The role of moisture monitoring in power transformers

Boosting transformer longevity and efficiency

ABSTRACT

In this article, we will explore how moisture impacts the operating performance and expected lifespan of transformers. We will show that implementing an effective online monitoring system allows for continuous assessment of the transformer's condition. Combined with routine testing, it becomes a powerful diagnostic tool enabling anticipation of necessary maintenance operations. This approach is particularly important for power transformers, as they are susceptible to moisture-related issues.

KEYWORDS:

power transformers, moisture monitoring, silica gel, breathers, monitoring, diagnostics

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Moisture inside the transformers negatively affects both the oil and the paper and, consequently, the paper-oil system's performance

1. Introduction

For over a century, power transformers have been manufactured by using a combination of paper and oil insulation, and the evolution of materials has yet to identify suitable alternatives.

To maintain the optimal performance of this paper-oil insulation, it is essential to control environmental conditions and avoid any sources of contamination.

Moisture is one of the primary threats to insulation.

2. The influence of moisture

Moisture inside the transformers negatively affects both the oil and the paper and, consequently, the paper-oil system's performance.

2.1 Moisture effect on oil

Moisture affects some dielectric performance, leading to a decrease in breakdown voltage. Fig. 1 illustrates this, using relative humidity instead of absolute humidity.

Relative humidity above 30% significantly deteriorates the breakdown voltage of both new and aged oil types.

This phenomenon can be explained by the fact that, statistically, saturation is more likely to occur locally in the presence of the electric field. The loss of solubility leads to condensation, which results in the formation of droplets. Consequently, a physical discontinuity between water and oil is created, causing a notable distortion of the electric field due to the large difference in the relative dielectric constants of water (80) and oil (2.2).

Moisture in oil, combined with oxygen, accelerates the ageing process by increasing acidity. This increase in acidity leads to the deterioration of the oil's chemical and physical properties.

Acidity is commonly expressed by the Neutralization Number (NN), which is the quantity of KOH (potassium hydroxide) necessary to make neutral one gram of oil (mg KOH/g).

Smart accessories enable continuous and remote monitoring and data gathering of transformer health.

Oil oxidation progressively depletes the dielectric properties, and in extreme cases, solid deposits (sludge) are formed, which can clog the cooling canals.

The following table (Table 1) is based on the limits suggested by IEC 60422 for transformers in operation.

2.2 Moisture effect on paper

Moisture plays both an immediate and long-term role on paper.

Immediately, there is a significant deterioration of the insulation to withstand voltage, as illustrated in Fig. 2.

The acceptable minimum limit for paper aging is usually considered to be the Degree of Polymerizations (DP)= 200

The paper is 90% made of cellulose, i.e., a natural linear polymer compound of glucose. The number of monomer units per molecule, called degree of polymerization (DP), for a new paper, assumes an average value greater than 1200 (DP = 1200).

Moisture in the paper also plays a role in ageing by accelerating the rupture of the polymer bonds of the cellulose with consequent degradation of all its physical properties.

The acceptable minimum limit for paper aging is usually considered to be the Degree of Polymerizations (DP)= 200.

The following diagram (Fig. 3) illustrates the development of paper mechanical properties as a function of DP.

Fig. 4 illustrates the negative impact of moisture on paper when the moisture content reaches 2.5%, which is considered a standard reference for transformers in operation. The ageing accelerates by five times compared to the ideal condition of the absence of moisture.

Relative humidity above 30 %significantly deteriorates the breakdown voltage of both new and aged oil types

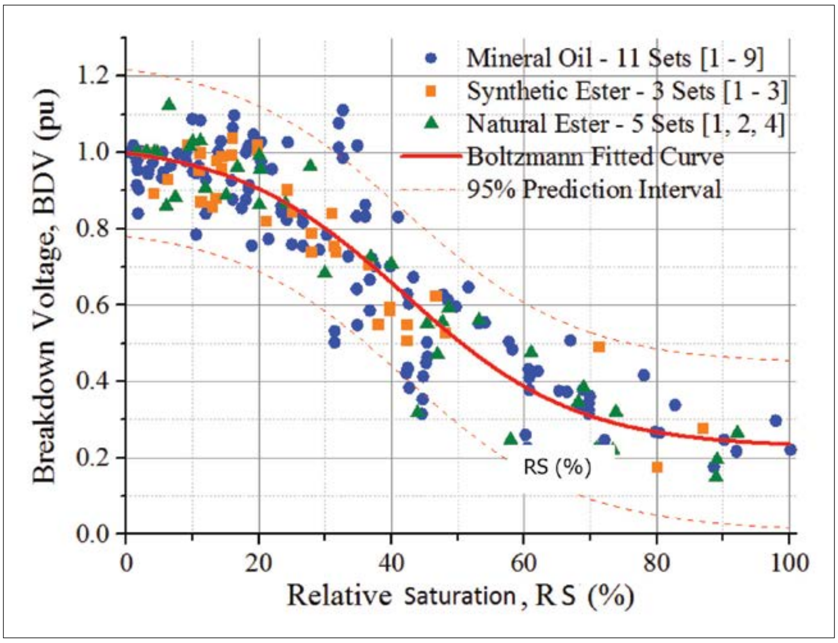

Figure 1. The weight of relative humidity (relative saturation in the graph) by comparing mineral oil with synthetic and vegetable oil [1]

