid would be assumed merely due to the transfer between liquid and solid insulation. If water content in liquid is measured offline in ppm, the relative saturation (RS) could be estimated in the liquid and the solid insulation using equation (1) and the curves of the moisture saturation content,

$$RS = \frac{C_w}{MS} 100$$

where, RS is the relative saturation [%],  $C_w$  is the water content [ppm] and MS is the moisture saturation content [ppm].

Along the same temperature scale, natural and synthetic ester liquids have higher moisture saturation compared to mineral oil. Therefore, the same relative saturation for both esters and mineral oil means different water content as the moisture saturation references are different at the same temperature. Water solubility of transformer liquids is temperature dependent, furthermore, it is directly affected by the liquid additives. Since, transformer commercial mineral oils typically have very little additive content compared to ester liquids, water solubility of different mineral oils is expected to be very similar.

The liquid moisture saturation curve can be expressed as,

$$MS = 10^{\left(-\frac{A}{T+B}\right)}$$

where T is the absolute temperature in K, A and B are the constants characterizing the liquid.

For a variable heat run temperature measurement on the case study transformer, the moisture saturation curves of SE in the hotspot region and the top liquid region are shown in fig. 2. It can be seen that the dynamic loading of the transformer causes the liquid saturation to change dynamically depending on the location and therefore the relative saturation is constantly changing.

The loading level affects the moisture saturation gap between

the hotspot region and the top tank liquid region. The change in the saturation gap during dynamic loading indicates that there is dynamic water content transfer in the liquid volume, as the other moisture transfer mechanisms are slower to respond to water content diffusion between solid and liquid compared to the rate of dynamic loading.

The moisture diffusion mechanism can be found by decomposing the dynamic moisture saturation (MS),

$$MS(t) = g_{Sh} \cdot e^{-\frac{t}{\tau_{Sh}}} + MS_m \cdot e^{-\frac{t}{\tau_{MS}}}$$

where, MS(t) is the change in moisture saturation with time,  $g_{Sh}$  is the moisture gradient at hot spot region over mean moisture saturation of transformer liquid,  $\tau_{Sh}$  is the moisture

