The Dielectric diagram and its use in the diagnostics of power transformers

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1. Introduction

The present dielectric diagnostics of power transformers is predominantly based on the measuring of the oil breakdown voltage Ud (kV/2.5mm). The method is simple in principle, based on oil sampling and subsequent semi or fully automatic laboratory measuring of the Ud-value. The entire method is well grounded in IEC norms and requirements regarding:

- **repeatability** (the effective repetition of exact measurements) and,
- **predictability** (the effective prediction of exact measurements for the dielectric behavior of a given transformer across the entire range of its operating temperatures)

is easy to accomplish and consequently, after correct interpretation, the essential question needs be answered - whether a given transformer can be securely operated or not.

However, the analysis of present measurement results shows something quite different. The basic problem is that this classical diagnosis produces the entire field of very dispersed Ud-values, even in case of the same transformer. This induces the fundamental question -

Can the breakdown voltage value itself, obtained by one sampling of the oil, credibly describe the dielectric conditions of the examined transformer?

The answer is no. The reason is simple - ***cold transformers always give high Ud-values and vice versa, hot transformers give low Ud-values.*** Therefore, it is clear that the single Ud-value cannot fully analyse a transformer's dielectric behavior throughout the entire range of possible operating temperatures.

In turn, this situation provokes additional fundamental questions:

- Can we base the security of the transformer on one measurement of the Ud-value ?
- Can we credibly measure a transformer's dielectric condition regardless of its temperature?
- at what temperature can the transformer be securely loaded according to IEC norm ?
- what Ud-value can be expected at 60C or 20C , with a measured Ud = 40kV/2.5 mm at 40C etc.

Evidently, present diagnostic methods are unable to provide us with any satisfactory answers to these questions.

2. Introduction of a temperature invariant value of the transformer

The major drawback of current diagnostics, based on quantitative Ud-value assessment, is the dependence of Ud-values on the temperature of a transformer.

To correctly describe the given system we need to find the temperature-invariant value as a "solid point" for our diagnosis. This means we must find the value or parameter which remains the same, as an invariant, on the actual temperature of the transformer.

This parameter represents a theoretical "keystone" for the following evaluation of the dielectric state of the examined transformer.

The reference [L1] shows that the searched parameter is obviously Cp (%) - the averaged water content in cellulose materials of the transformer.

Needless to say, this quantity is not directly measurable, but it is easy to determine it from directly measurable quantities by means of Nielsen diagram:

- water content in oil, Cw (ppm),
- average transformer temperature, T (C),

provided both measurements of quantity occurred in a given satisfactory temperature and concentration equilibrium [L4].

Example: On a transformer with a stable average temperature of T = 40C we have measured a water content in an extracted oil sample of Cw = 20ppm (mg water/ kg oil).

