The dielectric strenght of the transformer oil and its impact on the diagnostic of power transformers

Dipl. Ing. Altmann - ARS Group

1. Indroduction

Because of the tradition, avaiability of the equipment and the simplicity of the method, the dielectric strenght of an oil Ud (kV/2.5mm) still ranks as a most common field and laboratory oil screen test. In many facilities the dielectric test of oil is, even now, the only test applied to a transformer. The instrumentation available now for the oil test is quite compact, efficient and the semi-automatic test procedure elimitates most of the human errors in the laboratory [L1].

The oil-test procedure is strictly defined by the norm IEC 60 156 and the same way is a-priori implemented the direct connection between the boundary oil-test values and the dielectric of the transformer (IEC 60 422).

Its seems therefore that our usual demand on :

- **a repeatability** (How well can I expect to agree with myself by the same transformer and by the same laboratory ?, How can I simply identify a potential measuring errors ?)
- **a reproducibility** (How well can I expect to agree with other laboratories?)

should be easy achieved and consequently, after a correct interpretation, we must be able answer at least a basic question – can the given transformer be operated safely or not.

But the analyse of the operative oil test results shows something quite different. The clasic procedure give us mostly a very scattered Ud-values for the same transformer even if the oil does not contain any particles or other inhomogenities.

The cold transformer give us always very high Ud-values and on the contrary, at the full-load (the high temperatures), we will get for a wet transformer a very low and therefore potentially dangerous Ud-values.

The basic diagnostic decision (can I operate this transformer or not) is therefore very difficult because the diagnostic philosophy a single sample → single Ud-value → single diagnostic conclusion, obviously cannot give us a plausible and correct answer. Moreover, the clear and comprehesible time-log interconnection between old and new Ud-values → diagnostic conclusions is very weak at different temperatures.

What temperature should be used for a sampling to get a Ud-value which will be able to commonly represent the real dielectric of a given transformer ? Should be oil sampled always at the same operational temperature ? It is propably correct, but how can I it achieve at the different load levels. If the highest possible temperature is recommended, how can be it safely achieved etc. ?

The second drawback is, that the method is not able to give us any quantitative prediction what Ud-value we can expect at different temperatures. For a specific transformer and for a given boundary Ud-value we cannot therefore directly obtain any information about its maximal allowed operational temperature.

Under a dynamic operational conditions of a transformer and corresponding rapid temperature changes is the situation even worse. The method give us the completely different Ud-values even for the same sampling temperature.

2. The internal structure of the oil-celluose insulation system

For simplicity, we will suppose that our transformer oil represents a perfect homogenous dielectric liquid e.g. it does not contain any inhomogenities. The decrease of the Ud-value (and a transformer reliability) with the increase of the oil temperature describes e.g . [L1, L2] in the form of the logic chain:

increasing temperature of a transformer → increasing water content in a oil → decreasing Ud-value → decreasing dielectric reliability of a transformer

and a corresponding, strongly simplified, internal structure of the oil-cellulose system is shown at Fig.1.

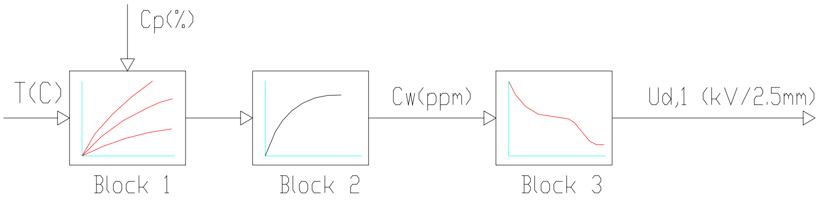


Fig.1 The block diagram of the relation Ud,1 = Ud,1 (T, Cp)

where :

T … main temperature of transformer (C)

Cw ….. water content in oil (ppm)

Cp ….. main water content in cellulose (%)

Ud,1 …… dielectric strenght of oil measured in laboratory (kV /2.5mm)

The Block 1 represents the oil-cellulose system (Nielsen equilibrium diagram) which output is Cw-value as a function of temperature T for given main water content in cellulose Cp. The dynamic of the system which corresponds the water migration between oil and cellulose represents Block 2 and the third block describes Ud-value as a function of Cw [L2].