Table 1. Acidity limits on transformers according to IEC 60422 [2]

Highest voltage for equipment (kV)	In-service acidity limits NN (mg_{KOH}/g_{oil})		
	Good	*Sufficient*	*Poor*
>170	<0,10	0,10÷0,15	>0,15
from 170 to 72,5	<0,10	0,10÷0,20	>0,20
<72.5	<0,15	0,15÷0,30	>0,30

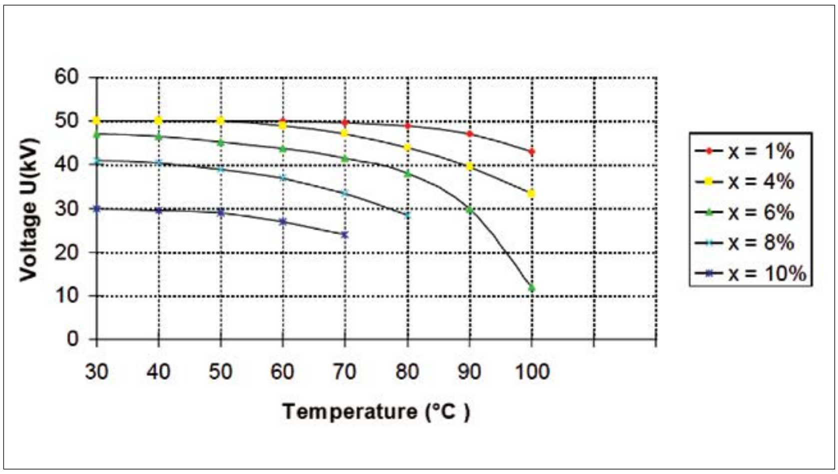

Figure 2. The discharge voltage of the impregnated paper as a function of humidity and temperature [3], X stays for Relative humidity

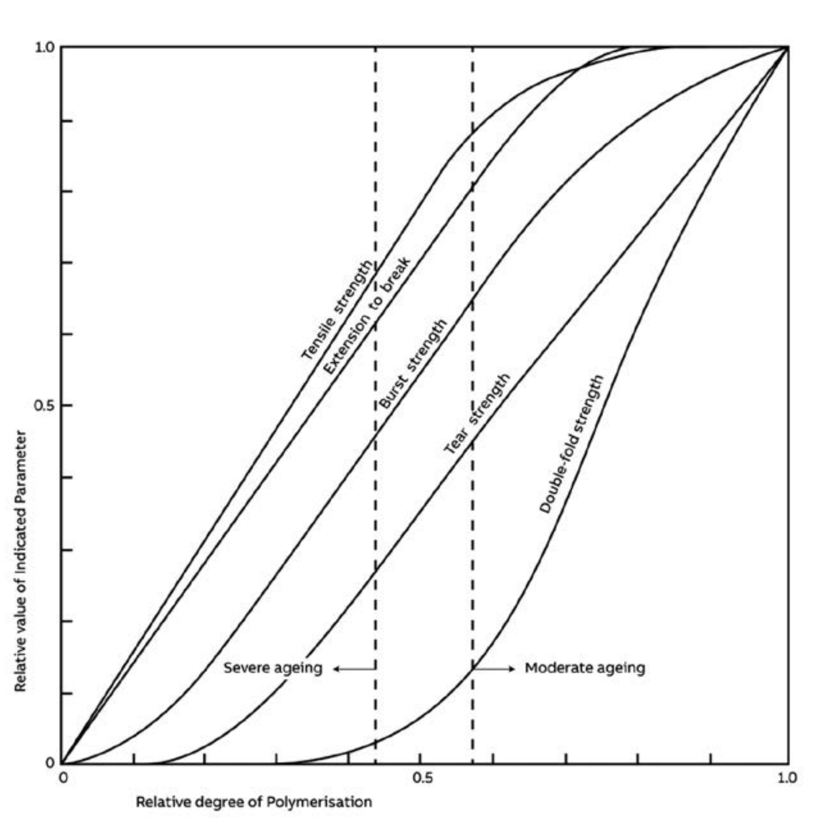

Figure 3. Paper mechanical properties are a function of the degree of polymerization [4]

