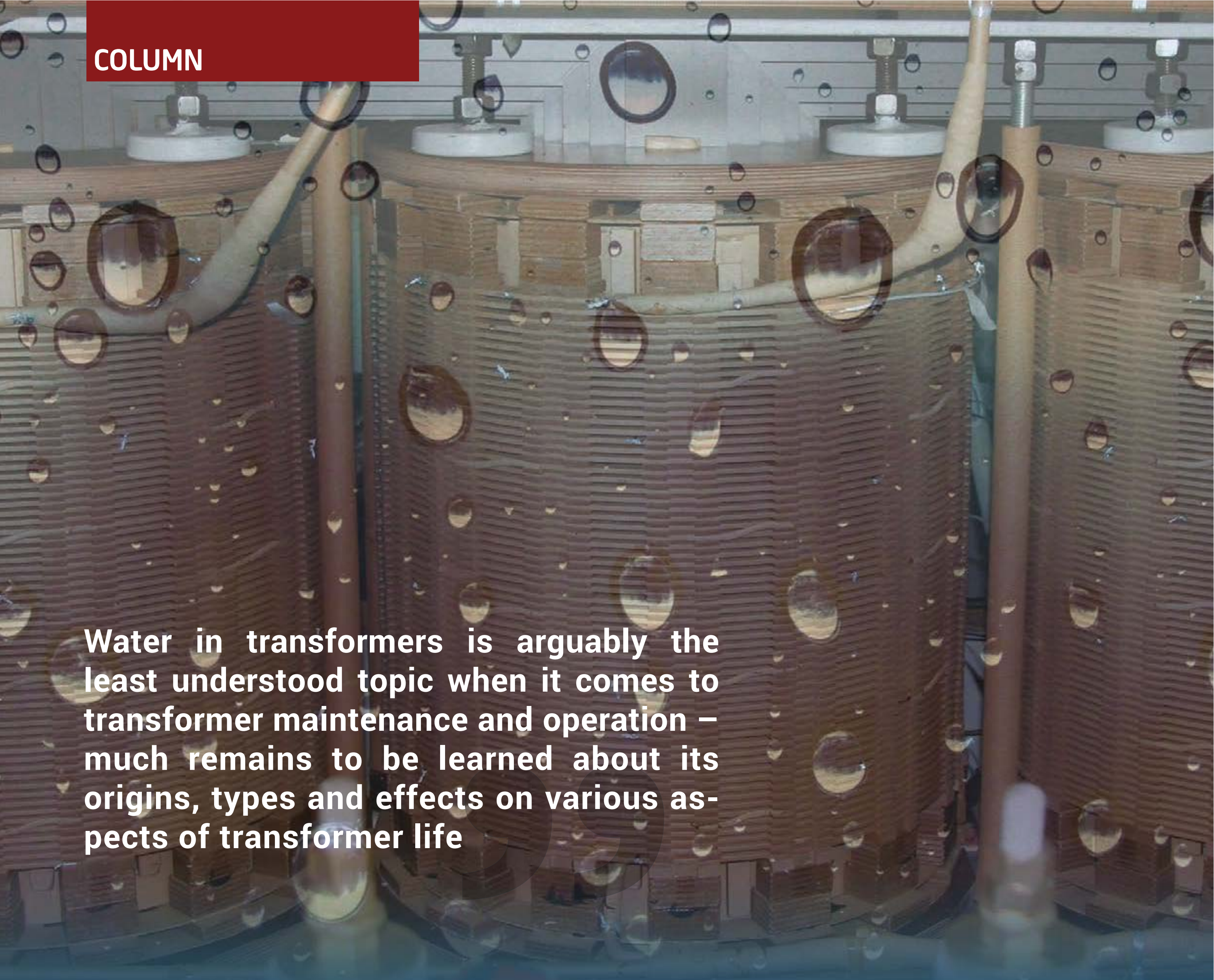

Water in transformers is arguably the least understood topic when it comes to transformer maintenance and operation – much remains to be learned about its origins, types and effects on various aspects of transformer life

Water in transformers

All you wanted to know about it, but were afraid to ask

1. Q&A about water in transformers

The idea to write a Q&A column about water in transformers for this magazine came from various speaking and consulting engagements. Very often during seminars, workshops or technical presentations I have been asked to explain and elaborate on 'seems to be trivial', but 'appeared to be' complex phenomena, statements or a fact related to presence and effects of water in transformers.