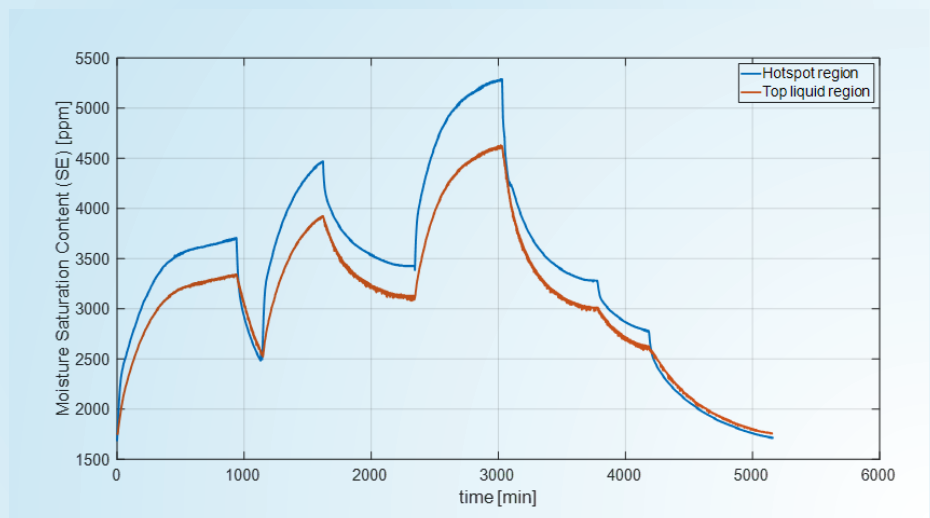
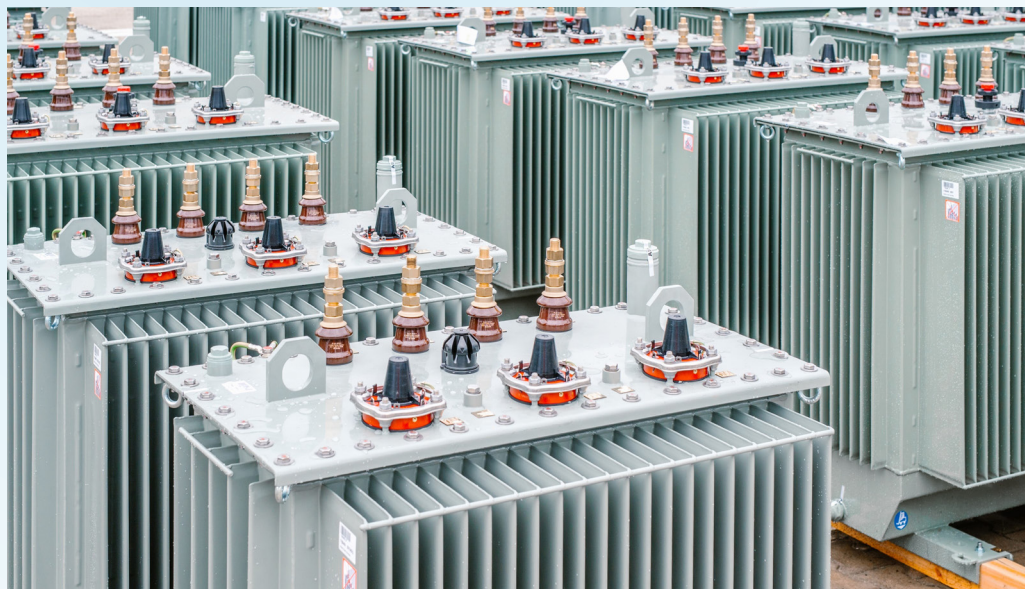


Figure 2. The dynamic moisture saturation curves of SE liquid-filled transformer at hotspot region and top yoke region.



saturation time constant at hotspot region,  $MS_m$  is the mean moisture saturation of the transformer liquid, and  $\tau_{MS}$  is the time constant at mean moisture saturation. The analysis of Eq. (3) is presented in Table I, which shows the moisture diffusion from the inside to the outside of the winding liquid under the influence of the relatively rapid diffusion of the hotspot liquid  $\tau_{Sh}$  to the tank liquid  $MS_m$  compared to the diffusion stabilization of the moisture inside transformer liquid volume  $\tau_{MS}$ .

Observing the moisture saturation content at different temperatures of the liquid in different location inside the transformer tank would give understanding how the moisture migration within the liquid volume takes place during a transformer dynamic loading. If the water content of liquid is assumed to be the same everywhere due to liquid circulation, the relative moisture content at hotspot area ( $RS_h$ ) can be calculated using the liquid saturation curve and the known relative saturation measured at top tank liquid sensor ( $RS_L$ ) as follows:

$$RS_h = RS_L \cdot 10^{\left[A \cdot \left(\frac{1}{T_h} - \frac{1}{T_L}\right)\right]}$$

From which a relative saturation ratio ( $RSR$ ) can be presented as follows:

$$RSR = \frac{RS_h}{RS_L} = 10^{\left[A \cdot \left(\frac{1}{T_h} - \frac{1}{T_L}\right)\right]}$$

Fig. 3 shows the hotspot gradient and the relative saturation ratio over the time range of the dynamic loading of the tested transformers filled with SE liquid. The  $RSR$  is inversely proportional to the hotspot gradient and indicates the negative hotspot gradient during extreme underloads or shutdowns. This indication is represented by an overshoot which causes the  $RSR$  to be greater than 1 when the hotspot gradient is negative, i.e. when the transformer has experienced extreme underload or shutdown.

With a reference liquid water content, which can be measured from a liquid sample taken on site before the transformer is switched on, relative liquid saturation can be observed at any operating temperature.