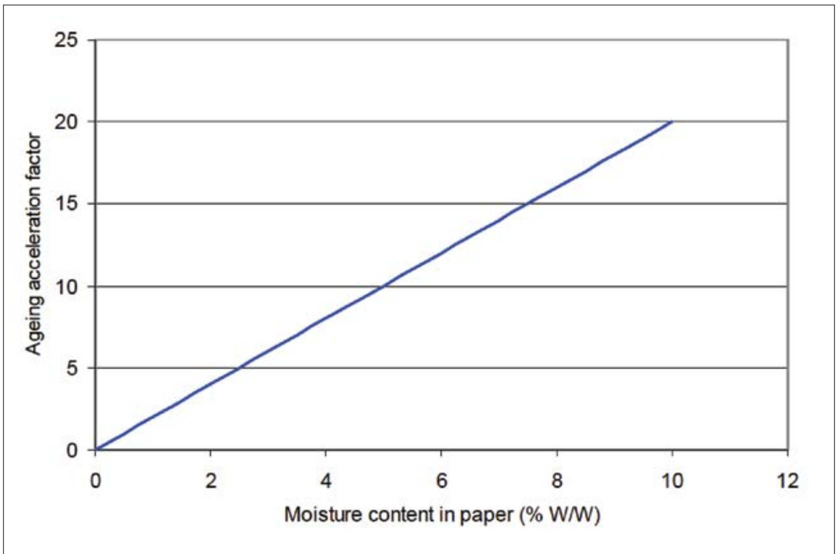

Figure 4. Increase rate of paper ageing in correlation to humidity [3]

When high temperatures are reached, any moisture impregnated in the paper can turn into vapour, leading to a dielectric discontinuity that can trigger electrical discharges

2.3 Moisture and the risk of bubble formation

It is important to consider the moisture content in the paper to avoid the formation of water vapour bubbles (bubbling). When high temperatures are reached, any moisture impregnated in the paper can turn into vapour, leading to a dielectric discontinuity that can trigger electrical discharges. The graph in Fig. 5 illustrates this effect.

When insulation is subjected to higher temperatures, it ages more quickly and thus compromises its life expectancy. However, there is a critical limit beyond which the risk of electrical discharge significantly increases. This means a definite maximum level of overloading should not be exceeded. The graph (Fig. 5) indicates that if the moisture content in the paper insulation reaches 2.5%, the maximum allowable temperature at the hot spot should not exceed 130 °C. Operators must consider this limitation.

A practical example of the maximum applicable temperature for preventing bubble formation as humidity in the paper is shown in Table 2.

Table 2. Bubbling formation as a function of temperature and humidity on paper [6]

	0.01%	1.78%	2.23%	4.45%	5.56%	6.98%	9.27%
120°C	No	No	No	No	No	No	No
125°C	No	No	No	No	No	YES	YES
130°C	No	No	No	No	YES	YES	YES
140°C	No	No	No	No	YES	YES	YES
155°C	No	No	YES	YES	YES	YES	YES
170°C	No	No	YES	YES	YES	YES	YES

2.4 Summary of the risks associated with the presence of moisture

Moisture introduces both short-term and long-term risks:

Short-term risks:

- **Reduced discharge voltage in the oil**
- **Reduced discharge voltage in combined insulation**
- **Limitations on overloading due to bubbling**

Long-term risks:

- **Deterioration and aging of the oil**
- **Deterioration and aging of the paper**

It is evident that moisture significantly affects the operation and lifespan of transformers, ultimately impacting their performance and, thus, the overall investment in them.

Therefore, it is essential to adopt systems that limit moisture ingress and, if possible, monitor moisture presence. This parameter is crucial for diagnosing the health status of the insulation.

3. Methods for limiting moisture ingress

Several measures are employed to mitigate moisture ingress:

- **Dehydrating breathers with hygroscopic salts:** These devices help prevent moisture from entering inside the conservator from the external environment. Today, this task is facilitated by devices that automatically regenerate salts (see Fig. 6a).
- **Hermetic environment with rubber bag including dehydrating breathers with hygroscopic salts:** This method ensures there is no direct contact between ambient air and oil (see Fig. 6b). The breathers prevent condensation from forming on the rubber bag, which, if it breaks, could come directly into contact with the oil.
- **Hermetic environment with nitrogen blanket and pressure control:** This system is primarily utilized in the USA and helps maintain optimal pressure conditions (see Fig. 6c).