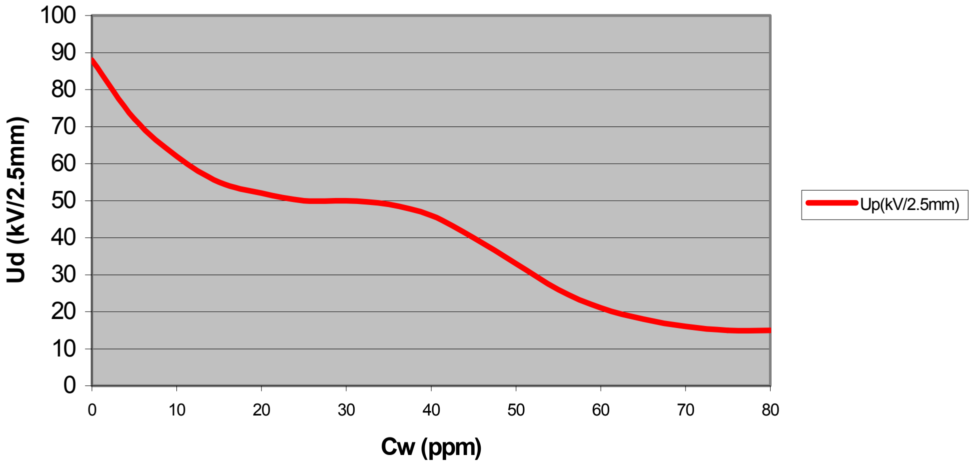


Fig.2 Dielectric strenght of oil as a function of its water content [L2].

Is above mentioned logic chain a-priori right or wrong ? Can be the behaviour of the oil-cellulose system explained by the structure showed at Fig.1 ? Can be, in general, the dielectric status of a transformer described by an one-shot (one sample) Ud-value philosophy ?

The answer for the first two question is **no**. The dielectric strenght ot the transformer oil is **not** the function of its water content only , but the function of two variables – the temperature and the water content of the oil. More precisely , the dielectric strength of the oil is function of its relative humidity RH [L3, L4 , L5] and the corresponding structure of the system is therefore quite different.

The answer at third question is **yes** – but we must use the different diagnostic method and strictly defined sampling conditions.

The experience shows that the measured Ud-value always depends on :

- temperature of given transformer
- water contamination of its cellulose insulants
- gradient of temperature change

and present diagnostic paradigma based at the relation

(1) Up,1 = Up,1 (T, Cp)

simply cannot explain all observed phenomenons – e.g. from the diagnostic point of view "dead“ transformers are working well for years and, on the other hand, transformers with relative good dielectric suddenly break down.

Mentioned discrepancies can be explained by following new three-step paradigma:

- new model must more precisely describe the stationary and dynamic behaviour of the oil-cellulose system
- plausibility of the model must be easy verified by the measured values under strictly defined conditions [L7]
- diagnostic conclusions have to be based at the Ud-curve for the whole range of the operational temperatures of the given transformer

The mathematical model of the oil-cellulose system corresponding to the new paradigma is shown at Fig.3.

