CONDITION MONITORING OF POWER TRANSFORMERS – WHAT INFORMATION CAN WE GET FROM RETURN VOLTAGE MEASUREMENTS

Rainer Patsch

University of **Siegen, Germany**
Institute of **Materials** & **Diagnostics** in **Electrical Engineering**
rainer.patsch@uni-siegen.de

Abstract: Return Voltage Measurements are an efficient tool to measure the dielectric properties of an insulating system and thus to characterize the degradation of **cellulose-oil insulations**. They are widely used for the diagnosis of paper oil insulated **power cables**. As a consequence of misinterpretations of the measurement results in the past, the use of Return Voltage Measurements for the diagnosis of **power transformers** has been abandoned. Nevertheless – performing a **physically meaningful interpretation** of the measured curves – the application on power transformers is also very promising, especially because the insulation system in a power transformer is close to the conditions described by the **Maxwell model for two dielectrics in series**. For the characterization of the degree of ageing and consequently the **reliability** of the insulation system a new diagnostic parameter, the **r - factor**, is presented. The results of measurements of differently aged power transformers show a correct ranking and also a correlation between the oil humidity and the **r - factor**.

1 INTRODUCTION

For the diagnosis of insulating systems, time dependent polarization/depolarization processes can be used [1, 2]. In insulating systems consisting of more than one component**, boundary polarization** can be considered as the dominant polarization process. This holds especially for the cellulose-oil insulations that are used in power transformers with **pressboard-oil insulation**.

2 EQUIVALENT CIRCUIT OF A TRANSFORMER INSULATION

Fig. 1 shows a simplified model of a power transformer insulation and the basic distribution of oil and cellulose [3]. **Fig. 2** shows a corresponding electrical equivalent circuit. The equivalent circuit basically consists of a **series connection of two dielectric materials**: Firstly the **cellulose insulation** of the windings and the **pressboard barriers**, secondly the oil ducts filled by an **insulating oil**. The main elements are R_B, C_B, R_O and C_O. The elements R_S, C_S, and R_D are of less importance, where the latter one represents conduction processes in the oil bypassing the barriers. In most cases, for dielectric phenomena the influence of R_D is negligible. The same holds for the influence of R_S and C_S in comparison to the phenomenon of **boundary polarization**. The RC series elements in parallel to C_B and C_S characterize additional polarization processes that are of minor importance for the basic behaviour that is determined by the **Maxwell circuit** formed by R_B, C_B, R_O and C_O.

The fundamental behaviour determined by the two dielectrics **cellulose** and **oil** is characterized in the equivalent circuit by the numerical values of these four elements. Interestingly in the **Maxwell circuit**, the absolute values of these elements are not of importance. Not depending on the actual geometric dimensions, the dielectric behaviour is fully determined by the specific conductivities σ_i and the relative permittivities ε_{ri} of the two insulating materials cellulose and oil. The characteristic voltage division between the high and low voltage windings and the grounded core and tank results from the **continuity equation of the current density** and the laws for the **electric field at boundaries**.

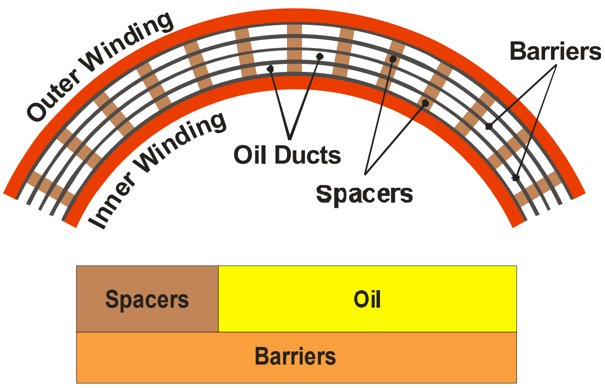

Fig. 1: Simplified model for a power transformer insulation with solid barriers and liquid oil

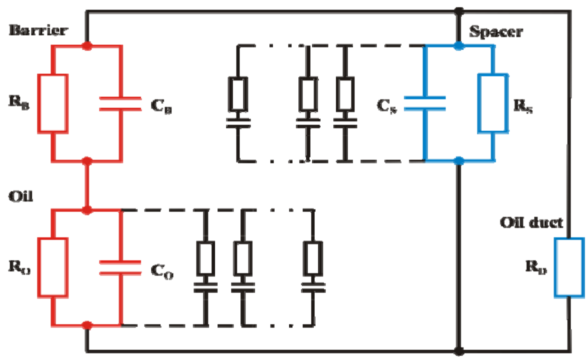

Fig. 2: Equivalent circuit of a pressboard-oil insulated power transformer insulation; the RC series elements in the middle are used for formal fits