It is essential to adopt systems that limit moisture ingress and, if possible, monitor moisture presence, which is crucial for diagnosing the health status of the insulation

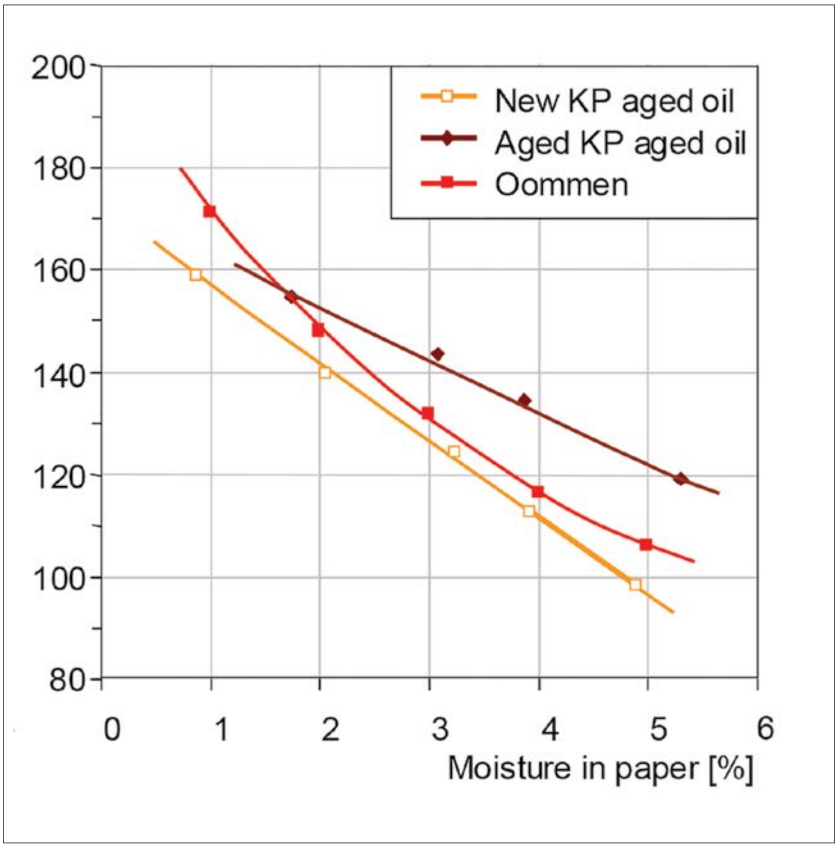

Figure 5. Vapour bubble formation temperature in case of the presence of moisture [5]

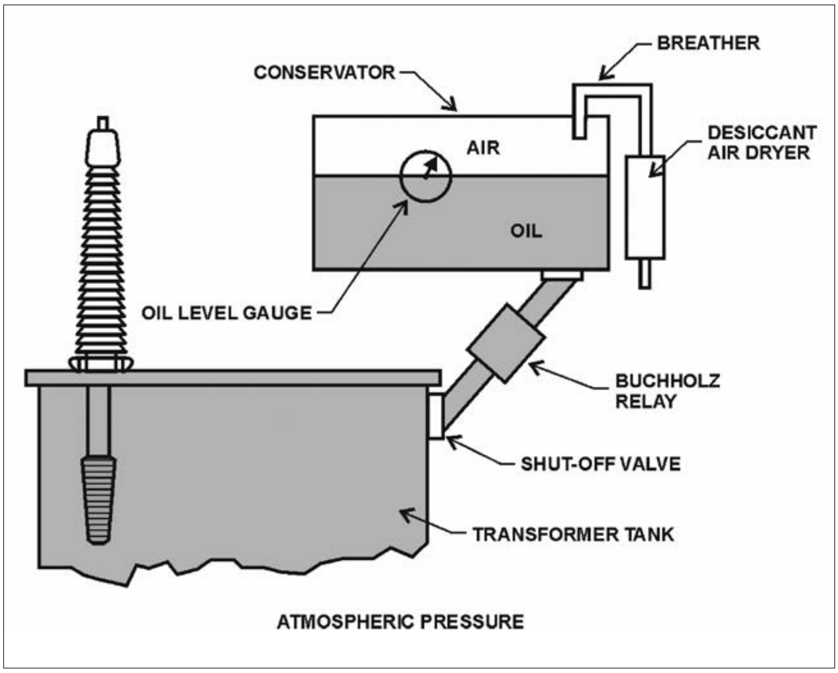

Figure 6. Oil segregation systems [7]
Figure 6a. Dehydrating breathers with hygroscopic salts

The moisture in the transformer is only marginally a consequence of external pollution: it mostly originates from the spontaneous decomposition of paper during the ageing process accelerated by temperature