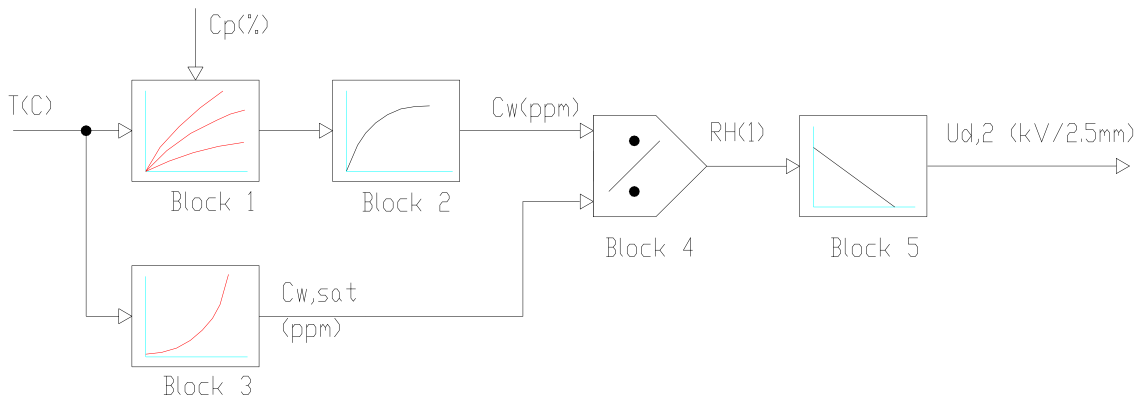


Fig. 3 Block diagram of new model od the oil-cellulose system Ud,2 = Ud,2 (T, Cp)

The Block 1 and 2 are the same as in Fig.3, but and the Ud-value is described more precisely as a function of Relative Humidity (RH) of oil

(2) $U_{d,2} = U_{d,2}(RH)$

The oil temperature as a main independent variable of our system affects the RH-value in two basic levels:

- with the delay – which corresponds the accumulation and the distribution of the heat energy in the system, a relatively slow migration of the water between oil and cellulose and a stationary Nielsen relation:

(3) $C_w = C_w(T, C_p)$

- without the delay – the solubility the water Cw,sat , which is described by Arrhenius form

(4) $\log C_{w,sat} = A - B / (T + 273.15)$, T (C), A = 7.42 , B = 1670 – See e.g. Oomen [L6].

is directly changed by the temperature T and therefore an instantaneous RH-value is then given as:

(5) $RH = C_w / C_{w,sat}$

The structure comparison shows an evident and basic contrast between both models:

- the old model (Fig. 1) shows always a time-delayed response of the Ud-value at a temperature change (T)
- the new model is different – jump-like change of the temperature T induces instantly the jump-like change of the Ud-value (via jump-like change of the water solubility in the oil - Cw,sat and the RH-value), but this process is then subsequently compensated by the slow change of the water content in the oil – Cw, induced by the presence of cellulose materials

3. The response of the oil-cellulose system under quasi-equlibrium conditions

Let suppose that we have a transformer with the main water content in the cellulose Cp = 3%. The oil was sampled at steady operational temperature levels T = 20, 40, 60 a 80C and corresponding Cw- and Ud-values was measured at laboratory temperature 20C and a operational temperature T. Following table then shows the Ud-values accordingly the old- and new model of the oil-cellulose system.

The Ud,1-value is taken from the diagram at Fig.2 and Ud,2-value is calculated by the relation

(6) $U_{d,2} = U_{d,max}(1 - RH)$, where $U_{d,max} = 90$ kV/2.5mm

Cp = 3%		Laboratory values				Operational values		
T	Cw	**Ud,1 (20C)**	Cw,sat (20C)	RH (20C)	**Ud,2 (20C)**	Cw,sat (T)	RH (T)	**Ud,2 (T)**
20	9	**> 60**	53	0,19	**72**	53	0.19	**72**
40	21	**~ 40**	53	0.39	**55**	122	0.17	**82**
60	51	**~ 20**	53	0.97	**~ 0**	255	0.2	**72**

80	121	**< 20**	53	> 1	?	491	0.25	**68**

The table shows a big and essential interpretation problem:

- Ud,1(20C)–values calculated by the old model are in the quantitative agreement with Ud,2(20C)-values of the new model under laboratory conditions – the oil is in both cases sampled at the operational temperature of the transformer and measured at the laboratory temperature T = 20C

but

- Ud,2(T)-values corresponding the sampling at operational temperature T and a measuring at the same temperature T are for T > 20C essentially higher than Ud,1(20C) and Ud,2(20C)/values.

Fortunately the explanation of this discrepancy is easy.

By the classical diagnostic procedure are, at the moment of the sampling of the oil, de.facto „removed“ all cellulose materials from our oil-cellulose system.

