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

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1. Introduction

The introduction of the breakdown voltage test Ud (kV/2.5mm) for insulating oils as a reliable basic value to define the quality of the liquid dielectricum, considerably over simplified the diagnostics for power transformers. Present diagnostics and condition analysis that is based mainly on the breakdown voltage (Ud) produces contradictionary and inconstistent results.

Two typical examples of this diagnostic discrepancy are:

- **Zombie** transformers - where the measured breakdown voltage of the oil is so low (Ud << 30 kV/2.5 mm) that the transformer should theoretically break down immediately according to contemporary diagnostic criterion. However they continue to operate for years without any problems.
- **Sudden death** failures - the breakdown voltage of the oil before the failure was viewed as acceptable, with the primary fault identified as a large temperature drop.

For both phenomena, the literature provides few convincing explanations, and in our opinion these type of cases should be more closely analysed.

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2. The Ud value identification based on measured data:

The value of the breakdown voltage of the oil could be commonly expressed as

(1) $Ud = Ud\ (C_{w,\ KF},\ NN,\ Mc,\ T)$

where:
$C_{w,KF}$ .... water content in oil (ppm) by the Karl Fisher method
NN .... Neutralisation Number (mg KOH/g)
Mc .... Number and size of particles
T .... temperature (C)

In Fig. 1 there are more than 400 Ud-values displayed as a function of $C_{w,\ KF}$. The numerical values of the measured data are in [L1].

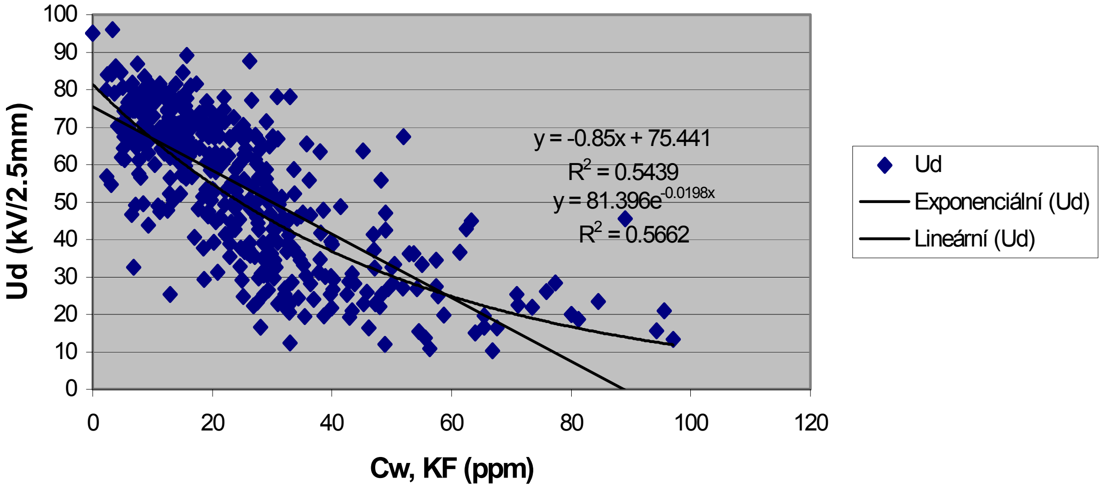

Fig. 1 Relation $Ud = Ud\ (C_{w,\ KF})$, NN < 0, 0.4 >, Mc = ?, T= constant.

The data dispersion is very high and the correlation index R^2 is therefore very low. This problem can be solved by using a specific variable grouping procedure, with approximate constant values and a specific variable. The data field is divided into groups, and in that group the variance is over very narrow interval.

In our case the NN is used as the reliable variable, because unless the oil sample is analysed for particles, the precise size and volume of the particle contamination is unknown and thefore the influence of the variable Mc on the Ud cannot be identified.

Six groups (G) with NN ≤ 0.4 (mgKOH/g) were selected for this analysis. They are G(NN=0.01), G(0.05), G(0.1), G(0.15), G(0.2) and G(0.4). The corresponding groups were selected so that within the NN intervals there is sufficient measured data.

In the next step we have to eliminate the influence of the particles. This is a little more complicated, because we first need a basic estimation of the correlation lines. The whole procedure is described in detail in [L6].

The result of "fission" of the original database to the single groups with “constant" NN values after the elimination of the influence of the particles is shown in Fig. 2.