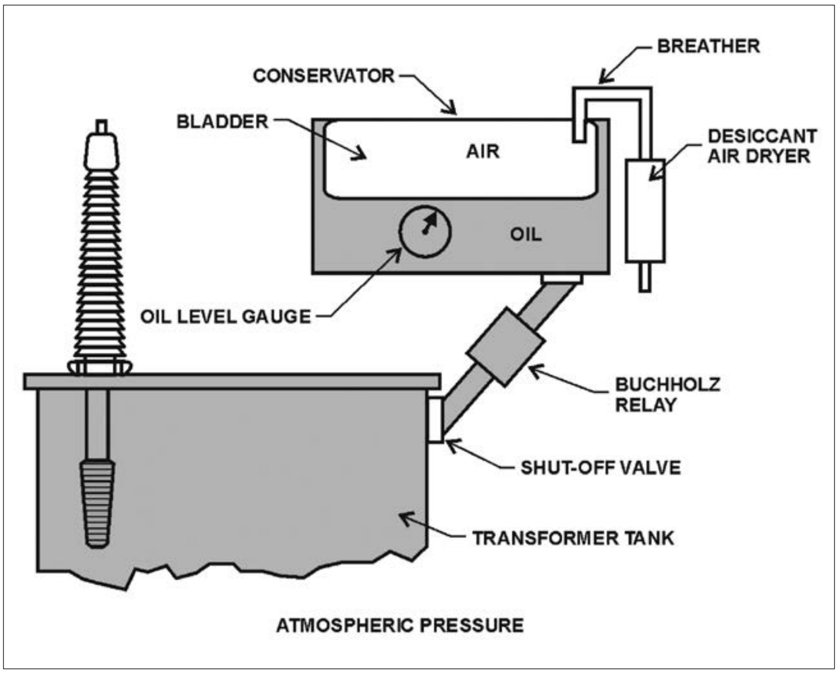

Figure 6b. Hermetic environment with rubber bag including dehydrating breathers with hygroscopic salts

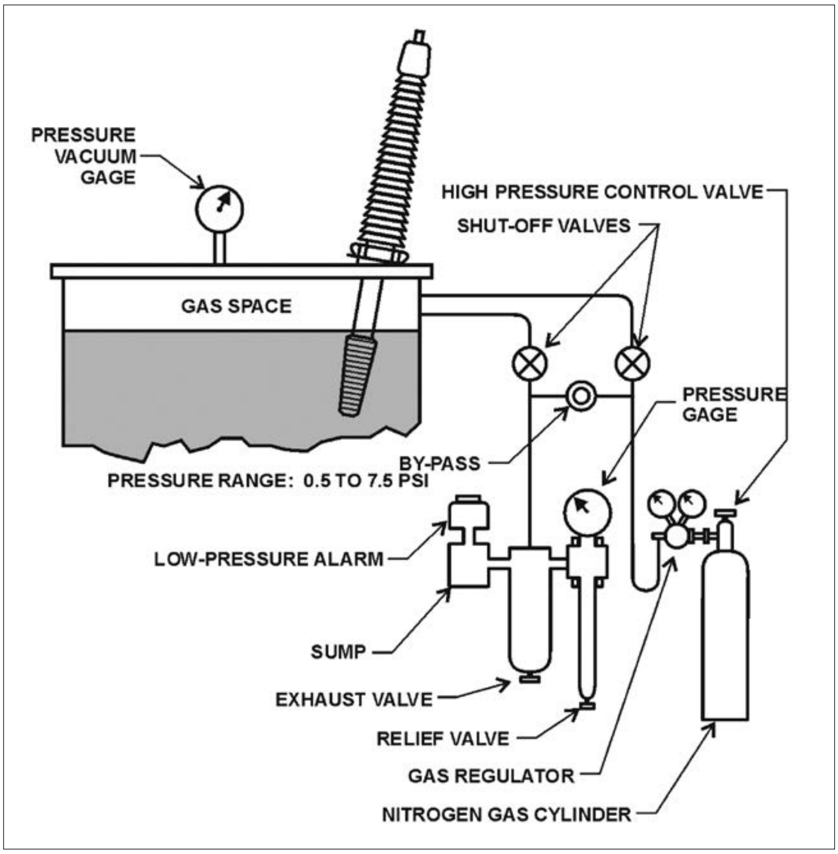

Figure 6c. Hermetic environment with nitrogen blanket and pressure control

- **Hermetic environment with sufficient gas cushion volume:** This arrangement allows for oil expansion while keeping pressure variations within acceptable limits (see Fig. 6d).
- **Hermetically sealed oil transformers:** normally manufactured with a sealed corrugated tank equipped with fins that allow the expansion at the temperature variations (see Fig. 6e).

The following chart (Fig. 7) clearly highlights the different behaviour between hermetic machines and breathing machines. It compares the increase in acidity over time (Neutralization Number NN) between two types of power transformers: hermetically sealed and those breathing through salt desiccant.

