The water problem of aged transformers.

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1. Introduction

According to EPRI, the average age of transformers in the USA is 37 years [L1]. A similar situation exists in Europe. According to EVU (Germany) the average transformer age is concentrated in the 31-35 statistical group [L.2].Minimal equipment reinvestment by systems owners boosts the average age each year by 0.6 per year[L1].

Despite of inherent redundancy of any network - power transformers at a most important points are doubled or even tripled - the potential reliability of the whole net sinks inevitably as well.

The reason is obvious. All reserve transformers grow old in spite of e.g. low loading (or even without any load) and moreover a proper measurements of their actual operational state under real operational conditions are rare or even non-existent.

Proper methods are therefore needed for optimizing required capital, considering replacement and/or life-extending maintenance of units in poor health or with a level of operational risk,based on a thorough engineering and financial analysis and understanding of possible risks.

The first and most fundamental problem of aged transformers is often their water contamination. The natural result is an inevitable decrease in their operational reliability, and a corresponding reduction of their life-expectancy.

Common practice means that, for simplicity and ease of availabilty, the most used diagnostic methods of the water problem are based on an indirect measuring procedure. The real amount of the water accumulated in the transformer is therefore not determined directly, but based on the measuring of:

- water content in the oil
- temperature of the transformer

The water content in the cellulose materials, as the most important parameter for an appropriate dehydration of a transformer, is then evaluated by means of equilibrium diagrams (Nielsen , Piper charts etc.).

These methods are based mainly on one-shot oil sampling and one-shot temperature reading. The repeatabilitity and credibility of the corresponding diagnostic results are unavoidably low [L3]. The subsequent maintenance is also often wrongly targeted.

It is not uncommon for controversial and paradoxical conclusions and statements to be made about the actual state of transformers. This follows, in particular, diagnostics based on the measurement of water in the oil using the Karl Fischer [KF] method, and the classic measurement of dielectric strength [Ud-value];such as:

- **magic oil -** the aged oil shows substantially higher Ud value than the new oil with the same KF reading
- **magic dehydration** – the KF reading strongly and sharply decreases (by the same Tx temp.) if the aged oil is replaced by new or reclaimed oil

- **snow-ball effect** – in spite of repeated short-term dehydrations of a transformer, the water content in the oil read by the KF method remains high and the NN-value continuously increases

These methods usually fail as the explanation in the following two phenomenons demonstrate;

- **zombie transformer** - a transformer considered as already „dead“ due to the extremely low Ud value and high water content in the oil, but , in reality works without any troubles for years.
- **sudden death** – measured Ud-value at a normal operational temperature is good, but the transformer breaks down after the warming-up / rapid cool-down cycle

It is an unfortunate fact that present Cw- and Ud-diagnostics of the transformer mostly fail because of these phenomenons and there would appear to be no real interest to explain them at all.

There is a surprisingly easy and plausible explanation however for all the these phenomenons when we use a different box of diagnostic tools based on the following premises:

- the dominant diagnostic parameter of any wet transformer is the **water content in the cellulose** because this parameter is temperature invariant (it‘s value does not change with the transformer temperature) [L4].
- evaluation of the water content in the cellulose is based on the equlibrium relationship. This means the reading of the water content and the transformer temperature(s) must be performed under strictly controlled equlibrium conditions as only
- for all new transformer oils the relationship between the solubility of the water in oil and its temperature is roughly the same
- dielectric strength of any kind of transformer oil Ud (kV/2.5mm), without particles, is dominantly determined by its Relative Humidity (RH) [L5, L6]
- only on-line reading of RH and the on-line reading of transformer temperatures guarantees us the required precision, credibility and repeatibility of diagnostic conclusions concerning water contamination of a transformer and its dielectrics.
- in aged oils we have to work with „two“ absolutely different kinds of water

It is often not accepted, nor the significance fully understood, that in the oil filling of any aged transformer there will always exist two kinds of water.Their behaviour in the oil-cellulose system,and especially their impact on the dielectric strength of the oil, is absolutely different.

Thesis:

- **diluted water** – is de-facto the water vapour which freely migrates, in the same way as gas, between oil molecules and this water only:
  - migrates between the oil filling and cellulose materials with the transformer temperature
  - is dominantly deponed in cellulose materials
  - dominantly determines the dielectric strength of the oil
  - can be directly and on-line read by humidity sensors
- **bonded water** – is chemically bonded in ageing products (especially acids) but :

- acid migration between an oil inventory and the cellulose is strongly limited, acids strictly and always remain in the oil filling
- acids and bonded water have no substantial or very low impact on the dielectric strength of the oil
- can only be off-line read by the KF method together with diluted water

The most important aspect of the proposed thesis, clearly evident from everyday practice, is that a very limited transportation of acids (a bonded water) between the oil filling and cellulose materials of a transformer is present.