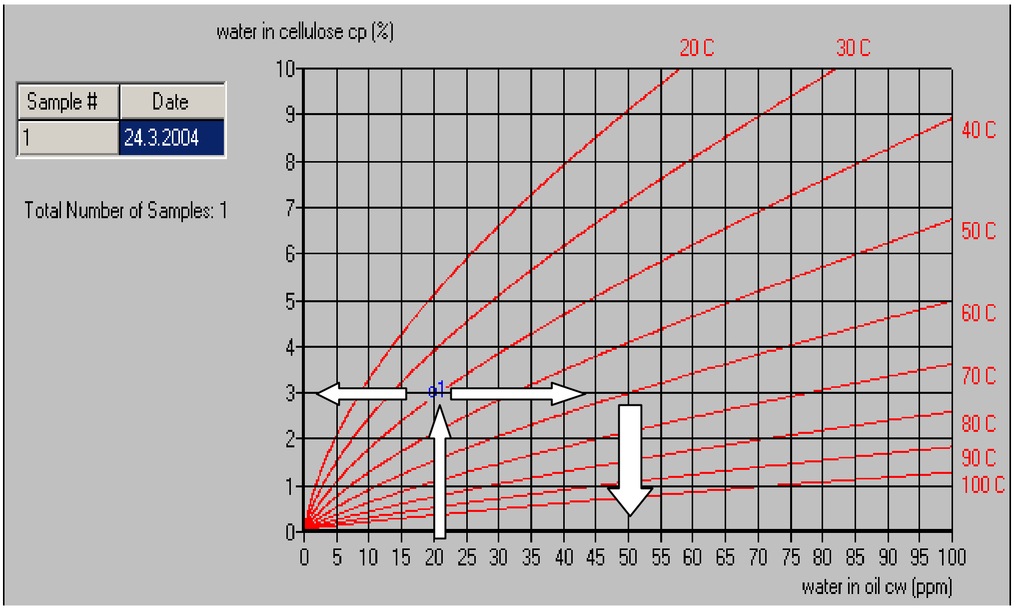

Fig. 1 Nielsen diagram, experimentaly verified (TRACONAL 2004 – [L2])

From the Nielsen diagram it is obvious that the average transformer temperature of T = 40C to the water content in oil of Cw = 20 ppm content, corresponds to the averaged water content in the cellulose Cp = 3%.

A question we may well ask is, is the Cp-value really the required invariant we are looking for? For this, the following analysis helps.

Let's suppose that the transformer contains 40 000kg of oil and 3 000kg of cellulose and we have measured Cw = 20ppm at T= 40C.

Thus, 40 000 × 20 / 1 000 000 = 0.8kg of water is diluted in the oil and the cellulose contains 3 000 × 3 / 100 = 90kg of water.

If we increase the temperature from 40C to 60C, the water content in oil increases from 20ppm to 50ppm (see Fig. 1), and accordingly, the absolute quantity of water in oil increases to 40 000 × 50 / 1 000 000 = 2kg, which implies that the quantity of water in cellulose decreased by 2 – 0.8 = 1.2kg of water.

The corresponding relative deviation of the Cp value is (0.8 – 2) / 90 = -0.013, i.e. -1.34%, and the relative deviation of water content in oil is even (50 – 20) / 20 = 1.75, i.e. +175%.

Conclusion: at any given moment, the Cp-value can be regarded as an invariant towards the T and Cw values.

3. Implementing the new diagnostic paradigm

Current diagnostic methods may be described by the following logical chain:

Oil sampling at arbitrary temperature of a transformer → measurement of Ud-value of oil in a laboratory → condition assessment according to the provided limit value of the IEC norm → Diagnostic conclusion

As evidenced, the present diagnostic paradigm is not able to effectively analyse the dielectric conditions of the transformer through the entire range of operating temperatures, so we need to find a more effective diagnostic paradigm.

Using the Cp-value as the base for a new diagnostic paradigm should prove more simple and the corresponding diagnostic method may be described by the following logical sequence:

Oil sampling at arbitrary temperature of a transformer → Measuring the water content in oil and the average temperature of a transformer in <u>equlibrium conditions</u> → Determining the temperature invariant of a given transformer Cp (%) → Theoretical prediction the Ud-curve for the whole range of a transformer's operating temperatures → Measuring of the Ud-value of a given oil sample in lab → Comparing the theoretically predicted and measured values of Ud-values at a given temperature → Condition assessment according to the limit Ud-value provided by IEC norm → Diagnostic conclusion

On face value, comparing both logical sequences may indicate that the new diagnostic paradigm is substantially more complex and time consuming.

This is not the case. Data necessary for implementing a new diagnostic procedure, i.e. the quantity of the Cw, T, Ud and even Cp values are at our disposal from current measurements.

Moreover, within the new paradigm the accuracy of measured Cw-values and Ud-values, may be improved by the critic comparison with theoretical Ud-values and subsequently, if necessary, refined by an additional measurement.