Fig. 7 shows that segregation by bag enables the oil's acidity level to be kept low, allowing, in most cases, the avoidance of oil change or regeneration until the end of life.

It is important to note that the moisture in the transformer is only marginally a consequence of external pollution: it mostly originates from the spontaneous decomposition of paper during the ageing process accelerated by temperature. Consequently, moisture can be present inside the transformer even if it is perfectly airtight.

4. Moisture limits

Historically, IEC standards have focused on defining moisture limits in oil using absolute values referred to 60°C, as summarized in Table 3 below.

Higher humidity levels are only acceptable for smaller distribution transformers operating at voltages that do not exceed Medium Voltage

It appears more appropriate to express these limits in terms of relative humidity. The IEEE (Table 4) has adopted this approach by establishing stricter limits for relative humidity in oil to reduce the moisture content in the associated insulation paper (as outlined in IEEE Std. C57.106).

In relation to the relative humidity levels in paper insulation, the IEC standard takes as a reference the corresponding IEEE, which offers an interpretive guide for the humidity in paper in equilibrium with the moisture in oil. See this in Table 5.

It is important to note that higher humidity levels are only acceptable for smaller distribution transformers operating at voltages that do not exceed Medium Voltage (MV).

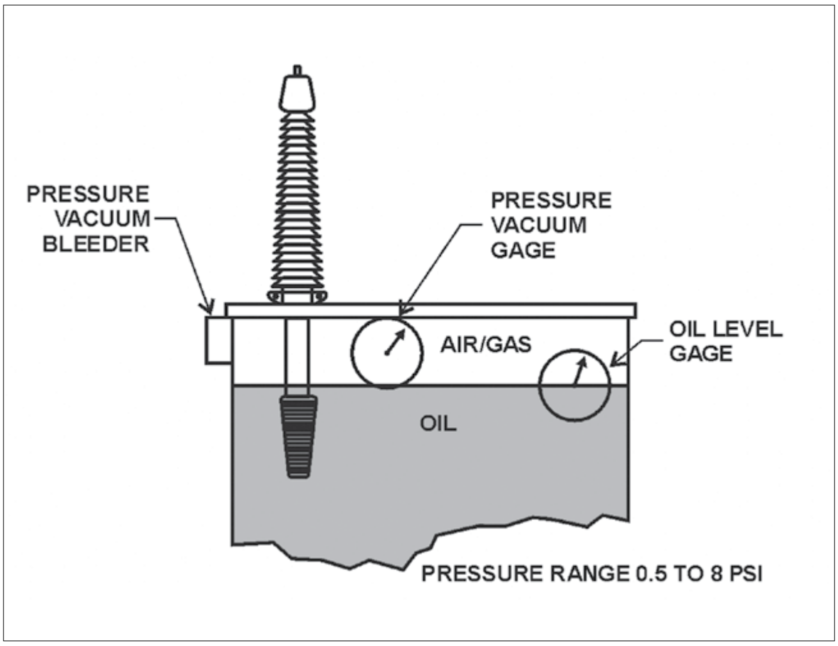

Figure 6d. Hermetic environment with sufficient gas cushion volume

Figure 6e. Hermetically sealed oil transformers

In medium power transformers, where oil segregation is typically used, it is essential to ensure the proper functioning of devices that use hygroscopic salts

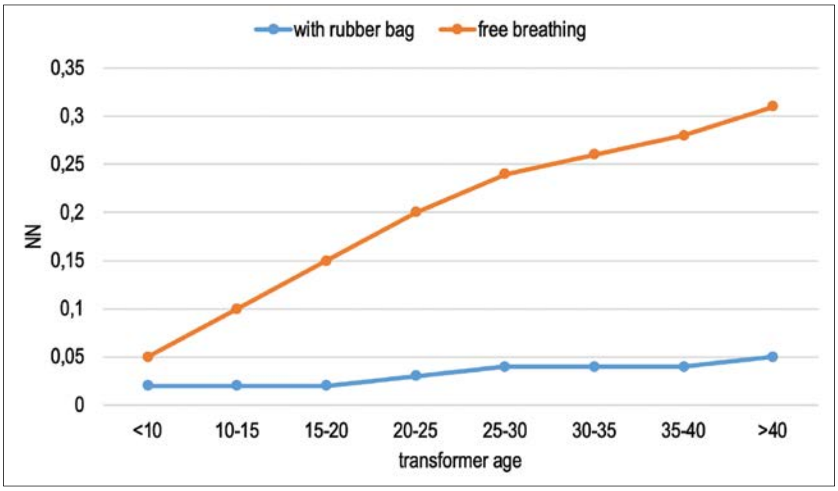

Figure 7. Oil acidity is expressed through the Neutralization Number (NN) as a function of age [8]