Water in transformers is an intriguing topic and usually attracts an interest of large groups of professionals in the field of high-voltage electrical equipment operation and maintenance. From the onset of transformer manufacture, drying of solid and liquid insulation presents an operational and technical challenge, consuming a lot of effort and resources. Even after a thorough job on drying, water finds its way into a transformer taking every possible path during its transportation from factory floor to the final destination. Water is often labelled as the worst enemy of transformers and numerous research papers have been published covering this uneasy subject. Water is the source of all life on our planet, but in transformers, this is one of the major life-threatening substance. Here comes the first question.

2. Water in transformers – So what!

This was the title of a paper written by Paul Griffin of Doble Engineering Co in 1996 [1]. The paper summarises some detrimental effects of water on transformer insulation and, in particular, the author focuses on reduction in dielectric strength of liquid and solid insulation, evolution of gas bubbles and accelerated ageing of transformer insulation, both paper and oil.

Recent findings show that DBV is affected by relative saturation of water in oil, and not by water in oil concentration (ppm) as was previously thought

b. The curve has pronounced S-shape. Within first 20 % of relative saturation DBV remains almost unchanged, and only beyond 20 % it starts to decrease until RS reaches approximately 60 %. At this point, the drop in DBV is approximately 70 % and it does not change much right until it is close to saturation.

c. The study clearly confirmed relatively recent findings [6] and demonstrated that DBV is affected by relative saturation of water in oil and not by water in oil concentration (ppm) as was previously thought. This is an important result as it raises a question of validity of almost all the moisture related parameters and limits specified in IEEE [4] and IEC [7] guidelines. As we are going to show in the next sections, it also raises a question with regards to validity and usefulness of measuring DBV as one of the key indicators of oil quality. This finding is in line with conclusion drawn by researches from Manchester University [8].

2.2 Bubble evolution: Why does it matter?

When a transformer is energized at full load, the temperature of the winding conductor rises at a speed exceeding the speed at which water vapour dissolves in the oil. Under such conditions, water vapour bubbles can be formed, provided there is excessive amount of water stored in cellulose insulation. Water vapour bubble, free gas within the oil/cellulose insulation system of a transformer, is a cause for concern because of the extremely low dielectric strength of the gas relative to oil or cellulose. When gas bubbles are generated in large quantity, a chain of bubbles can be formed resulting in sharp decrease of oil/paper dielectric integrity. In this case water vapour bubbles should be seen as impurity for liquid insulation. In fact, evolution of free gas bubble during service operation of power transformers has been known to result

2.1 Reduction in DBV: What is a key parameter to consider?

As it is well known, insulation dielectric strength is measured by dielectric breakdown voltage (DBV) and the corresponding tests exist and are detailed in ASTM [2] and IEC [3]. The effect of water on DBV of liquid insulation has been studied extensively and one can refer to Annex B of IEEE 57.106 [4] to learn more about historical background. The dependence of DBV on water in oil is represented by nonlinear relationship, as shown in Figure 1. An experimental validation of this relationship is discussed in very fine details in [5].

From Figure 1 the following should be noted:

a. DBV is normalised between 0 and 1 so various types of insulating liquids can be compared. Very dry liquid at its highest DBV was assigned to 1 p.u.