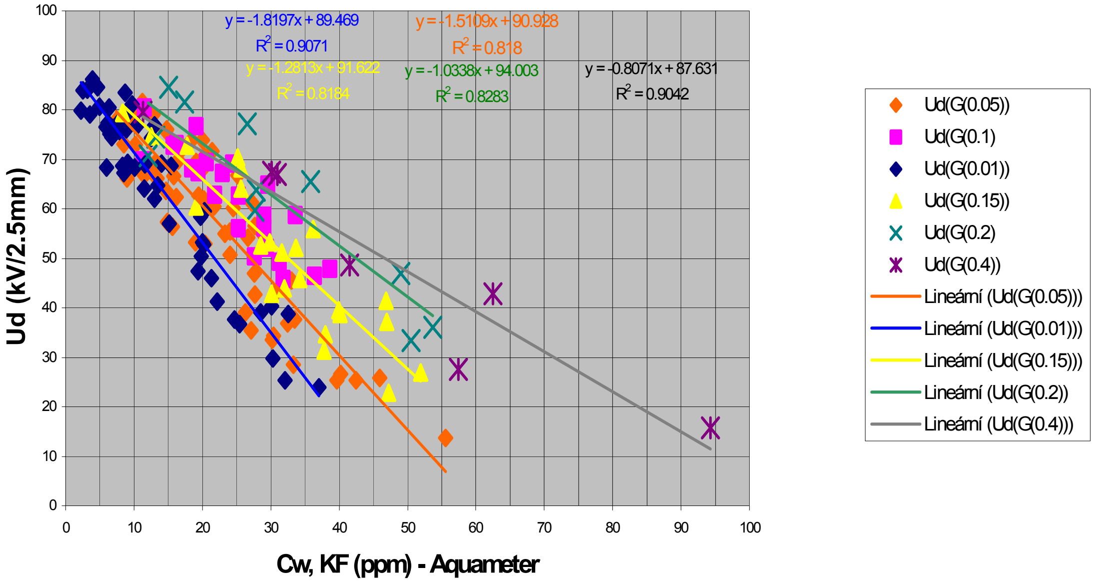

Fig. 2 Relation Ud = Ud ($C_{w,KF}$) for all groups

The exclusion of the particles in the grouping procedure better defines the result. The correlation index R^2 is now improved for all groups and confirms the proceedure.

Comparing two NN catagories at the same oil in water content of say $C_{w,\ KF}$ = 30 ppm, the correlation line of the group G(0.05) indicates a Ud of 35 kV/2.5mm, while the correlation line of group G (0.4) has a Ud of 64 kV/2.5 mm, almost double value. This explains the wide spread opinion that “aged oil endures" a higher breakdown voltage.

The Aquameter was used for all water in oil measurements (uses the Karl Fischer method – KF). But we know from [L3] that:

- The Aquameter measures not only the dissolved water in the oil, but also the acid and particle bound water.
- Bound water is not interactive with the cellulose during load temperature change, only the dissolved water in the oil can migrate between cellulose and oil and consequently affect the Ud value

During the traditional sampling procedure oil is removed from the transformer oil-cellulose (O-C) system at normal operating temperature. The laboratory Ud tests are then conducted at 20C. This does not reflect the actual di-electric conditions of the oil cellulose system in the transformer when the oil was removed.

For an accurate measurement, the Ud should be measured at the recorded operating temperature. The relative humidity of the oil sample alters considerably with temperature, which directly effects the Ud strength.

3. The introduction of relative humidity as a basic variable of the oil-cellulose system.

Relative humidity oil (RH is defined as:

(2) $RH = C_{w,F} / C_{w,s}$

Where:

$C_{w,F}$ … content of dissolved water in oil (ppm)

$C_{w,s}$ … water solubility in the oil, where: $C_{w,s} = C_{w,s}(T)$ is given by Arrhenius form see. e.g . [L2]

It simplifies the analysis, because the two limit points of curve Ud = Ud (RH) is previously established between RH=0 (peak dielectric) and RH =1:

For RH = 0 …. Ud maximum of (~ 90 kV/2.5 mm)

For RH = 1 …. Up→ 0, is getting near the emulsion area with free water starting to form in the oil.

To correct the KF data we have used the correction equation from [L 3]:

(3) $C_{w,KF} = (1 + 1.22 . NN). C_{w,F} + 2.5$

The result is visible at following chart.