If the temperature of the oil then sinks at the laboratory temperature level 20C (the Cw-value remains the same), the water solubility in the oil Cw,sat adequately drops. The RH-value therefore increases and Ud-value consequently drops as well.

Of course in the real transformer are conditions completely different. By normal slow decrease / increase of the operational temperature T , is the change of the water solubility Cw,sat always effectively compensated by the change of the water content in the oil Cw induced by the migration of the water between the oil and the cellulose.

Example:

Let suppose that our transformer has the water content in the cellulose Cp = 3% again, our transformer has the operational temperature T = 60C, the sampled oil has therefore the water content Cw = 51 ppm and we want to know what Ud-values can be expected by the classical diagnostic and in the real transformer after the slow decrease of the oil temperature from 60 C at 20C. For the calculation of the Ud-value will be used the relation (6) .

Classical diagnostic procedure shows that:

- after decrease of the oil temperature from 60 C at the (laboratory) temperature 20 C, drops the water solubility of the oil from Cw, sat (60C) = 255 ppm at Cw,sat (20C) = 53 ppm
- water content in the oil Cw = 51 ppm remains the same, the relative humidity of the oil increases from the value RH (60C) = 51 / 255 = 0.2 at the value RH 20C) = 51 / 53 = 0.962
- dielectric strenght of the oil therefore drops from the Ud,2 (60C) = 90 (1 – 0.2) = 72 kV/2.5 mm (See relation (6)) at Ud,2(20C) = 90 (1 – 0.962) = 3.42 kV/2.5 mm

Real transformer

- after decrease of the oil temperature from 60 C at the (laboratory) temperature 20 C, drops the water solubility of the oil the same way - from Cw, sat (60C) = 255 ppm at Cw,sat (20C) = 53 ppm

but

- because of the migration of the diluted water from the oil back into the cellulose ***decreases*** the water content from Cw (60C) = 51 ppm at Cw (20C) = 9 ppm and consequently the relative humidity of the oil ***decrease*****s** from the initial value RH(60C) = 0.2 at RH(20C) = 9 / 53 = 0.16
- the Ud-value therefore **increases** from the initial value Ud,2(60C) = 72 ppm at Ud,2(20C) = 90 (1 – 0.16) = 75,6 kV/2.5mm

The classical Ud-value measurement therefore represent the complete „switch-off" of the main stabilisation effect of the cellulose materials in the transformer.

The first and crucial question therefore is,

what actually represent the Ud-value as an ouput the present diagnostic procedure

The kernel of discrepancies is obvious. We want screen a dielectric status of a transformer at a normal operational temperature, but standard Ud-measurement offers us something diametrically different and moreover the applied procedure evidently violates basic law of any correct measurement.

It is always and strictly forbidden to change a structure or parameters the measured system during the measurement procedure.

By sampling is at first changed the structure of the measured system (by sampling is the cellulose "removed" from the original system) and then is de-facto freely changed the basic parameter – Ud-measuring is not strictly performed at the original system temperature T.

The structure violation is not so important, because after a sampling remains the basic Cw-parameter (water content in oil) of the original system the same , but the impact of a arbitrary change of the system temperature T obviously spoils any validity of results.

The second crucial question therefore is – can be found, under an usual operational conditions, a place or a process in the transformer with the same undesired impact at Ud-value ?

The answer is yes - but only qualitatively. There exists at least one potential place and one potential process where the stabilizing effect of cellulose materials is "switched-off" the same way as by the Ud-diagnostic.

This potentially dangerous place is situated in the output of oil coolers of ONAN(OA) or ONAF(OF) transformers. Without circulating pumps can be the temperature difference ΔT between upper (oil inlet) and bottom (oil outlet) of the cooler more than 20- 30C, the temperature of the oil is getting near to the laboratory temperature 20C and the Ud-value decrease is therefore always substantial.

Example:

Let suppose we have our exemplary transformer with Cp = 3% and a operational temperature measured in its upper part T = 60C is virtually identical with inlet temperature of the oil cooler , the water content in the oil is Cw = 51ppm, ΔT = 30 C and the (outlet) temperature of the oil which flows back from the cooler into the main tank is therefore 30C.