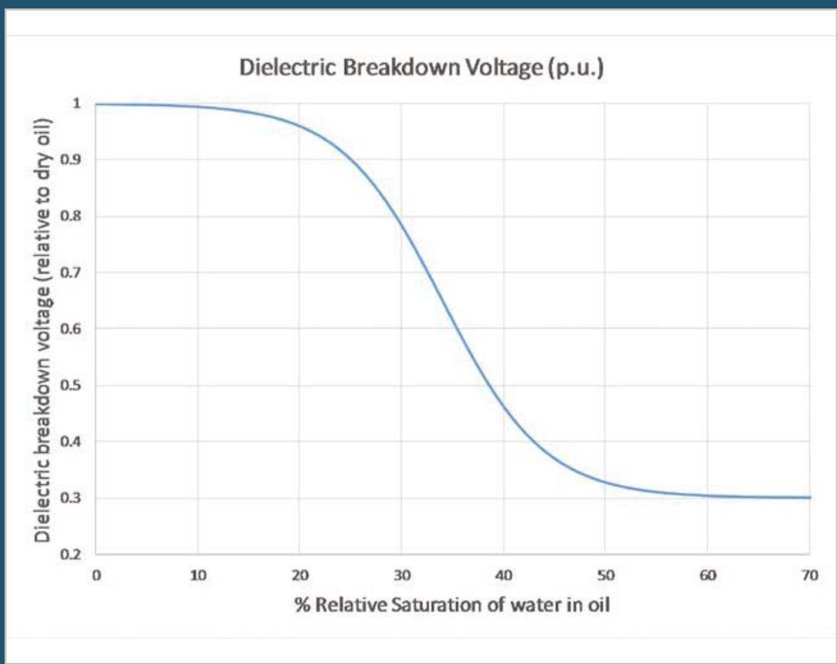

Figure 1. Dielectric breakdown voltage as a function of relative water saturation with an approximative model fitted to the data experimentally obtained in [5]

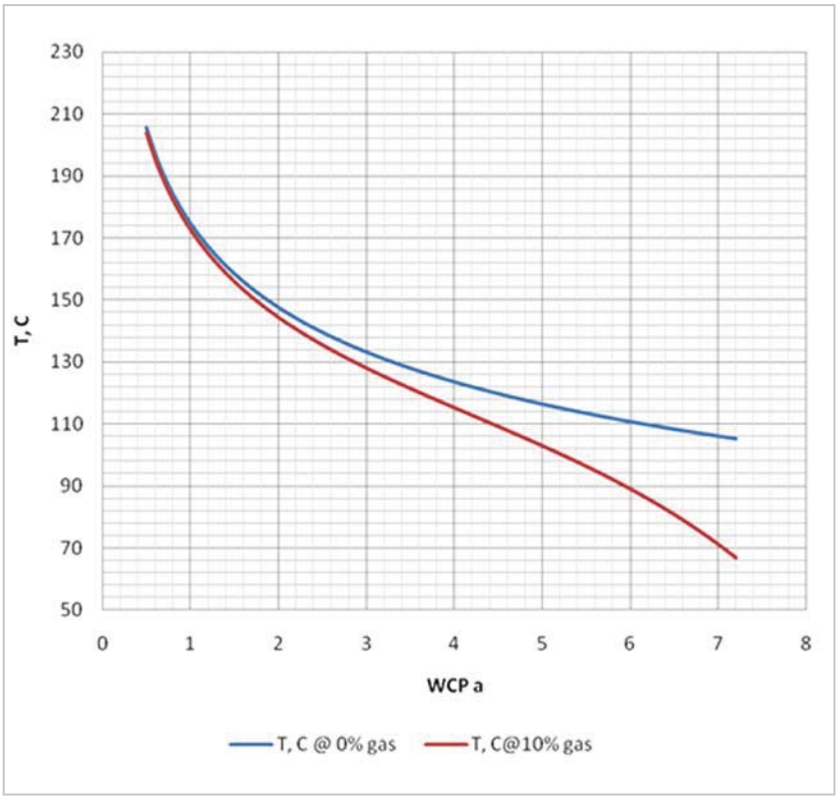

Figure 2. Water vapour bubble incipient temperature as a function of water content of conductor temperature

When the temperature of the winding conductor rises at a speed exceeding the speed at which water vapour dissolves in the oil, water vapour bubbles can be formed

in dielectric breakdowns in several instances [9]. Breakdown of liquid insulation in the presence of gas bubbles is very complex phenomena and the curious reader is referred to the latest research on the subject [10].