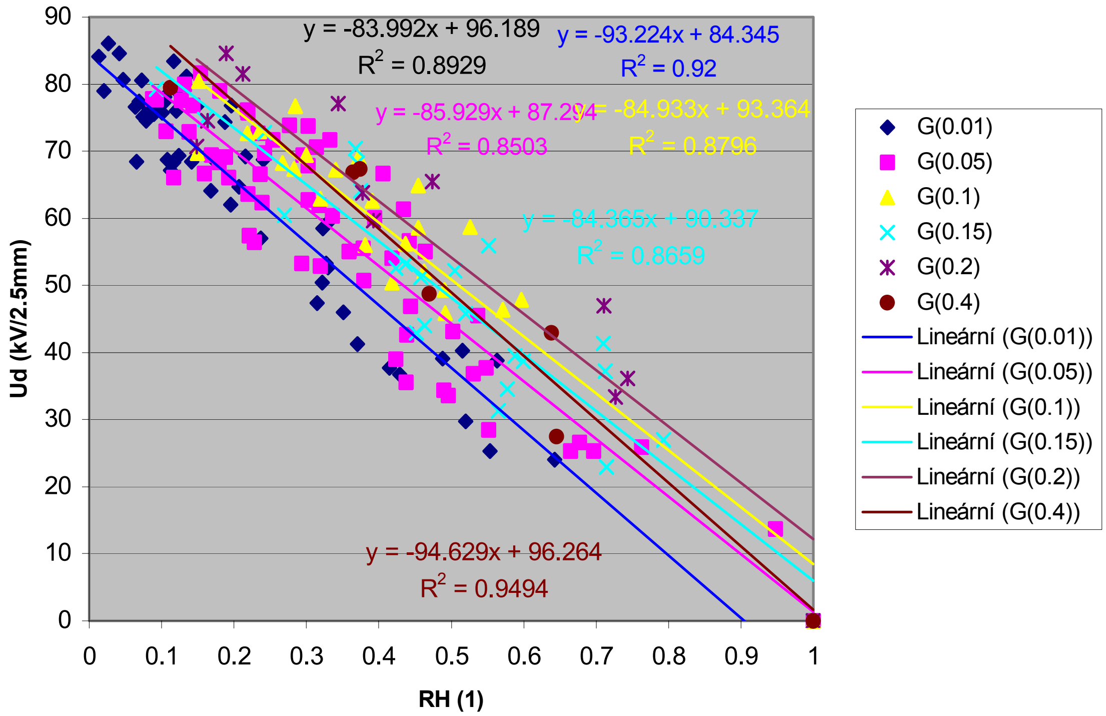

Fig. 3 The effect of relative humidity on the break-down voltage of insulationg oil.

All of the measured data is now in a relatively narrow diagonal belt, which begins at a maximum of RH=0 and the end point RH=1. The correlation index R^2 for all groups is relatively good over 0.85 and all correlations are represented by straight lines.

Therefore we can declare as a good first approximation that the breakdown voltage of insulating oil is a linear with relative humidity.

Which can express it as:

(4) $U_d = U_{d,max} (1 - RH), \; RH < 0 , 1 >$

The dispersion of the data is relatively small ca. + - 15% for all groups, and fits well with the partially probabilistic character of the break-down voltage test procedure.

In comparison with the values in the literature, it is a very substantial improvement (See. e.g. relations Ud = Ud (Cw) from [L4]). In addition our linear model corresponds very well to the measured data in [L5] (FIG.7).

We can therefore conclude that the influence of the ageing products on the Ud value is small or insignificant. The positive deviation of the Ud increasing with the NN is because the KF-method always overestimates the water content in aged oil. On the contrary, if the water content is measured using water in oil sensor probe method which measures the relative humidity of the oil, the undesired deviation is eliminated.

4. The influence of oil temperature on the breakdown voltage

According to our new theory we can now potentially predict the Ud value for any oil temperature and water content variable of the oil.

The water solubility in the oil Cw,s as a function of the temperature T is best described e.g. by Oommen [L2], and for our purposes we can use the approximation:

(5) $C_{w,s} = 24.34 \, . \, e^{0.0375\,T}$

An adequate expression for our break-down voltage therefore is:

(6) $U_d = U_{d,max} (1 - C_w / C_{w,s}) = U_{d,max} (1 - 4.109^{-2} \, . \, C_w . \, e^{0.0375\,T})$

The relationship of break-down voltage and temperature was examined experimentally. A tiny heating rod and temperature sensor was fitted to the test tube of the BAUR test-apparatus. The oil was continuously stirred in the classical way and the relation Ud = Ud (T) was measured. The results are shown in the following diagram.