After a standard replacement of the old oil filling that originally had a very high Neutralisation Number (NN), the NN-value of the new oil only slightly increases and does not change with the transformer temperature (the same transformer,hot or cold,always has the same NN-level). This means that a strong transportation of acids (and bonded water) doesn´t exist there. This is a very simple and proveable fact.

Alternatively, if there existed an intensive transportation of acids (and bonded water) between the oil filling and the cellulose, similar to the transportation of diluted water, then after the replacement of the aged oil we would observe :

- a very strong increase of the NN–value in the oil (though actually, by the same temp. of the transformer, the NN-level should be de-facto the same as before)
- a strong variation of the NN-value with the transformer temperature.

These effects have never been reported as a result of this practice. If there had been, the replacement of the aged oils wouldn´t make any sense. Aged oil replacement and this very simple „experiment" strongly supports the premise that the transportation of ageing products between the oil filling and the cellulose materials is very weak and can be neglected.

This basic fact has of course a very direct impact. When a transportation of acids does not exist, then there cannot also exist a transportation of bonded water. The bonded water always remains in the oil filling and it's precise amount is therefore quantitavely comparable with the amount of diluted water in the oil filling.

Compared to the amount of diluted water in the cellulose the amount of bonded water in the oil filling is then negligible.

For the dehydration of a transformer it therefore makes no sense to measure the water content in acids.

In contrast the KF method, which reads both the diluted and bonded water, essentially distorts the precision and veracity of the volume evaluation of **diluted** water in aged transformers as based on equilibrium charts

To avoid any doubts and objections concerning the above mentioned thesis and it's premise a very simple experiment [L4] shown at Fig. 1 was used.

The transformer is here simulated by the hermetized vessel where the massive paper insert is situated and immersed into the transformer oil.

The required temperature and concentration equlibrium between the oil filling and the paper is achieved here by forcing the oil through the paper insert by means of the circulating pump. The required temperature level (constant during reading) of the oil-cellulose system is performed by the heating rod and a simple control loop.

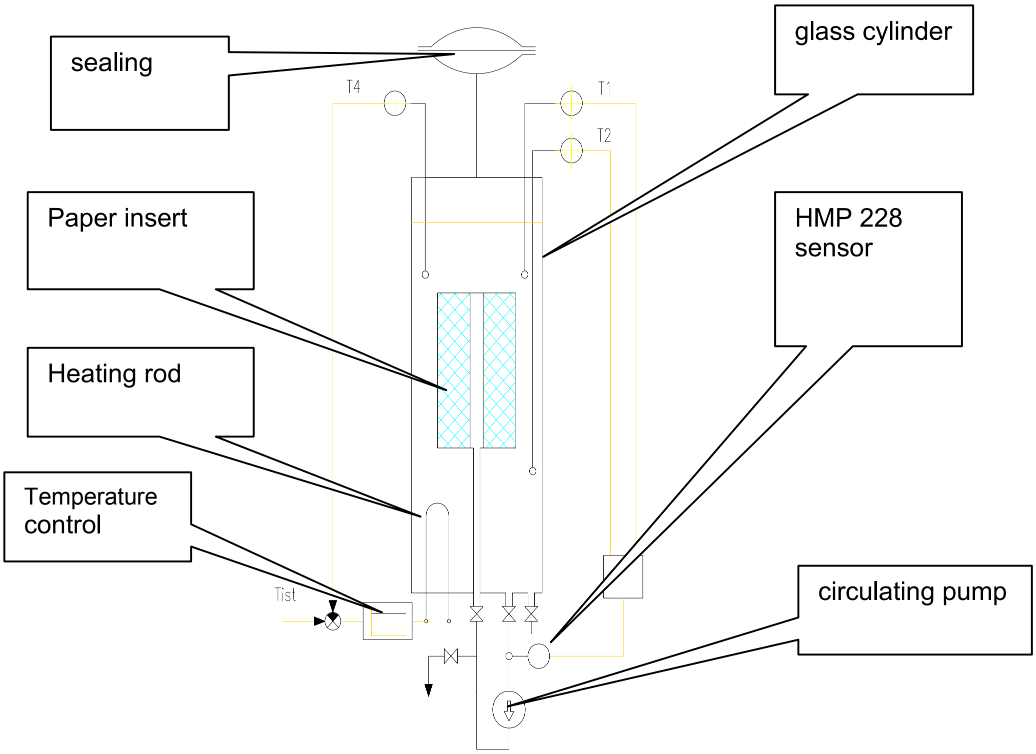

Fig. 1 The simulator of water behaviour in the transformer oil-cellulose system.