While energizing a transformer, it is always prudent to consider winding hot spot temperature and make sure that it does not exceed an incipient bubble temperature. That critical temperature is dependent on many factors, among which are the following:

- Active water content of paper (water content of paper at the interface with the oil)
- Water content of oil at the interface with the paper affected by the bubble formation
- Capillary property of paper
- Gas voids in paper
- Surface tension of oil
- Temperature gradient of oil-paper interface
- Rate of temperature rise
- Static head pressure of the liquid above the area of bubble formation
- Dissolved gas content of oil, and
- Type of the oil preservation system

When many of the above parameters are not considered, very crude approximation of the bubble incipient temperature dependence on water content is shown in Figure 2. The mathematical model for calculation of that temperature is given in Annex A of the IEEE loading guide [11].

It must be noted that a decision to limit winding hot spot temperature (WHS) temperature to 140 °C in both IEC and IEEE loading guides was based on an assumption that 2 % of water in the conductor wrap paper can initiate the bubble evolution at 140 °C. This also can be seen from Figure 2.

2.3 Paper aging: What is the role of water in in the process of oil/paper degradation?

Expert opinions on this question vary widely. When insulation is dry with low oxygen content, the rate of aging is often given by two equations – one for non-thermally upgraded paper (1) and the other for thermally upgraded paper (2) [12], as follows:

$$V = 2^{(\theta_h - 98)/6} \quad (1)$$

$$V = e^{\left(\frac{15000}{110+273} - \frac{15000}{\theta_h + 273}\right)} \quad (2)$$

The destructive process of aging in accordance with (1) and (2) is called pyrolysis or thermal degradation. Numerous attempts have been made by both IEEE and IEC communities to correct these equations to account for effect of water and oxidation. This work is still in progress and there is no confirmed mathematical model which could describe ever-changing process of cellulose degradation under combined influence of temperature, water and oxidation.

The best approximation has been made by the research work funded by EPRI [13]. In this experimental work the effect of water on insulation aging was studied and the summarised results have become a part of the new edition of IEC Loading Guide [12]. In its simplest form and for the purpose of this introduction only, the reduction in expected insulation life can be illustrated by log linear curves shown in Figure 3 [14].

It must be noted that a more sound approach to calculation of expected insulation life due to moisture was presented in the EPRI report referenced above.

3. How does water get into a transformer?

This is probably the least controversial question of all and most of the practitioners agree on the main sources of water ingress. Cellulose insulation may have from 4 % to 8 % of water content before an active part is subjected to drying. At the end of factory acceptance tests, before a transformer leaves a factory floor, water content of solid insulation should be around 0.5 %. Water content of the liquid insulation (e.g. mineral oil) has to be in the range specified by the respective industry guidelines [4], [8].

During transportation, water can enter a transformer from atmosphere if the transformer is not hermetically sealed. Then during onsite assembly and installation, water could enter through various openings. The amount of water entering the transformer during transportation and installation could only be a guesstimate and is never known accurately. Even in the hermetically sealed transformer during operation water is generated as a result of chemical reactions, such as hydrolysis of cell-house and oil. Mostly in Europe, but in many other parts of the world as well, there is a large population of free-breathing transformers with no means of oil preservation. These are open to atmosphere with the insulation moisture content pretty much as high as it is in a piece of paper on your desk top ranging from 4 % to 6 %. Poor gaskets and seals are common spots for water ingress.