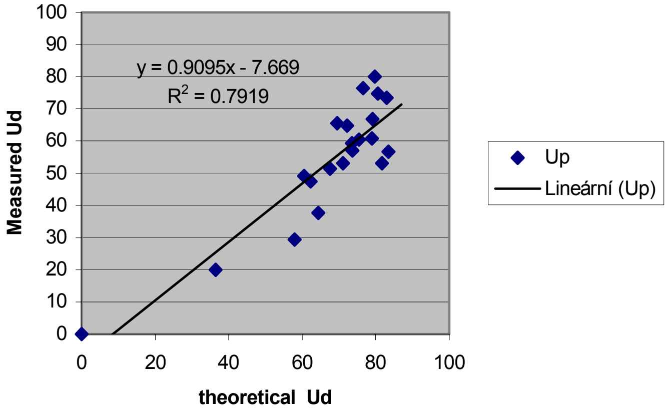

Fig. 4 Theoretical verification of Ud = Ud (RH) via measured data , T < 20, 70 > (C)

Our introduction shows only a basic congruence between the theory and the measured data. Correlation index R^2 is relatively low and we need therefore more experimental data to achieve the better results.

5. The zombie transformers.

Ours present and classical prediction of Ud value is based only on only one variable $C_{w,KF}$

(7) $Ud = Ud\ (C_{w,KF})$,

But our new theory declares that Ud is a function of RH only – or for a better understanding – the function of two direct measurable variables $C_{w,F}$ (ppm) and T (C) .

(8) $Ud = Ud\ (C_{w,F}\ ,T)$,

i. e. The oil breakdown voltage is now **the product** of the diluted **water content in oil $C_{w,F}$** and **oil temperature T of the oil-cellulose system at that given point in time.**

This theoretical introduction alone can explain, or better eliminate, most of our zombie transformers.

Practical example:

Let´s say we have a transformer with $C_{w,F}$ = 50ppm at T= 60C, the oil is without particles, and the laboratory gave a Ud = 15 kV/2.5mm **at 20C**. The traditional diagnostic result would therefore be clear – classical zombie and highly likely to fail.

But our new theory shows us a quite different picture. Because the oil-celulose system temperature is relatively high ~60C, and the relative humidity of the oil relatively low RH = 0.22 ($RH = C_{w,F} / C_{w,s}$, where $C_{w,s}$ (60C) = 231 ppm). The calculated Ud value (see Fig. 3) of the oil at **60C** is therefore ca. 68 kV/2.5 mm. The difference between lab result and the actual in-transformer Ud-value is enormous, in fact more than 400%. Our transformer according to the new theory is in the "green", or safe area.

This is of course is only a very rough estimation, and the transformer is in fact heavily contaminated with water and our diagnostical result is valid only under stationary conditions.

This conclusion gives quite a new point-of-view. However we have forgotten something very important – the water content in the cellulose Cp (%).

We need therefore a new paradigma for the break-down voltage, but not for the **oil** alone, but for **oil in the oil-cellulose (O-C) system**, which can be commonly expressed as:

(9) $Ud = Ud\ (T, Mc)$

Now the only input variable of the O-C system is the temperature T (the Mc value which represents amount and size of particles is regarded as a boundary condition value).

The Cp, Cw and RH values are now internal variables of our O-C system and the output is Ud – the break-down voltage of the oil.

The practical impact of the new paradigma of our diagnostic procedures is shown in Fig. 5