As shown before the relative humidity of the oil in the intake of the cooler is relatively low, RH(60C) = 0.2 and corresponding Ud-value is therefore relatively high Ud(60C) = 72 kV/2.5mm.

But in the outlet of the cooler is the situation dramatically different. The water solubility of the oil sinks at Cw,sat (30C) = 82 ppm (See relation (4)) and the relative humidity of the oil grows at

RH(30C) = 51 / 82 = 0.62 and consequently the dielectric strength of the oil sinks at Ud(30C) = 90 (1 – 0.62) = 34 kV /2.5mm, it means at less than ½ of its initial value**.**

If, in addition exists a possibility that the transformer temperature increases over 70C, then the water content in the oil Cw will increase over 78 ppm , the Ud-value sinks deeply under allowed limit e.g. 30 kV/2.5mm.

The findings that the dielectric strenght of the oil radically decreases with the drop of the temperature in oil coolers and, on the other hand, that the Ud-value can expressively increase with the oil temperature in the active part of the transformer, is obviously the main and fundamental advantage of the mathematical model shown at Fig.3.

Compared to the standard model (Fig.1), where the Ud-value was intuitively presupposed the same in the whole oil inventory of the transformer - because the approx. the same water content in the oil (Cw ≈ const.), it is of course a completelly different a new point of view on the dielectric especially of ONAN and ONAF transformers.

4. Dynamic response of the oil-cellulose system at sudden temperature change

The mathematical model at Fig. 3 shows, that the output of the classical diagnostic method corresponds the same manner to response of the oil-cellulose system at the jump-like drop of the temperature from a operational at laboratory level.

If we change the oil temperature T in the jump-like manner the oil-cellulose behaves itself as if there the cellulose does not exists – but only at the moment of the jump.

Following Fig. 4 can help to understand the dynamic behaviour of the oil-cellulose system under consideration.

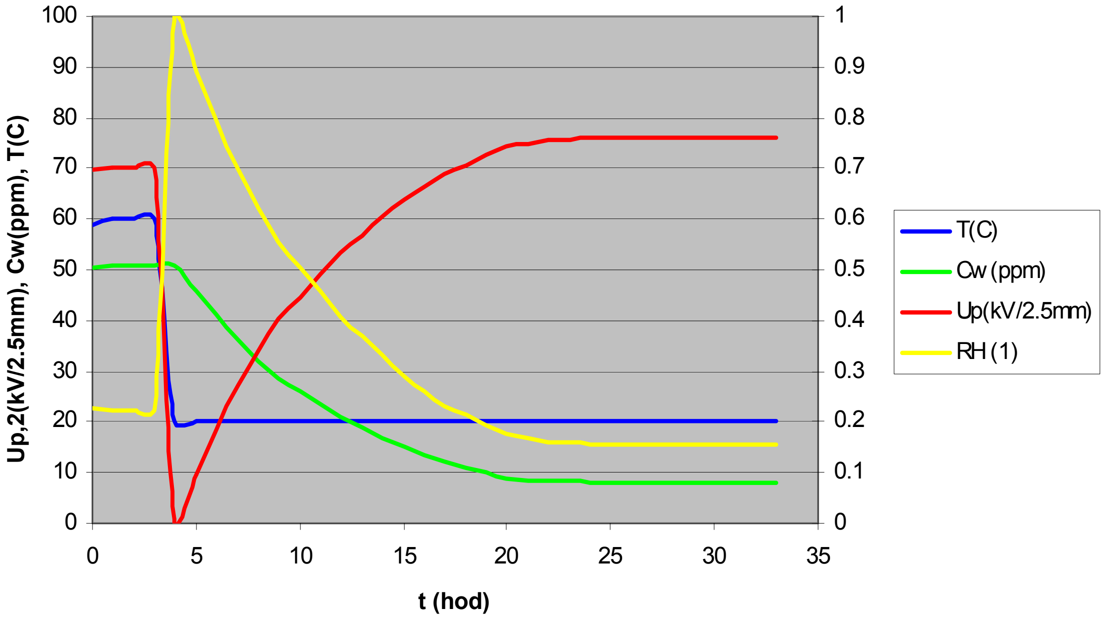


Fig. 4 The simulation of the dynamic response of parameters of a transformer oil at a sudden drop of the transformer temperature