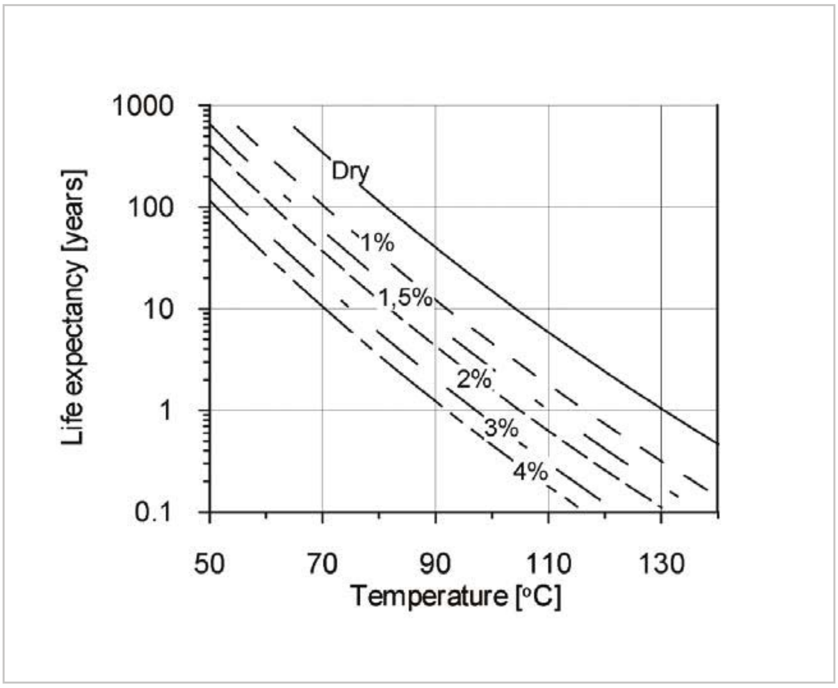

Figure 3. Expected life as a function of temperature and moisture content

4. The many faces of water in transformers: Why so many?

Water can be expressed by many physical units, which are used to describe either quantitative measure of water or its effect on transformer performance

One explanation of why water in transformers is difficult to understand lies in the quantity of water parameters used in the industry. Unlike voltage or current with respective units of volt and ampere, the water can be expressed by many physical units, which are used to describe either quantitative measure of water or its effect on transformer performance. It can exist in many forms and can be measured in many ways. Let's start with two different terms we use when we talk or write about water in transformers.

4.1 Water or moisture?

Although these two terms are used almost interchangeably, there is a difference. So far in this column we have not used the word "moisture" and many technical papers do not use it either. According to Oxford dictionary [15], **moisture is *water or <u>other liquid</u> diffused in a small quantity as vapour, within a solid, or condensed on a surface.*** Moisture also refers to the amount of water vapour present in the air. As it follows from the definition, moisture can be other liquid, not necessarily water. While the word "moisture" can be replaced by the word "water", it would be incorrect to use "moisture" in all instances in place of the word "water". There is no moisture molecule, or moisture potential, or moisture vapour pressure. Therefore, to be on a safe side, it is suggested using the word "water" when in doubt. The following terms and definitions related to water in transformers are adopted from various dictionaries and found in the technical literature [16].

4.2 Water content of paper

This is the most important and most difficult parameter to measure. Defined as ***a ratio of water weight and dry weight of a paper sample expressed as a percentage***, water content of paper (WCP) must be managed so that at the start of transformer operation it does not exceed 0.5 %. The majority of transformer manufacturers would claim that they are able to achieve this undoubtedly stringent requirement. The question remains as to how to validate this claim. In the absence of factory acceptance tests on residual water content, one can only speculate that their transformer is made to the specs. A task to determine the WCP for the operating transformer is not less challenging and requires a good understanding of water dynamics and its distribution across solid and liquid insulation. The WCP in the operating transformer can raise to 5-6 %, which would put such transformer into very wet category. Nevertheless, there are methods to roughly assess WCP in operating transformers, which are going to be discussed in this column in the follow-up issues.

4.3 Water content of insulating liquid

Often labelled as WCO, water content of oil is ***the ratio of masses of water and insulating liquid***. Normally, the insulating liquid is assessed before drying (wet basis) and the ratio is expressed in parts per million (ppm) or gram of water per ton of oil.