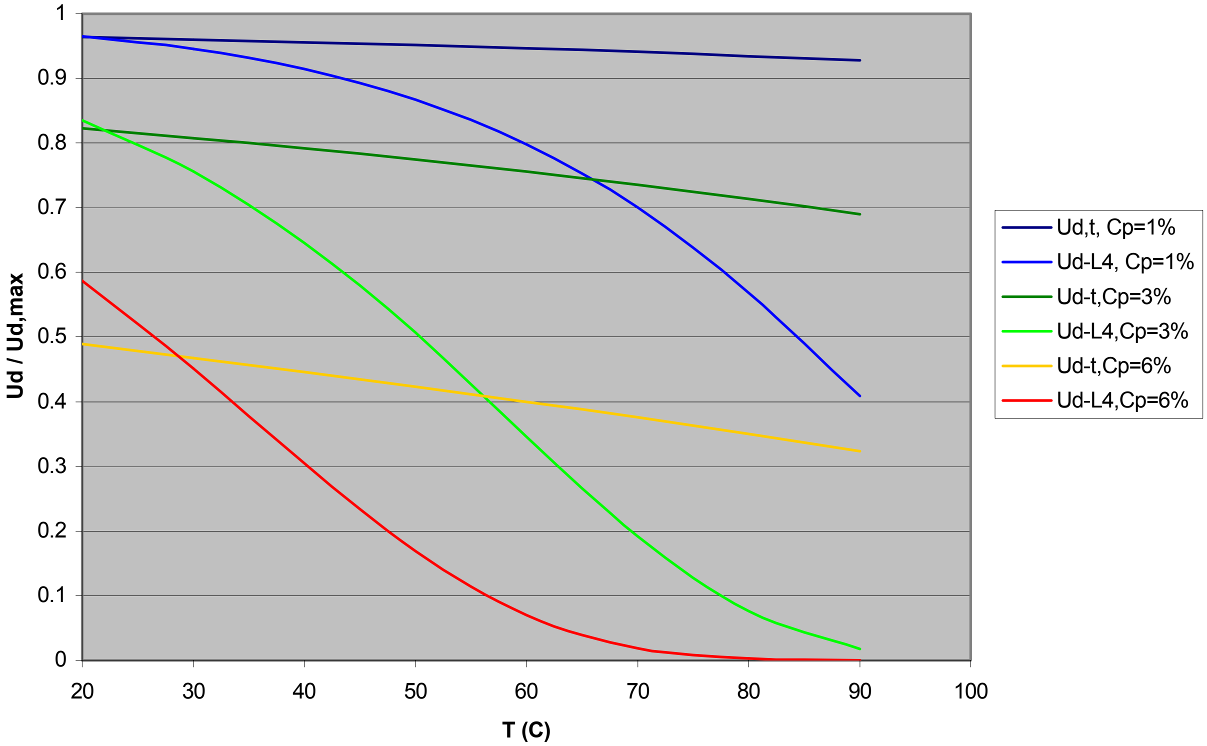

Fig. 5 The comparison Ud-values predicted by new paradigma and classical diagnostic

The relative values of maximum theoretically available break-down voltage Ud,t are calculated by the equation (4) and the “classical“ relative values Ud-L4 are determined by the curve Ud = Ud (Cw) from [L4].

The water content in the oil is in both cases calculated from the Nielsen diagram [L3] approximation for Cp = 1, 3 and 6% and for given temperature T.

In Fig, 5 it is very visible, that the difference between the Ud predictions grows generally with the temperature. Both methods are predicting the same or similar Ud value only near 20C (the lab temperature).

For Cp=1% the theoretical value Ud,t drops from 97% (0.97) at 20C to only to 94% at T= 90C. On the contrary, the clasical method gives the same Ud value at T=20C but at T=90C the value has dropped to 40% of the maximum Ud.

For Cp=3% the difference becames greater and greater. Our “clasical“ method now predicts that we may not operate the transformer above 62C, because the Ud-L4 value has already dropped to under 30% and below the 30kV/2.5mm limit (EEC-Norm).

A transformer with Cp=6% is, by the “classical” diagnosis a typical zombie, because the 30% Ud level is already violated at T = 40C.

On the contrary if we judge the last transformer (with Cp=6%) by the new paradigma, the condition is far better. The transformer has a generally reduced Ud level but can be loaded to a temperature T ~ 90C without any restriction.

All these considerations are valid only for stationary or quasistationary equilibrium conditions and, this is very important, and for oil without particles. If there is a sudden and large drop in the transformer temperature in wet transformers (and potentially particle contaminated), there is a completely new and very dangerous situation in the form of a break-down (voltage) hole.

6. The break-down voltage hole

The very dramatical drop of the break-down voltage can be always induced by the sudden increase of RH value (drop of temperature).

Let´s suppose an average-wet transformer with Cp=2%, where we read Cw = 30ppm at 60C and the transformer is switched off and cools down fast.

The simulation of the corresponding dynamical response of the oil-and-cellulose system is showed in Fig. 6.