The response of the relative humidity and consequently the Ud-value at the temperature drop from 60 C at 20C (blue line) is instantaneous and the water content in the oil remains therefore constant. The relative humidity jump-like manner increases from RH(60C) = 0.2 at RH(20C) = 0.998 and therefore drops Ud(20C) → 0.

But immediately after the temperature jump begins the slow process of the „system recovery“ induced by the adsorption of the diluted water in the cooled cellulose.

The water content in the oil (Cw – green curve) sinks , therefore sinks RH-value (yellow curve) too, and Ud-value (red curve) gradually grows. The process then continues until the new steady state is reached where the Ud-value corresponding to the new steady state situation is **higher** as.the intial Ud-value.

In the real case cannot of course come to the jump-like change of the operational temperature of the transformer and the mentioned process is only the theoretical demonstration of the extreme case which has, for very limited time-interval, the same quantitative effect as a classical Ud-diagnostic.

5. Diagnostic software TRACONAL (**TR**ansformer **C**ontamination **A**na**L**ysis

As shown, the present Ud-diagnostic represents a process where is the sampled oil “violently” removed from the examined oil-cellulose system regardless of necessary equilibrium conditions which are unavoidable for the precise measurement, cooled down at the laboratory temperature which has mostly nothing to do with the operational temperature as a main parameter of this system, then is the Ud-value measured and consequently interpreted as a main diagnostic value.

It hardly looks like as a precise and credible diagnostic method at all, but it is a very wide-spread and accepted method and therefore any new and better diagnostic tool must be able to use an existing data at least for the verification of the better and more comprehensive mathematical model of the system.

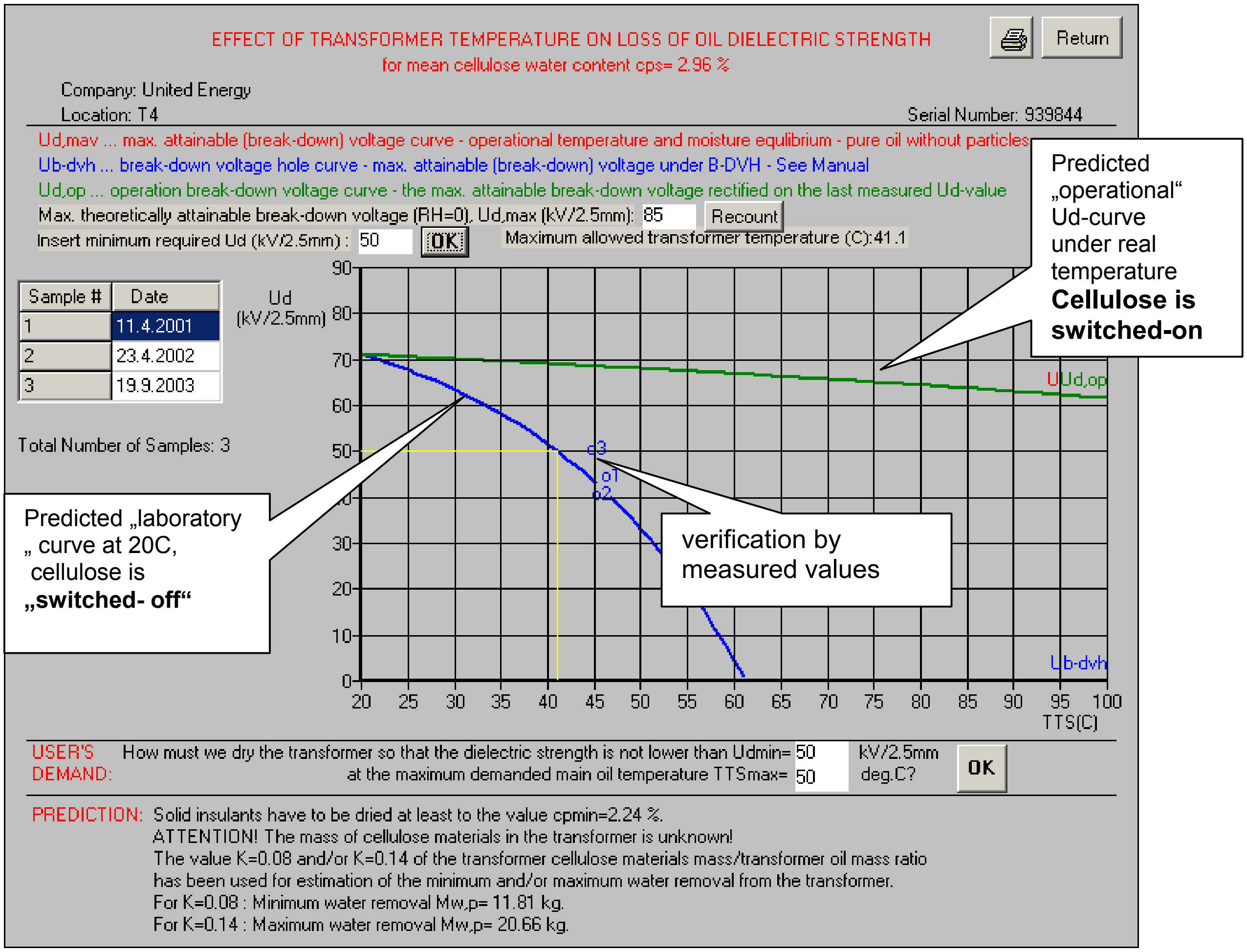
We have obviously found a real “content” of Ud-value, but it does not mean that we are able by this value convincingly describe a dielectric status of a transformer at the whole range of the operational temperatures.