WCO is another important parameter used in moisture in transformers assessment reports and research. WCO is the only water parameter used in various guidelines across both IEC and IEEE standards. This is the limiting factor when it comes to evaluating water in transformers, and until there is a consensus that other parameters such as relative saturation, water activity, etc. can better

Water content of paper is a ratio of water weight and dry weight of a paper sample expressed as a percentage

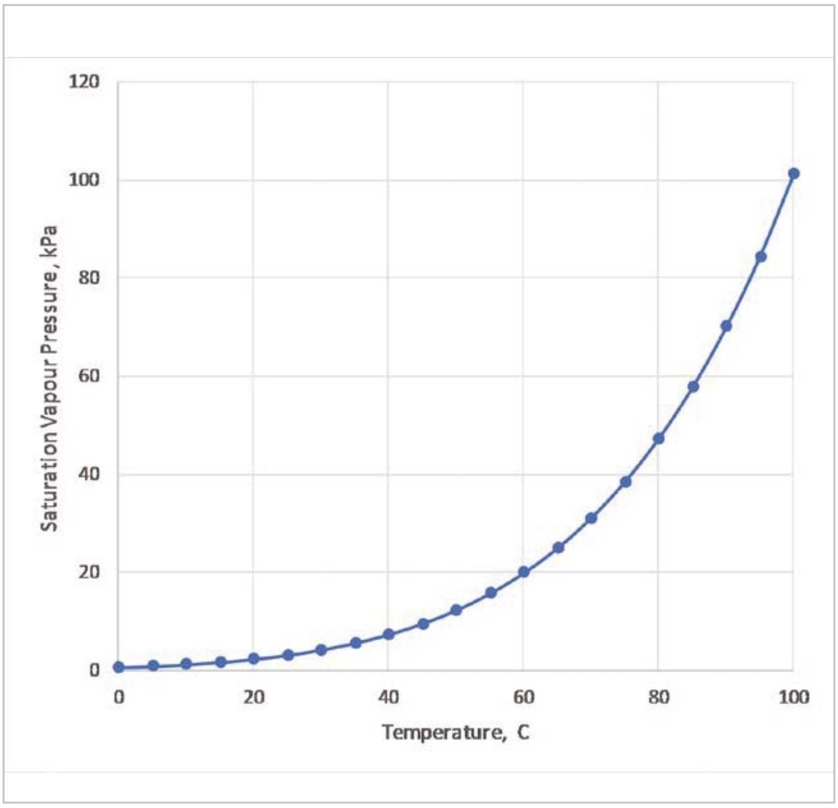

Figure 4. Saturation water vapour pressure

represent detrimental effects of moisture in transformers, we are bound to measure, assess and report it. Depending on voltage class, WCO is limited to the range from 10 ppm to 35 ppm. WCO is useful when commissioning the oil before filling in a transformer. WCO also needs to be measured or estimated when one wants to evaluate the amount of water available for dry-out and how much water is actually removed as a result of oil treatment by dry-out equipment. Water content of insulating liquid is often confused with oil humidity, which brings us to the next definition.

4.4 Humidity

Humidity is ***a quantity representing the amount of water vapour in the atmosphere or in a gas***. Sometimes mistakenly the term humidity is used to describe water vapour dissolved in insulating liquid. This is incorrect. More specifically humidity is grouped in two main quantities – absolute humidity and relative humidity. But before we introduce these two terms, it is essential to understand the concept of partial water vapour pressure.

4.5 Partial water vapour pressure

In a gas mixture such as air, the total pressure of the gas is the sum of all the individual pressures of its gas components. The atmospheric pressure, usually around 100 kPa, is the total of the individual (called partial) gas pressure of nitrogen (~77.5 kPa), oxygen (~20.5 kPa), water vapour (~1 kPa), argon (~1 kPa) and a number of other gases with lower partial pressures. So, water vapour pressure is about 1 % of the total air pressure and this is ***a pressure of water vapour in the gas mixture***. This is a key parameter used for many equilibrium curves starting with well-known Piper curves [17].

4.6 Saturation water vapour pressure

This is the partial pressure of water vapour in any gas mixture in equilibrium with solid or liquid water. In other words, this is the pressure at which water vapour is in thermodynamic equilibrium with its condensed state.

The ability of water to be in gaseous form is strongly dependent on its temperature. The air temperature dictates the maximum partial water vapour pressure in air, Figure 4.

From Figure 4 we can observe that the maximum partial vapour pressure of water at 60 °C is 20 kPa. Above that pressure at the same 60 °C the water condenses and is not in the gaseous state any more. The moisture which forms as a result of pressure increase or temperature drop is called dew. And ***the temperature at which the dew forms is called dew point***.