To simulate real conditions in the transformer, approx. the same weight relationship is used. The dry weight of the paper insert is ca 10% weight of the whole oil filling.

The experiment is based on the following very well known and essential facts:

- the amount of water in the paper insert (where there is deponed more than 98-99% of water included in the whole oil-cellulose system) cannot be substantially changed after the replacement of the oil
- the maximal experimental error induced by the replacement of the oil filling corresponds to 1-2% and is comparable with the precision of applied measuring methods.

The total amount of the water in the oil-cellulose system remained approx. constant - this means that, under equilibrium conditions, the water content in the oil has to be the same regardless of the kind of oil filling and every measuring method must show the same results.

The simplfied experimental procedure then proceeds in two steps:

1) The paper insert is placed in the vessel, which is filled by the new oil, and the circulation pump is started. The RH-reading of the Vaisala HMP 228 sensor, as a very sensitive tool, is used for the evaluation of the concentration/temperature equilibrium . The sampling of the oil for the KF reading and the Vaisala reading was performed.

   Result :

- water contents read by the KF and Vaisala show the same value (with 1 – 3% deviation) for the whole temperature range 30 – 80C.

2) The new oil is discharged and the vessel is filled with an arbitrary aged oil. The same evaluation of the equilibrium conditions and the measuring of the water content by the KF and Vaisala is performed.

   Results :

   - the Vaisala reads the same water content in new and aged oil(s) - for the whole temperature range 30 – 80C.
   - the KF method always reads substantially higher water content in aged oils than the Vaisala for the whole temperature range 30 – 80C.

and the same procedure was repeatedly performed with different kinds of the aged oil.

This experiment represents de-facto a „qualitative trial – Yes or No“ as to whether current methods of reading the water content in the oil is usable for the evaluation of the **amount of the water in aged transformers** or not:

- a humidity sensor shows that after replacement of the oil there is **no substantial deviation of the measured water content** and **the water content in the „transformer“ was not changed** – the answer is therefore **YES** - the reading of the water content in the oil via the humidity sensor is the correct method and can therefore be used for the evaluation of the water amount in aged transformers
- KF reading always shows a **strong deviation of the measured water content** after the oil replacement, **the water content in the „transformer“ was not changed -** the answer is therefore **NO** – this method is unsuitable for the evaluation of the water amount in an aged transformer, because it is corrupted by reading needless values.

The KF reading of aged oils clearly has an inherent systematic error induced by acids in the oil. This therefore often leads, not only to the wrong diagnostic conclusions, but also to wrong maintenance procedures. These not only measureably decrease the operational reliability (e.g overdrying of a transformer) but also the life expectancy of a transformer as well. Repeated dehydration of a dry transformer deteriorates the oil filling and, subsequently, the cellulose insulants too.

In a proper diagnostic approach, and taking all these points into consideration, the above mentioned discrepancies and paradoxes can be explained simply and clearly;

2. **Magic oil** - a high dilelectric strength versus the high KF reading of aged oils is only virtual. The Ud reading is induced by the diluted water only, but KF reads not only the diluted water (proper value), but all water-near substances in aged oils as well (balast information)

The paradox immediately disappears if we use a humidity sensor that selectively reads only diluted water .

Conclusion: ***Magic oil is an illusion induced by the simultaneous KF reading of the diluted water <u>and</u> the water bonded in ageing products.***

The ageing products have no, and cannot have, any positive effect on the dielectric strength of oils.

3. Magic dehydration of transformer

The higher water KF readings,before the replacement of the aged oil inventory, is induced again by acids in the oil. In the new oil inventory the KF reads de-facto the real and required level of diluted water.

If the humidity sensor is used and the transformer works at the same operational temperature as before, the reading of the water content in oil shows approx. the same value before and after a replacement of the oil inventory.

Conclusion : **The magic dehydration of a transformer by the replacement of its aged oil filling is only virtual.**

A wet transformer cannot be effectively dehydrated by the oil exchange only or the one-shot dehydration of the oil filling alone, because the amount of water removed from the transformer is too small.

4. snow-ball effect is another typical example of a wrong and dangerous approach caused by the maintenance of the wet and aged transformer based on the wrong interpretation of a ***high KF reading against a high Ud reading,*** and this combined with the improper dehydration method.

A simultaneous high reading of the water content and a high reading dielectric strength is of course a clear discrepancy and nonsence in itself (See Magic oil) , but nobody cares and the dehydration of the transformer is recommended.