4. Dielectric diagram of power transformers

From the last logical chain it is apparent that to implement the new paradigm, the theoretical prediction of the Ud-value in dependence to the diagnosed machine's average temperature (T), is necessary.

In other words, we need to find the relation between the breakdown voltage (Ud), the temperature invariant (Cp), and the examined transformer's average temperature (T).

Firstly we need to determine the plausible relation between the Ud-value, the Cw-value and the oil temperature (To), where, for simplicity, we will assume the oil temperature is the same as the transformer's average temperature (T).

As demonstrated in L1, both experimentally and by the measured data of 200 transformers, the Ud-value (breakdown voltage of oil without mechanical impurities), can be analyzed by the following with sufficient accuracy:

(1) $Ud = Ud, max\ (1 - RH)$

where:

Ud, max … maximum breakdown voltage of perfectly pure oil,
Ud,max ~ 88kV/2.5mm

RH …. relative humidity of oil

The real accuracy of this prediction is illustrated in the following diagram (Fig. 2), where measured Ud-values of transformers in operation are plotted in dependence to their relative humidity.

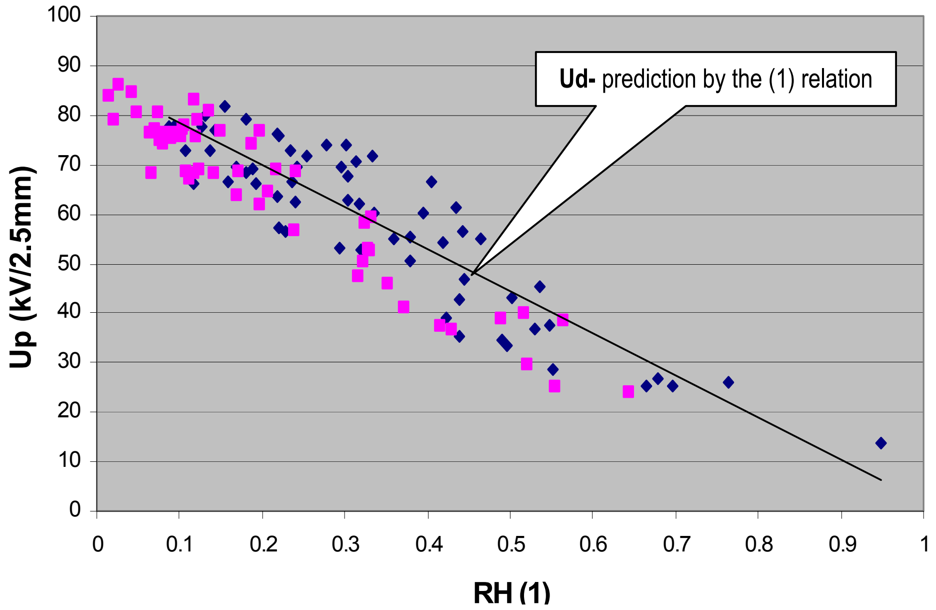

Fig. 2 The verification diagram of Ud = Ud (RH) relation

Fig. 2 shows that the Ud-values predicted by the (1) relationship, correspond sufficiently to the measured values, especially if we know that the oil sampling was not accomplished under controlled equlibrium conditions and the Ud-measurement itself is not fully deterministic.

The relative humidity of oil is then given by the following expression:

(2) $RH = Cw / Cw, max$

where:

Cw,max … water solubility of in oil at a given temperature T, by Arrhenius form:

(4) $\log Cw, max = A – B / (T + 273.15)$, T (C), A = 7.42, B = 1670 – see e.g. Oomen [L5]:

and, from Fig. 3, the strong exponential relationship of the Cw, max value and the oil temperature T, is apparent.