4.7 Relative humidity and relative saturation

Coming from atmospheric chemistry, ***relative humidity is the ratio, expressed as a percentage, of the partial pressure of water in the atmosphere at some observed temperature to the saturation vapour pressure of pure water at this temperature. It is also termed percent relative humidity*** %RH. Monitoring relative humidity (%RH) over long period of time in the vicinity of a free-breathing transformer can give a rough indication of the moisture state of the oil/paper insulation. The long term data signature of %RH can also be used for determination of water activity – a parameter which plays a vital role in relating %RH to WCP as it will be shown in the forthcoming sections. Equilibrium relative humidity is a percent of relative humidity at equilibrium, abbreviated as %ERH. Relative humidity is a special case of relative saturation which refers to ***the ratio, expressed as a percentage, of the partial pressure of water in the solid, liquid or gas at some observed temperature to the saturation vapour pressure of pure water at this temperature***. Thus, from the definition, the ratio of water vapour pressure in insulation liquid to the saturation vapour pressure of pure water at this temperature is the ***water relative saturation*** or ***percent relative saturation of water*** %RS. When it is in equilibrium, we call it %ERS or the degree or extent to which water is dissolved in oil or absorbed by paper compared with the maximum possible, usually expressed as a percentage %ERS.

Water activity is a measure of water available for exchange between paper and oil

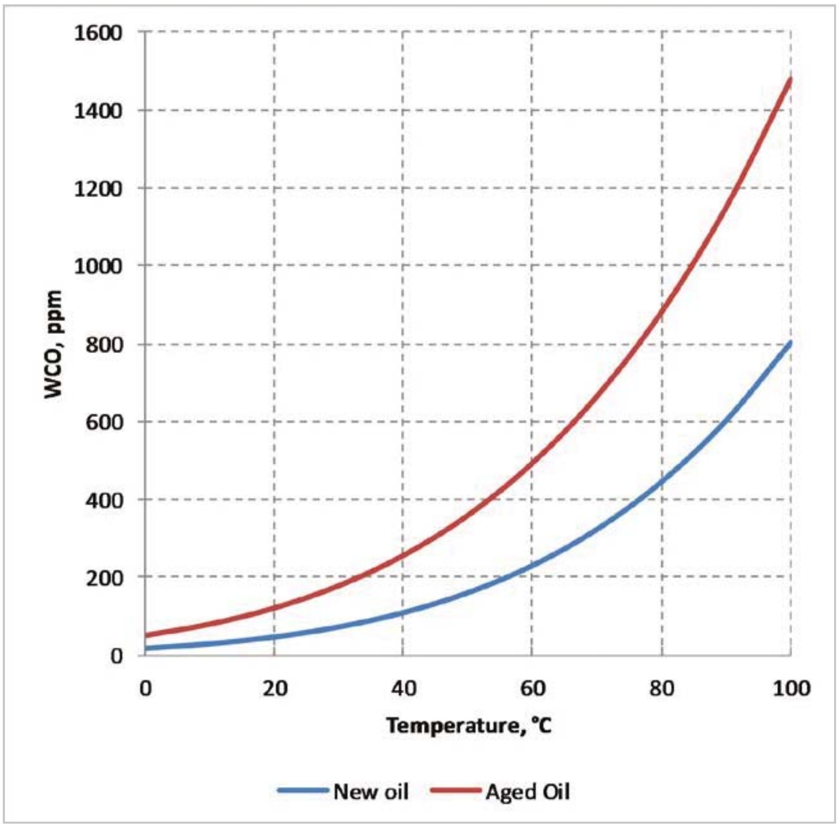

Figure 5. Solubility of water in mineral oil for new and severely aged mineral oils

4.8 Absolute humidity [kg/m^3]

When water is measured above the oil or at the entrance of dehydration breather or during transformer installation prior to oil filling, it is important to know the water content of the air at the interface. ***The amount of water vapour present in a unit volume of air, usually expressed in kilograms per cubic meter, is defined by absolute humidity***. Despite its clear definition and ease of understanding, this parameter is almost unused in connection to water in transformers.