The short term dehydration performed usually by a big dehydrator is, at first, effective and quickly removes the water from the oil filling. The removal process however then substantially slows due to a very slow diffusion of the water from the cellulose into the oil filling. The hydraulical power of a big dehydrator is therefore secondary, because we can only reduce the water content quickly in the oil filling this way, but not the water content in the cellulose.

Because big dehydrators usually work with high temperatures and a high vacuum, the partial deterioration of the oil (and subsequently the cellulose) is unavoidable and the content of ageing products in the oil inevitably increases (the NN-level grows).

The problem is that a KF reading performed immediately after the dehydration is usually very good (***the content of diluted water and subsequently of bonded water was strongly reduced***). A new KF reading however after, say, one month, (***the diluted water migrates back from the cellulose into the oil filling and is bonded again in the ageing products***) give us the high KF reading again, due to a higher content of ageing products in the oil.

Then a new, and usually the same, dehydration procedure is recommended and begins a typical snow-ball effect which slowly and inevitably deteriorate not only the oil filling, but its cellulose materials and the whole transformer as well.

Conclusion: **snow-ball effect is potentially very dangerous because we can loose the transformer relatively quickly that way. The good news is that the effect is easy to discover by the RH reading. The rapid ageing of a transformer can then be stopped by the replacement of the aged oil filling or,better, by the reclaiming of the oil inventory**. **Subsequently, if needed, the on-line dehydration can be used.**

5. Zombie transformers

Basically all known zombie transformers are in a class of their own – represented most often by oven transformers working with an OFAF or OFAN cooling system and at approx. constant load. This means the operational temperature never rapidly changes in time and the vertical temperature drop in the transformer is small, say only 2-5 C.

The oil cellulose system therefore works under near homogenous and „stationary“ conditions.The water content is, though, high, but the internal RH value is relatively low due to high temperature in the whole oil cellulose system. The real Ud value of the oil is thus relatively high.

The „zombie“ phenomenon is then based on absolutely different RH levels in the transformer and in the lab under „quasi-stationary“ conditions.

The RH value is generally given

(1) $$RH = \frac{C_w}{C_{w,sat}}$$

where :

C_W ..... water content in the oil

$C_{w,sat}$ .... water solubility in oil, $C_{w,sat} = C_{w,sat}$ (T), [L7]

and the Ud value of the oil can be here expressed for simplicity as a linear approximation of the real relation [L5, L6]

(2) $$U_d = U_{d,\max}(1 - RH)$$, $U_{d,max}$ = *85 kV/2,5mm*

and the observed „zombie“ phemomenon, is then simply and only induced by different „stationary“ temperature levels of oil in the lab and in the transformer.

In both cases the water content in the oil (C_W) of course remains the same, but the water solubility in the oil ($C_{w,sat}$) is different and therefore the RH- and Ud value is different.

Example: Let us suppose that the water content in the oil sample (C_W) is 45ppm and the „ oil temperature“ in the transformer is 60C:

- the lab Ud reading is, according to norm, always performed at a lab temperature of 20C. This means the solubility of the water in the oil ($C_{w,sat}$ ≈ 52 ppm) is relatively low. For a given relatively high water content in the oil, 45 ppm, the RH value of the oil is thus very high (RH = 45/52 = 0.88) and the corresponding Ud value (Ud = 85 (1 – 0.88) = 10 kV/2.5mm) is dangerously low and again, according to the norm, unacceptable.
- if the same oil „works“ at an operational and substantially higher temperature than is due, 60C, the water solubility in the oil is **5 x higher** ($C_{w,sat}$ ≈ 255ppm).The „operational RH value“ is therefore substantially **lower** (RH = 0.18) and the „operational Ud value of the oil (Ud = 70 kV/2.5mm) is substantially **higher** which is, according to norm, fully acceptable.

Conclusion : **the actual dielectric strength of oil in a very wet OFAN and OFAF transformer working under high and constant temperature conditions is substantially higher than a laboratory value. If these transformers**

operate at constant temperatures they work, from the point of the dielectric strength, in a relatively safe area, but, any rapid decrease of its oil temperature will always be very dangerous.

6. **Sudden death of a transformer** is always a pure dynamic process induced by an temperature change in its oil-cellulose system.
   - the long-term warming up of the cellulose rapidly increases the water content in the oil.
   - the jump like decrease of the **oil** temperature then immediately and markedly increase the RH value of the oil - there is not enough time for the back-diffusion of the water from the oil into the cooling down cellulose- and simultaneously decreases the Ud value
   - the slow back-diffusion of the water from the oil into the cooling down cellulose will slowly decrease the RH level, and, slowly increase the Ud level. In a new quasi-equlibrium the RH level is **lower** and the Ud level **higher** as before.