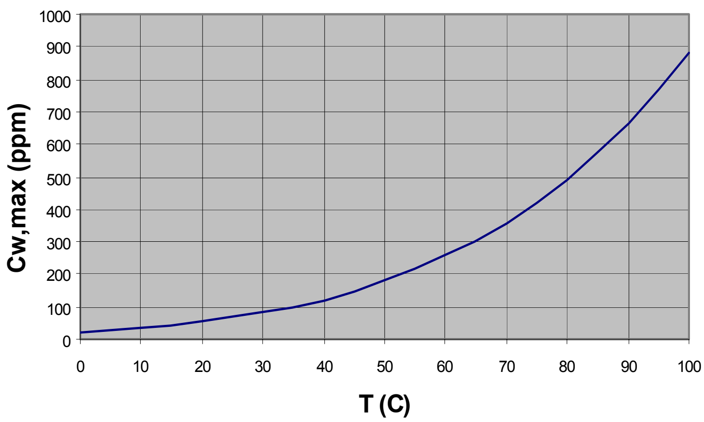

Fig. 3 Relationship between water solubitity of transformer oil and its temperature

Fig. 3 effectively illustrates the strong non-linearity of Cw, max-values of the oil temperature T, and subsequently we are able to project this fact into the Ud-relationship, firstly in the homogenous oil system and then in the heterogeneous oil-cellulose system.

Let's suppose we have an oil system with Cw = 20ppm and temperature of T = 40C. The Cw, max is therefore approx. 122ppm (See Fig. 1) and we get RH = Cw / Cw,max = 20 / 122 = 0.164. The breakdown voltage will therefore be, Ud (40C) = 88 (1 – 0.164) = 74kV/2.5mm.

When we warm up the system, at T = 60C, we get Cw,max = 262 ppm, (Cw-value remains the same 20ppm), RH = 20 / 262 = 0.076 and Ud (60C) = 81kV/2.5mm. In other words, **the Ud-value increases with temperature.**

Naturally, these relationships are only valid for the oil itself.

In an oil-cellulose system, when the water is released from cellulose to the oil with increasing temperature and the Cw-value increases according to Nielsen diagram, it follows that not only the Cw, max-value but Cw-value also grows, and together, influences our RH-value (See relationship 2). The effect of the temperature increase at RH and consequently at the Ud value, is, in this way, effectively compensated in the oil-cellulose system.

For measured values, Nielsen diagram gives us T = 40C and Cw = 20ppm (Cp = 3%); thus the relative humidity of oil will be, equally as before, RH = 0.164 and corresponding Ud (40C) = 74 kV/2.5mm. Due to the increase of a transformer's temperature to T = 60C, water content in oil will increase to Cw (60C) ~ 50ppm, RH = 50 / 262 = 0.18 and Ud (60C) = 71 kV/2.5mm.

In the oil-cellulose system with uniform temperature distribution, the Ud-value will not distinctly decrease with **increasing temperature.** This provides **the best possible case** for a given transformer.

However, during any classical laboratory measurement we find something quite different.

After sampling of the oil with Cw = 20ppm at the temperature of T = 40C from the exemplary transformer and cooling the oil down at the standard laboratory temperature of 20C, the relative humidity of oil will increase to RH = 20 / 52 = 0.385 and the subsequent measurement will provide us with the value of Ud (20C) = 54kV/2.5mm. In this case, the classical measurement shows a sharp decrease of the Ud-value with an increase in the transformer's temperature. This case therefore represents **the worse possible case** for a given transformer.

Therefore, the basic question is - what describes the dielectric condition of a transformer correctly ? Measuring a Ud-value at operational or laboratory temperature? The Dielectric diagram shown in the following figure will help to solve this problem.