Conventionally, information on moisture can only be obtained through oil sampling and DGA analysis in the laboratory, but today, this information can be accessed continuously

Table 3.IEC limits for moisture

Highest voltage for equipment (kV)	H_2O (ppm) at 60°C	IEC 60422 - 2013		
		H_2O (ppm) at 60°C on duty		
		Good	*Sufficient*	*Poor*
>170	<10	<15	15÷20	>20
from 170 to 72,5	<10	<20	20÷30	>30
<72.5	<20	<30	30÷40	>40

Table 4. IEEE limits for moisture in oil

Highest voltage for equipment (kV)	Maximum moisture content in oil (ppm)			Relative moisture in oil
	50°C	**60°C**	**70°C**	
<72,5	27	35	55	15%
from 170 to 72,5	12	20	30	8%
>170	10	12	15	5%
Saturation in mineral oil	175	245	335	

Table 5. IEEE interpretation guide (as outlined in IEEE Std. C57.106)

% saturation water in oil	Condition of cellulosic insulation
0-5	Dry insulation
6-20	Moderate – wet, low numbers indicate fairly dry to moderate levels of water in the insulation. Values toward the upper limit indicate moderately wet insulation.
21-30	Wet insulation
>30	Extremely wet insulation

5. The importance of air-dehydrating devices in free-breathing transformers

As discussed previously, particularly in Fig. 5, avoiding oil contact with a humid environment is crucial. In medium power transformers, where oil segregation is typically used (as shown in Fig. 6a), it is essential to ensure the proper functioning of devices that use hygroscopic salts. These salts help prevent oil from encountering moisture in the air. It is recommended that these air-dehydrating devices be checked and regenerated periodically, ideally every 1 to 3 months. Today, there are systems available that can prevent moisture from entering the conservator and can automatically regenerate the salts, ensuring their effective operation. In smaller distribution transformers operating at voltages not exceeding Medium Voltage (MV), slightly higher moisture levels may be acceptable.

6. The importance of moisture monitoring

Understanding moisture levels in transformers is crucial to preventing risks and degradation that can significantly shorten their lifespan. In the past, this information was limited; it could only be obtained through oil sampling for chemical-physical analysis and Dissolved Gas Analysis (DGA) in the laboratory. Today, this information can be accessed continuously, and it becomes essential to monitor it regularly.

It should also be emphasized that it is difficult to clearly determine the humidity in the paper, starting from moisture in oil. However, there are models obtained from laboratory tests that give indications of this magnitude. The internal thermal dynamics are complex and vary significantly with temperature, which fluctuates considerably between the lower part of the tank and the upper areas of the winding.

When considering the exchange mechanism between paper and oil, it's important to note that this process can take a considerable amount of time, often several days, especially if the paper is thick.

Self-dehydrating breather protects the transformer from moisture intake and allows for continuous moisture monitoring

Verifying the dielectric response of variable frequency insulation has now become a standard practice, which allows indirect assessment of the moisture contamination in the paper and the oil

For cost-effective predictive maintenance, it is essential to continuously integrate data about asset health through a data aggregator that can collect data from multiple sources.

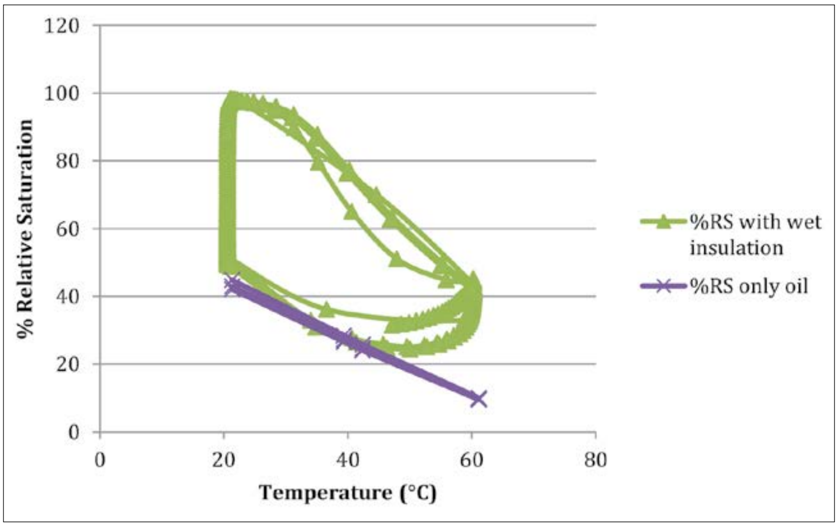

Figure 8. Monitoring moisture in oil, comparison between dry and wet paper [1]

When a parameter is monitored continuously, its historical data gains significant value, allowing for evaluations that cannot be derived from a single data point

Humidity measurements taken from the lower part of the tank often do not accurately reflect conditions in windings, a critical zone, which is typically located near the upper winding header. To obtain reliable data, it is advisable to conduct sampling under thermal equilibrium conditions for at least one day. This practice allows for a more accurate comparison between the relative humidity at the sampling point and the relative humidity in other internal zones of the transformer.