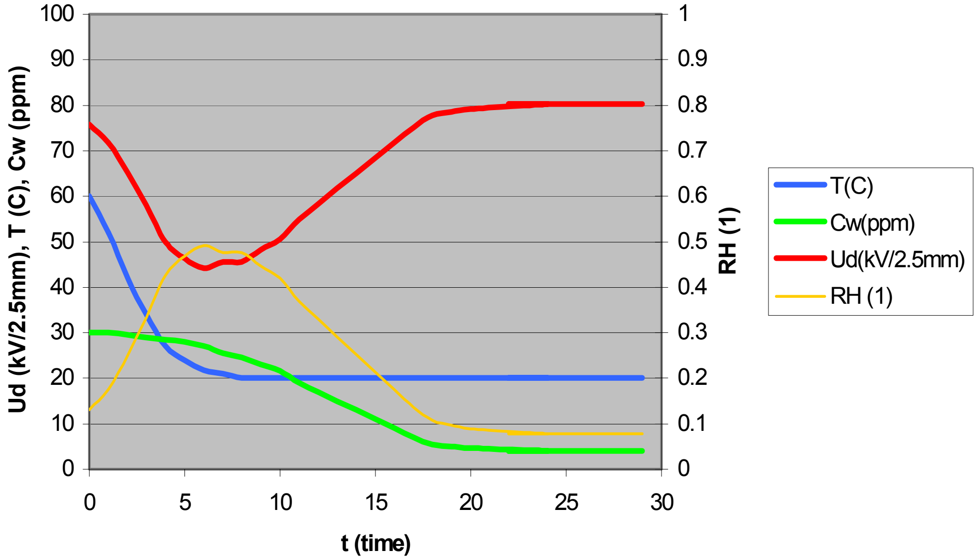

Fig. 6 The simulation of the break-down voltage hole.

The initial water content in the oil of Cw = 30ppm, can not be reduced quickly enough by the cellulose during rapid cooling (the diffusion of water back in the hot cellulose is very slow). The relative humidity of the oil grows rapidly from 0.12 to 0.5 and the Ud value drops from the initial calculated value 75 kV/2.5mm to a “bottom“ value calculated at 45 kV/2.5mm. If the level of particles increases in the oil, the break-down voltage can dynamically sink into the dangerous area.

As the temperature of the cellulose finally drops, the water difuses slowly back into the cellulose reducing the RH value and increasing the Ud-value. The Ud end point value is then greater than the initial value. The “classical laboratory” diagnostic method is evidently not able to predict the dynamic of the break-down voltage hole phenomenon but, and this is very curious, it unknowingly predicts the its **lowest point** (at 20C).

If our transformer cools down very rapidly (until the lab temperature of 20C), the effect of the cellulose on the reducion of the water content in the oil (Cw) is very weak as it still retains the latent heat of the windings. The Cw value remains roughly the same, but the temperature T of the oil drops, the RH grows, and the Ud sinks.

This exact process occurs in the oil after the oil sampling procedure although we have almost very little cellulose in the oil (particles) to adsorb the water. The break-down voltage therefore drops from the operational level to the laboratory level and, in contrast to transformer, remains at this level.

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6. **Conclusion**.

The analysis and practical work explains some discrepancies in the break-down voltage of the oil between field observations and the dignostic results from laboratories.

Most of the discrepancies can be eliminated by better understanding the real physical structure of the oil-cellulose system and by respecting of the real linkage of its internal variables.

The empirical interpretation of laboratory measured break-down voltage level as a real operational dielectric of any given transformer is obviously not correct with the exception where the sampling temperature of oil is near the laboratory temperature.

But the measured Ud value alone is nevertheless very important – its describe us very well the real impact of the particles on the break-down voltage and give us in addition new and very important statement about the maximal depth of the break-down voltage hole at 20C.

Ön the other hand, the Ud value calculated by the new paradigma give us the highest achievable Ud value by any temperature of given transformer.

The suitable connection of both values gives us therefore the new opportunity to improve our diagnostic procedures.

Literature

L1 ….. Bukviš
Laboratory data log
(Výpis hodnot z provozního deníku)
Intern Report ARS 2003-2

L2 ……. Y.Du, M. Zahn at all
A Review of Moisture Equlibrium in the Paper-Oil Systém
Department of Electrical Engineering and Computer Science

MIT, Cambridge, MA 02139 USA

L3 ……. Altmann, Bukviš
The oil-replacement-moisture problem of aged transformers
Preprint pro EW

L4 …… **Isolierflűssigkeiten**
WDEW-Ölbuch, Band 2, 1996

L5 ……. Lewand, Griffin
Development of a continuous moisture-in-oil sensor and its application in the power industry.
Doble Engineering Company

L6 ……. Altmann
The infuence of contaminants on the break-down voltage
(Vliv kontaminantů na průrazné napětí oleje).
Interní zpráva ARS 2003-3