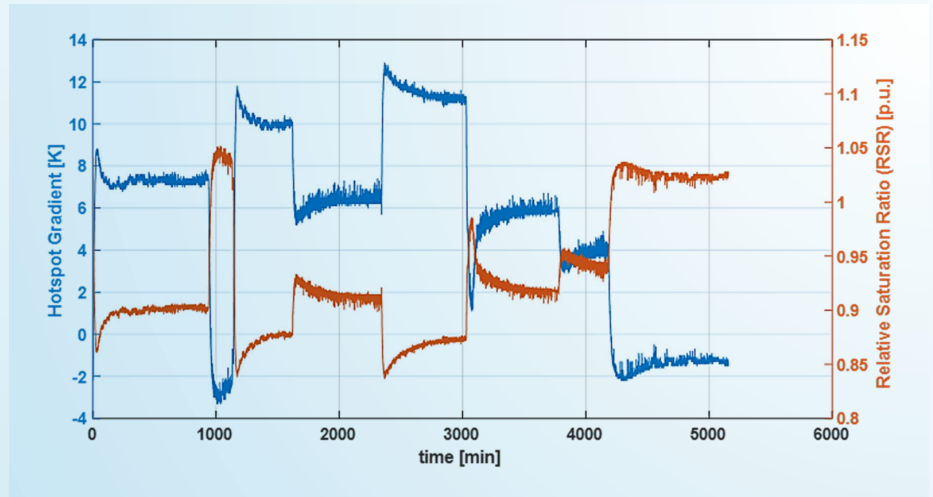


Figure 3. Hotspot gradient and the relative saturation ratio (RSR) over the time range of variable-stage dynamic loading of the case study transformer.

### DIFFUSION TIME CONSTANT FOR PAPER-LIQUID AT HOTSPOT REGION

Location	$g_{Sh}$ [ppm]	$\tau_{Sh}$ [min]	$MS_m$ [ppm]	$\tau_{MS}$ [min]
HS	605.6	15.9	3133	798

Table 1. Diffusion time constant for paper-liquid at hotspot region

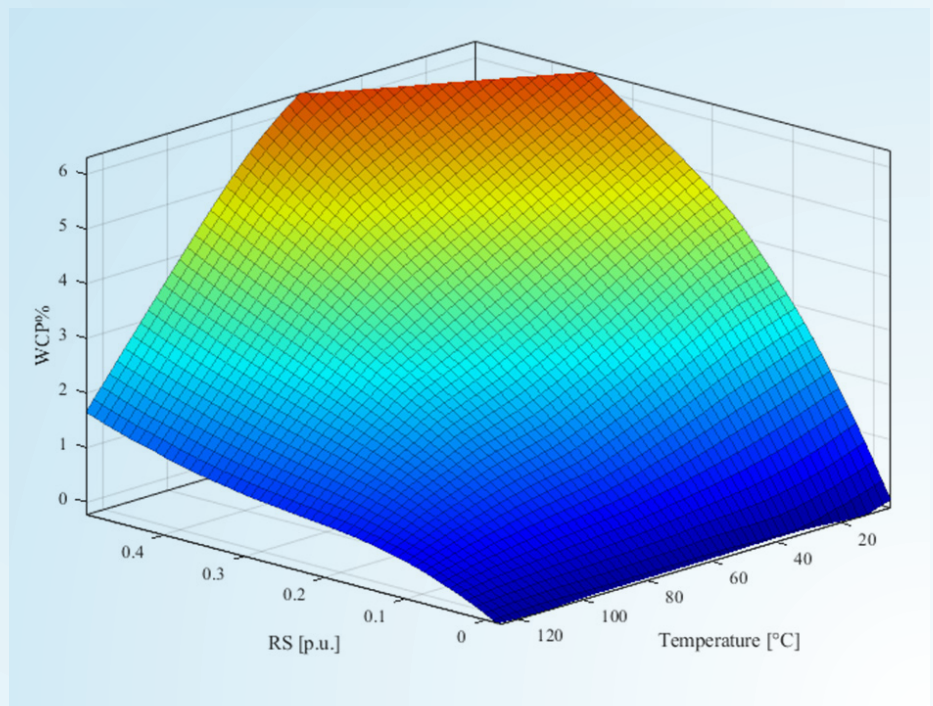


Figure 4. Equilibrium isothermal curves relating relative moisture in synthetic ester to water content in paper at different temperatures.