Moreover, we still have no reasonable utilization for measured Ud-values at all – for example we still cannot make a plausible and quantitive prediction of Ud-value with the transformer temperature.

The diagnostic software TRACONAL based at the mathematical model according Fig. 3, solves the problem as follows:

- the main water content in the cellulose Cp (%), has to be found and on this base can be then predicted all desired parameters and values inclusive Ud-values [L6] for a given transformer
- Ud(20C)-curve of the transformer is simulated as a function temperature T under conditions “cellulose is switched-off” (the “laboratory” curve)
- “laboratory” curve (and therefore the mathematical model as well) is verified by measured Ud(20C)-values
- Ud (T)-curve, or “operational” curve (the cellulose is “switched on”) is simulated which corresponds to the real operational temperature of the transformer

The example of one output of the TRACONAL procedure for a real transformer is shown at Fig. 5.



EFFECT OF TRANSFORMER TEMPERATURE ON LOSS OF OIL DIELECTRIC STRENGTH
for mean cellulose water content cps= 2.96 %

Company: United Energy
Location: T4
Serial Number: 939844

Ud,mav ... max. attainable (break-down) voltage curve - operational temperature and moisture equlibrium - pure oil without particles
Ub-dvh ... break-down voltage hole curve - max. attainable (break-down) voltage under B-DVH - See Manual
Ud,op ... operation break-down voltage curve - the max. attainable break-down voltage rectified on the last measured Ud-value

Max. theoretically attainable break-down voltage (RH=0), Ud,max (kV/2.5mm): 85
Insert minimum required Ud (kV/2.5mm) : 50
Maximum allowed transformer temperature (C):41.1

Sample #	Date
1	11.4.2001
2	23.4.2002
3	19.9.2003

Total Number of Samples: 3

USER'S DEMAND: How must we dry the transformer so that the dielectric strength is not lower than Udmin= 50 kV/2.5mm at the maximum demanded main oil temperature TTSmax= 50 deg.C?