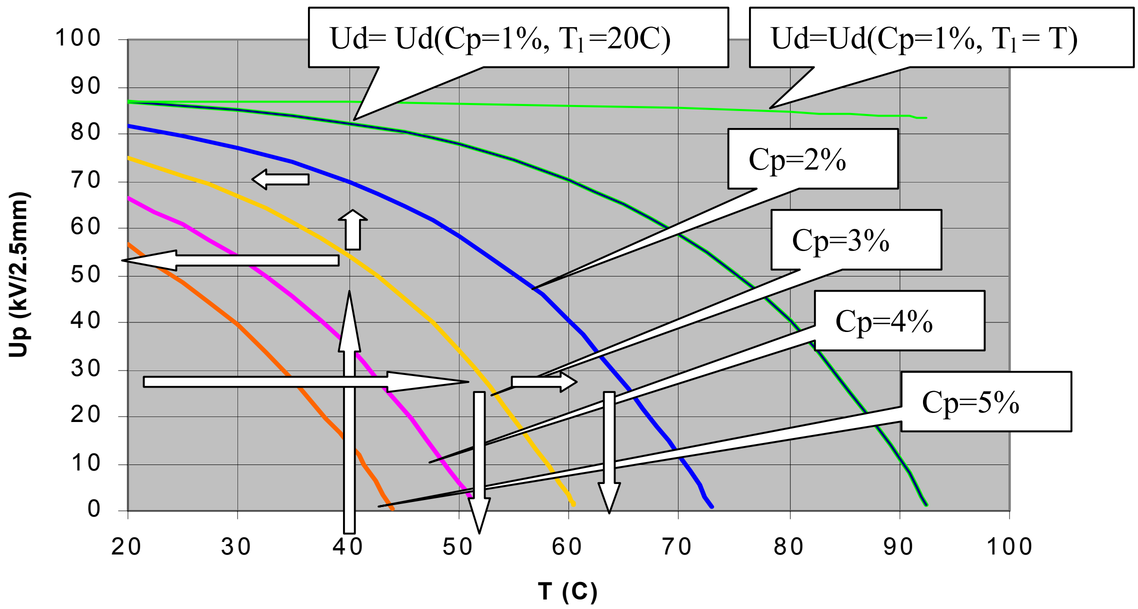

Fig. 4 Dielectric diagram Ud = Ud (T, Cp = const.)

From the Dielectric diagram in Fig. 4, the worst / best possible case is readily apparent.

- The thin green curve, Ud = Ud (Cp=1%, T_l = T), represents the situation where the oil is sampled and measured at the same operational temperature (here, T_l is a laboratory temperature) and the value of Ud quantity decreases very slowly with the T temperature – therefore, this situation represents the best possible case.
- The thick green curve, Ud = Ud (Cp=1%, T_l = 20C), represents a classical measurement where the oil is sampled at the operational temperature but measured at the laboratory temperature of 20C, the Ud-value sharply decreases with the increasing transformer temperature – therefore, this represents the worst possible case

The analogy of the best / worst possible situation is described in detail in references [L1] and [L3], which also shows, from a practical viewpoint, that it is always necessary to use the worst possible case model. Only this approach will secure the necessary given security level for the transformer and moreover, it provides a simple verification by means of measurable data by accessible instruments.

Example -

We will use the same measured data as in previous examples which correspond to the real measurement of a 10MVA furnace transformer. The sampling was performed under controlled quasi-equilibrium conditions.

Average temperature of transformer, T = 40C

Water content in oil, Cw = 20 ppm

Breakdown voltage of oil, Ud (20C) = 56 kV/2.5mm

The new diagnostic process must follow three steps:

1. Firstly, the main Cp (%) parameter, i.e. the temperature invariant of a given transformer, is determined. From Fig. 1, it is apparent that in the case of Cw = 20ppm and T = 40C, the average water content in a transformer's cellulose materials is Cp = 3%.
2. Then, from the Dielectric diagram in Fig. 3, we need to find the theoretical value of oil breakdown strength for Cp = 3% and the temperature of T = 40C. In this case, the Ud value will be about 53kV/2.5mm.
3. Thirdly, we need to compare the predicted and measured values for the following diagnostic conclusion.
   - Both values, measured (Ud= 56kV/2.5mm) and predicted (Ud = 56kV/2.5mm) at T=40C correspond with each other very well. Therefore, the yellow Cp-curve (Cp=3%) satisfactorily predicts the effective Ud-change in the entire temperature range of our transformer from 20C to circa 60C. The possible difference between predicted and measured Ud-values may be used for the overall validity check (it also provides an indication of the increased content of mechanical particles in oil).
   - Accordingly, to IEC permissible Ud, min = 30 kV/2.5mm, the transformer may only be loaded to the average temperature of ca 50C.
   - The transformer needs to be dried as soon as possible because the normal operational temperatures may be higher than 50C, and the Ud-value will then sink under the permissible Ud,min-value. Moreover, at this level of water contamination, there is always a real risk of accelerated cellulose aging.

   The drying effect of the transformer is easy to estimate. If the Cp-value is reduced, say from 3% to 2% (from yellow to blue curve), a substantial improvement of the dielectric condition will occur – the Ud value at T= 40C will rise from 53 to 70kV/2.5mm. That is, by almost 50% in comparison with the original condition and, at the same time. Consequently, from this point, increased loading of the transformer is possible, to the average temperature of T ~ 64C.

5. Conclusion

A Dielectric diagram is the logical extension of the current diagnostic method, which evaluates the degree of a transformer's water contamination by means of Nielsen diagram.

The Nielsen diagram provide us with the required temperature invariant (Cp (%)) by which we can unequivocally analyse the moisture problem of a given transformer.

The Dielectric diagram will subsequently show us the actual dielectric problem of a given transformer by the means of the Ud-curve (Cp=const) for the whole range of its operational temperatures.

With the combination of the Nielsen and Dielectric diagram, answers to most of the questions mentioned in the introduction become readily available.

- **Can we base the security of the transformer on one measurement of the Ud-value ?**

  No – the measured Ud-value is always valid only for the sampling temperature. Thus, the single Ud-value cannot analyse the transformer's dielectric behaviour throughout the entire range of its possible operating temperatures. This value is suitable only for verification of the predicted Ud-curve or, for the retrospective assessment of the measurement accuracy, the influence of particles in oil, etc.

- **Can we credibly measure a transformer's dielectric condition regardless of its temperature and ?**

  No – any Ud-measurement without exact measurement of a transformer's temperature and without precise assessment of the equilibrium condition is useless in principle, because it inevitably contains errors, which cannot be determined.

- **At what operational temperature can we securely load a given transformer?**

  The transformer may be securely loaded to the temperature read from the Dielectric diagram for a given minimum allowed breakdown strength Ud,min.

- **With a specific Ud-value measurement at the transformer's temperature of 40C, what Ud-value could I expect on the level of 60C and 20C?**

  The Dielectric diagram verified by measurement(s) provides good quantitative assessment of oil breakdown voltage values throughout the entire range of a given transformer's operating temperatures.

Above all, the Dielectric Diagram itself, is intended to provide a quick orientation to a given problem. For a fully detailed and exact assessment, for both the dielectric condition of a transformer and for potential transformer treatment, it is more appropriate to utilize the TRACONAL software [L2].

References:

L1 … Altmann

Průrazné napětí transformátorového oleje a jeho význam pro diagnostiku výkonových transformátorů

(The breakdown voltage of transformer oil and its significance for the diagnostics of power transformer)

ARS Group 2004
www.ars-altmann.com

L2 … **TRACONAL**

TRansformer **CO**ntamination **A**na**L**yse

www.ars-altmann.com

L3 … Altmann

Vlivnost teploty na průrazné napětí izolačního oleje v soustavě olej – celuloza výkonových transformátorů

(The influence of temperature on breakdown voltage of oil in the oil-cellulose system of power transformer)

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L4 **…** **SIMMS**

Solid **I**nsulants **M**obile **M**easurement **S**ystem

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