Conclusion : **a „sudden death of a transformer“ is an inherent feature of its oil-cellulose system and,in theory, any transformer can be afflicted.**

This effect can be elegantly described again by the relations (1) and (2), but in this case a „sudden death-effect“ is induced, not by a „stationary“ temperature change of the oil (transformer temp. → lab. temp,), but because of the **rapid and almost jump-like decrease of the oil temperature in a transformer itself.**

The reason is obvious, any change of the oil temperature (T) **immediately** changes:

solubility of the water in the oil (Cw,sat) → RH-level → Ud-level of the oil

In contrast the change of the water content in the oil (Cw) is strongly time-delayed due to the limited intensity of the water diffusion between the oil filling and cellulose materials.

The result is a so-called transient-derivative response of the system. After the jump-like decrease of the transformer temperature, the RH value jump-like increases and Ud value jump-like decreases and vice-versa. These strong peaks of both values then gradually decrease as the system is getting near to a new quasi-equilibrium [L8].

Despite a relatively low water content in celulose insulants, a sufficiently strong and long-term increase of the operational temperature of a transformer will always increase the water content in the oil very substantially. A subsequent, and marked jump-like decrease of the oil temperature strongly increases the RH value and dangerously decreases the Ud value.

The historical, popular and dramatic explanation for the corresponding fatal failures of „ massive raining“ in a transformer is therefore superfluous – the real explanation is substantially less dramatic and is trivial in principle. Whenever the RH value of the oil increases, say over 0.6, the probability of the fatal failure of a transformer is always and inevitably very high.Fatal failure of a transformer will most probably occur **before** the water oversaturation of its oil filling.

This specific problem can be very easily solved with the on-line measuring of the RH level by a suitable humidity sensor and its interconnection to the safety circuits of a transformer.

The good news is that in the normal water contamination of the cellulose (say < 3%) and the usual loading curve and usual loading / cooling manner the probability of a „fatal“ accident of a transformer is very low.

7. Resume

If properly maintained and loaded, the oil-cellulose system of power transformers generally represent a very robust and reliable system. It is therefore always very frustrating to observe the devastation of aged transformers due to improper diagnostics and incorrect maintenance.

It should be emphasised in advance that our dehydration target is to properly dehydrate a **transformer and not only its oil filling** . This means to remove **diluted** water from its **cellulose materials**. From this point of view the amount of diluted and bonded water in its oil filling is negligible.

The oil serves here only as a „porter“ of information of how much **diluted** water is actually accumulated in the **cellulose**. The reading of **diluted** water in the oil by a suitable and precise humidity sensor therefore represents an ideal solution of our diagnostic problem.

In contrast the KF method, which reads the content of **diluted** and **bonded water simultaneously,** is clearly unsuitable and even dangerous because, for example, a relatively dry aged transformer can be considered as a wet one.

In practice the situation is even more complicated if the KF and humidity sensor readings are performed simultaneously. In aged oils humidity sensors always give us a substantially lower reading than the KF method, but the reading of the humidity sensor is usually interpreted as false because it‘s too low and the laboratory technicians will always want to be „on the safe side“.

Nobody takes care that there does exist an futher, obvious and evident discrepancy between the high water content and the high Ud-value of the oil .

Thus the typical lab recommendation based on a KF and Ud reading will be :

Gentleman, your Ud value is very good and corresponds excellently to norms, only the water content in the oil should be strongly reduced.

That the **HIGH Ud- reading AND the HIGH water content in the oil** is a clear contradiction, is either completely avoided or missed.

As a result the producers of humidity sensors are forced into a „re-calibration“ of their transmitters to achieve the „conformity“ between their readings and the KF readings of aged oils in transformers.

The result is that the correct and precise humidity reading most highly relevant for transformer diagnostics is effectively falsified to achieve conformity with the wrong KF reading.

Historically the KF method was developed for reading the water content in lubricants and hydraulic oils where, under standard conditions, the water content is mostly over 1000 ppm.

In these cases the KF reading is fully relevant because a huge „cellulose accumulator“ of the diluted water doesn’t exist there and the amount of the water in the oil alone is naturally given by the sum of diluted and bonded water in an oil filling.

But in aged transformers where the amount of water is quite obviously defined by the amount of **diluted** water deponed in **cellulose** materials (mostly a hundred times higher than the amount of diluted + bonded water in its oil filling) makes the use of this „historical“ approach unsustainable.

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