Using dynamic thermal modelling, RSR could be implemented and continuous monitoring of relative saturation in paper would be possible. For long shutdown periods, it is recommended to update the reference water content value in the liquid to have a more accurate input for the calculation of relative saturation in paper and liquid.

After calculating the relative saturation in the hot spot area, the water content in the paper can be calculated using equilibrium moisture isotherm curves. These curves have been described in a 3d surface as shown in fig. 4.

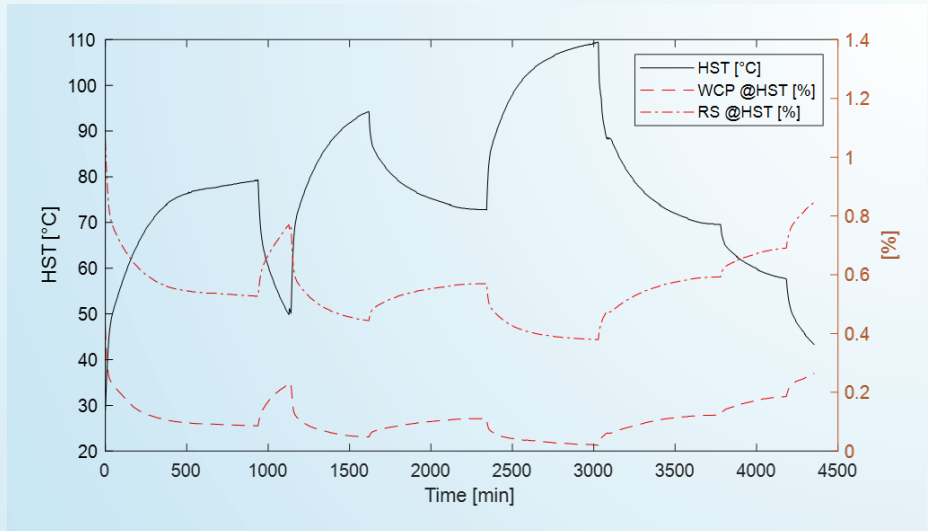


Figure 5. Variation of water content in paper (WCP) and relative moisture saturation in liquid at the hotspot region with temperature.

### Thermal-moisture dynamic modelling

The assessment of dynamic water content in paper at the hotspot region is implemented in the model according to the following procedure:

- Measuring the water content of the liquid in [ppm] on a sample taken from the case study transformer before heat run.
- Calculation moisture saturation at hotspot region using the measured temperature using FOs.
- Calculation of the relative saturation at hot spot region using water content in the liquid and the moisture saturation curve of fig. 1.
- With knowing hotspot temperature and relative saturation at the hotspot region, applying the equilibrium surface of fig. 9 leads to calculate water content in paper (WCP) that would apply under dynamic thermal loading condition shown in fig. 4.

Results of the WCP and RS are shown in fig. 5. It ought to mention that these calculations were based on assuming that the water content in the transformer remains the same due to liquid circulation.

#### References

References available upon request.

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**OBSERVING THE MOISTURE SATURATION CONTENT AT DIFFERENT TEMPERATURES OF THE LIQUID IN DIFFERENT LOCATION INSIDE THE TRANSFORMER TANK WOULD GIVE UNDERSTANDING HOW THE MOISTURE MIGRATION WITHIN THE LIQUID VOLUME TAKES PLACE DURING A TRANSFORMER DYNAMIC LOADING.**