When a parameter is monitored continuously, its historical data gains significant value, allowing for evaluations that cannot be derived from a single data point. Continuous monitoring of moisture content provides detailed insights into the relationship between oil and paper. **These insights are difficult to achieve through occasional moisture measurements in the oil. Furthermore, consistent temperature conditions can be referenced more easily compared to relying on random sampling.**

There is much more that can be achieved.

Fig. 8 illustrates the monitoring in two different scenarios: one with dry paper and the other with wet paper. In the case of dry paper, as the load and oil temperature change, there is minimal moisture exchange between the paper and the oil. Conversely, in a transformer with wet paper, temperature changes result in significant hysteresis due to the relatively slow process of moisture exchange between the paper and the oil. The magnitude of the hysteresis cycle observed over time may indicate the average moisture content in the paper.

With experience and ongoing monitoring of similar transformers, it will be possible to establish a more reliable criterion for extrapolating the moisture content in the paper, surpassing the equilibrium graphs obtained in the laboratory. Soon, we will also be able to define limits for the hysteresis cycle, which will help set alarm thresholds.

It is important to note that verifying the dielectric response of variable frequency insulation (DFR) has now become a standard practice. By conducting this method, we can indirectly assess moisture contamination in the paper and the oil.

The installation of moisture monitoring greatly enhances the knowledge of the state of health of the insulation, especially since the trend of the parameters is available and not just momentary information

Monitoring moisture levels in the oil can significantly aid in confirming the results of the DFR response.

6.1 Characteristics of a moisture monitoring system

When evaluating a moisture monitoring system, it is important to consider the following characteristics:

- **Reliability**
  The system must be dependable, ensuring that its operations and measurements are trustworthy.
  A good guideline is that the reliability of the monitoring system should match or exceed that of the object being monitored. Ideally, the system should also include self-diagnostic features for added assurance.

- **Cost-effectiveness**
  Capacitive sensors are currently employed to ensure both reliability and cost-effectiveness. The expense of the monitoring system should align with the cost of the monitored transformer and/or its operational significance.

- **Ease of data transmission, collection, and processing**
  It is essential to have an architecture that simplifies data collection and is compatible with other data monitoring and transmission systems. The information must be processed with predefined algorithms to report the instantaneous data, track time trends, and provide additional information such as alarm signals and projections of moisture levels on insulating paper, breakdown voltage

- **Easy installation**
  Installation should be unobtrusive and ideally feasible while the transformer is in service.

7. Conclusion

We have shown how moisture affects transformer operating performance and expected lifespan. Until now, this information has been difficult to access and has mainly been applied to large power transformers during periodic oil checks. However, the relatively low cost of monitoring, combined with its proven reliability, now allows for a significant increase in the number of monitored transformers. This improved monitoring provides greater insight into machine reliability, enabling us to anticipate necessary maintenance operations, such as oil changes or insulation treatments.

Even large transformers monitored periodically through oil analysis can provide timely information that helps make more informed maintenance decisions.

Until now, the basic monitoring for power machines consisted of a system for detecting temperature and the hydrogen (H_2) dissolved in the oil, which allows the exercise to be alerted to the presence of partial discharges and other phenomena that can evolve into power discharges.

The installation of moisture monitoring greatly enhances the knowledge of the state of health of the insulation, especially since the trend of the parameters is available and not just momentary information.

Bibliography

[1] CIGRE Technical Brochure 741: *Moisture measurement and assessment in transformer Insulation,* 2018

[2] IEC 60422: *Mineral insulating oils in electrical equipment – Supervision and maintenance guidance*, 2013

[3] T. A. Prevost, Weidmann Ind., *Degradation of Cellulose Insulation in Liquid-Filled Power Transformers*, W-ACTI 2005

[4] W. G. Lawson, M.A. Simmons, and P.S. Gale, *Thermal Ageing of Cellulose Paper Insulation,* IEEE Transactions on Electrical Insulation, vol. EI.12, pp. 61-66, 1977.

[5] [CIGRE Technical Brochure 349: *Moisture equilibrium and moisture migration within transformer insulation systems,* 2008

[6] Lance Lewand: Conference "Doble do Brasil". 2008

[7] U.S. Department of the Interior Bureau of Reclamation: *Transformer: basics, Maintenance, and Diagnostics*, Denver, 2005

[8] CIGRE Technical Brochure 526: *Oxidation Stability of Insulating Fluids*, 2013

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