PREDICTION: Solid insulants have to be dried at least to the value cpmin=2.24 %.
ATTENTION! The mass of cellulose materials in the transformer is unknown!
The value K=0.08 and/or K=0.14 of the transformer cellulose materials mass/transformer oil mass ratio has been used for estimation of the minimum and/or maximum water removal from the transformer.
For K=0.08 : Minimum water removal Mw,p= 11.81 kg.
For K=0.14 : Maximum water removal Mw,p= 20.66 kg.

Predicted „operational“ Ud-curve under real temperature **Cellulose is switched-on**

Predicted „laboratory „ curve at 20C, cellulose is **„switched- off“**

verification by measured values

Fig. 5 Transformer dielectric diagnostic by TRACONAL

The blue curve predicts Ud-values corresponding the response of the oil-cellulose system of a transformer at the jump-like temperature drop from a operational (sampling) temperature at the laboratory temperature (T=20C). Consequently, the validity of blue curve, and the validity of the mathematical model can be therefore quantitatively verified by Ud-values measured in a laboratory.

This way we get the curve which de-facto determines the worst possible case area – the real Ud-value of the **pure** oil (without particles) for the given temperature T should be **over** the blue curve.

The green curve then predicts a Ud-values which corresponds a maximal attainable dielectric strength (the best possible case area) of the **pure** oil at arbitrary operational temperatures. Real attainable Ud-values should be **under** the green curve.

After the verification and a calibration of the predicted blue curve by measured Ud-values, we attain therefore a new and a qualitative and quantitative better diagnostic tool which enables us to describe and understand the dielectric behavior of our transformer at the whole range of its operational temperatures.

For details about all aspects the utilization of TRACONAL See [L5].

6. Conclusion

The dielectric screen of the power transformer, based at one-shot measurement of the dielectric strength of the transformer oil has obviously at least two major drawbacks - underestimates the natural dielectric robustness of a oil-cellulose system of a transformer and has very limited predicative character.

At a normal operational temperature is the real dielectric strength of a pure oil in a transformer, always higher as a value measured in the laboratory and the undesired deviation between the reality and the laboratory strongly grows with the increase of operational temperature of a transformer.

The one-shot character is another and a very serious drawback of the present diagnostic method. The measured Ud-value describes not the actual dielectric strength Ud(T) at the sampling (operational) temperature T of the transformetr, the but the worst possible case corresponding the laboratory temperature 20C. The prediction both Ud-values at different temperatures is theoretically impossible.

All mentioned drawbacks of the present method can be substantially reduced by a new three-step diagnostic paradigma: corresponding mathematical model of the oil-cellulose system → verification of the model by measured Ud-values → Ud-value (blue and green) prediction at the whole range of a operational temperatures of a transformer.

This way can be relatively easy identified the contamination level of oil by a impurities and/or the measurement errors can be excluded. The mathematical model is then used for a basic evaluation of present state of a transformer – can be the transformer safely operated or not , at what max. temperature, what dynamic change of the oil temperature are acceptable etc.

In the second step is examined how can be improved the present state of the transformer for future – e.g. how much water has to be removed, what improvement of Ud-value can be expected etc.

L1 …. Myers, Kelly , Parrisch

A Guide to Transformer Maintenance
TMI , Transformer Maintenance Institute, S.D.Mayers, Inc.,
ISBN 0-939320

L2 ….. Isolierflűssigkeiten

WDEW-Ölbuch, Band 2, 1996

L3 ..... Wasserberg at all
Drying of liquid immersed insulations using a hydroscopic insulating liquid
University of Hannover, Germany, Institute of Electric Power Systems
www.unics.uni-hannover.de/shering/PDF/Wasserberg

L4 ..... Altmann,

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

ARS Group, 2003
www.ars-altmann.com/news

L5 ..... Lewand, Griffin

Understanding Water in Transformer

www.netaworld.org

L6 Y. Du et al.:

Moisture equilibrium in transformer paper-oil systems”,

IEEE El. Ins. M.,1999, Vol.15, No 1

L7 … **SIMMS**

Solid **I**nsulants **M**obile **M**easurement **Systém**

www.ars-altmann.com

L8 **TRACONAL**

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

www.ars-altmann.com