4.9 Dew point

When air is cooled below a certain temperature, the excess of water vapour appears as tiny droplets or crystals of ice depending on the temperature of the air mass. That temperature at which water vapour present in the atmosphere is just enough to saturate it is called dew point. Dew point is the characteristic of water in gaseous form and does not apply to water in oil, as sometimes mistakenly used.

Water in transformers is present in all insulation media: gas, liquid and solid insulation. In a closed system, water is partitioned between gas space, liquid and cellulose according to thermodynamic equilibrium. This prompts us to elaborate on the next very important concept.

4.10 Water equilibrium (Thermodynamic equilibrium)

Water equilibrium is ***a state of a system in which the macroscopic properties of each phase of the system become uniform and independent of time***. If the temperature is uniform throughout the system, a state of thermal equilibrium has been reached; if the pressure is uniform, a state of hydrostatic equilibrium has been reached; and if the chemical potential of each component is uniform, a state of chemical equilibrium has been reached. If all these quantities become uniform, the system is said to be in a state of complete thermodynamic equilibrium. As it will be shown in the forthcoming sections, even though an operating transformer is never in the state of complete thermodynamic equilibrium, the key thermodynamic properties appear to be instrumental for understanding of many physical chemical processes occurring during transformer lifetime.

4.11 Water chemical potential

As it was mentioned above, along with the temperature and pressure, chemical potential of water has to be uniformly distributed across cellulose, oil and head space in order for thermodynamic equilibrium to exist. It is a certain amount of energy required for dissolution of water in oil. A measure of that energy change (scientifically defined as partial derivative of the Gibbs energy with respect to the amount (number of moles) of water) is called the chemical potential of water in oil. And given that, when the temperature is kept constant, chemical potential is directly proportional to water in oil concentration. The water vapour (water molecules) tends to move from the area of high chemical potential to the area of low chemical potential exactly in the same manner as it tends to move from the area of high concentration to the area of low concentration.

4.12 Water in oil solubility

The maximum concentration of water that can exist in insulating liquid (e.g. mineral oil) at thermodynamic equilibrium at specified temperature and pressure is known as solubility of water in oil. The knowledge of water in oil solubility is paramount because it is used for determination of water content in oil – a parameter discussed earlier. When we use moisture sensors, we have to convert %RS to WCO to check the water level against the limits specified in corresponding standards. Common measures of solubility include mass of water per unit mass of oil (mass fraction), mole fraction, molality, molarity, and others. Most frequently used unit is parts per million (ppm), being a mass fraction.

Water in oil solubility function relating WCO and temperature at saturation is called solubility curve. This relationship does not stay the same and changes during the lifetime of transformer in operation. It is also different for different insulating liquids such as mineral oil and esters. Figure 5 shows the solubility of water in oil for new and aged mineral oils [18].

As shown in Figure 5, the solubility of water at 80 °C is nearly two times higher for the aged oil with high acidity value than for the new well-refined oil. Later it will be shown that not considering a change in solubility characteristic of water in oil can lead to significant error in moisture assessment and consequently in decision to maintain a transformer. There is also a large error that may occur when relating a WCO to WCP using equilibrium charts.

4.13 Water activity

When a solution of water and oil is not an ideal solution (as is the case for aged and contaminated oil), then water chemical potential is proportional to the thermodynamic property called **water activity**. In simple terms, ***water activity is a measure of water available for exchange between paper and oil***. Water activity with respect to insulation paper is called water in paper activity and was coined by Roizman in the study on water in transformers [18]. A more scientific definition of water activity can be adopted from [19], according to which ***water activity is a measure of the "effective concentration" of water in oil***, meaning that the water's chemical potential depends on the activity of a real water in oil solution in the same way that it would depend on concentration for an ideal solution. Water activity is a property of oil/paper complex and not just a parameter of one medium. It is also the basis for all known equilibrium curves, that will be discussed in much more details in the forthcoming issues of this column.

The introduction of the main parameters characterising water in transformers has now set a solid foundation to explore the topic of water in transformers in more detail in the forthcoming issues of this column.

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