2.1 Dielectric time constants

For an insulating material the **dielectric time constant** τ is proportional to the **relative permittivity** ε_r and inversely proportional to the **specific conductivity** σ. Hence the time constant τ is sensitive to changes of σ and ε_r, whereby for cellulose materials the **specific conductivity** σ **is very sensitive on the contents of water** or other degradation products. For a parallel circuit of **R** and **C** the dielectric time constant is given by τ = **RC** or - introducing the characteristic material parameters ε_r and σ to get rid of the actual geometric dimensions - by $\tau = \varepsilon_0\, \varepsilon_r / \sigma$. Hence the actual time constants τ_B and τ_O of the two insulating materials **cellulose** and **oil** do not depend on the geometric dimensions of the measured test object and consequently a diagnostic parameter derived from the two time constants is meaningful for all transformer geometries and sizes. In contrast to other diagnostic methods no fits according to the geometry of the tested object are needed.

3 AGEING OF TRANSFORMER INSULATION SYSTEMS

In power transformers the ageing of the insulating system is on one hand due to **ageing** and **degradation processes in the cellulose** and on the other hand due to **ageing** and **degradation of the oil**. Especially the degradation of the cellulose depends on the **temperature** of the insulation and any **partial discharge activities**. The degradation or depolymerisation of the cellulose generates also water molecules that will accelerate this degradation process. In addition water that comes from the outside via the surrounding oil may also intensify the degradation process. So **water** is on one hand an **indicator of degradation** and on the other hand also a **reason for accelerated degradation**.

3.1 Monitoring and maintenance of transformers

The oil of a transformer may be analyzed during service especially by taking a sample and measuring the contents of water or other degradation products, mainly dissolved gases by means of **DGA**. The oil can be upgraded by **drying processes** either continuously or in a separate offline process or the oil can be **exchanged**. By this also the water contents of the cellulose can be decreased, but only by diffusion processes that lead to a new **equilibrium** between the **water contents in the cellulose and the oil**. Generally the concentration of water molecules in the cellulose – and also the total amount of water – is much higher than in the oil. Hence an attempt to dry the cellulose by drying the oil is a very slow process.

The cellulose cannot be analyzed directly because it is not possible to take a piece of the paper or pressboard out of the transformer. Hence the **condition of the cellulose** can be determined only indirectly from the analysis of the oil by means of calculations on the basis of the different solubilities of ageing and degradation products under thermodynamic equilibrium conditions, or by the **use of the corresponding dielectric time constants** of cellulose and oil, a method that is a unique possibility of the Return Voltage Method.

4 RETURN VOLTAGE MEASUREMENTS

Water in the cellulose leads to an increase of the concentration of mobile carriers, thus to an increase of the **specific conductivity** σ_B and hence a decrease of the dielectric time constant τ_B. The same holds to a lower extent for a decrease of τ_O due to water and degradation products in the oil. If the transformer insulation system behaves like a Maxwell circuit, Return Voltage measurements are a good method to monitor degradation processes in transformer insulations, because the **dielectric time constants of the two dielectrics** $\tau_B = R_B C_B$ and $\tau_O = R_O C_O$ can be calculated numerically from the shape of the Return Voltage curve.

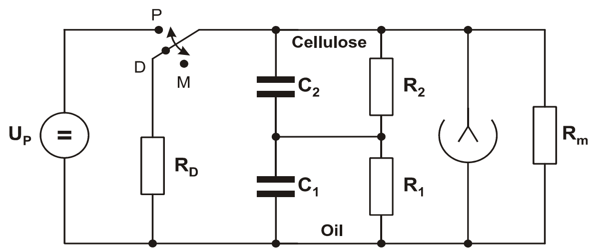

Fig. 3: Equivalent circuit of a paper-oil dielectric with $\tau_B = \tau_2 = R_2C_2$ and $\tau_O = \tau_1 = R_1C_1$ with $\tau_B > \tau_O$ and the basic measuring circuit

Fig. 3 shows the basic measuring circuit for a Return Voltage measurement with $\tau_2 = \tau_B$ and $\tau_1 = \tau_O$. Under the assumption that the measuring resistor R_m is sufficiently higher than the resistors R_2 and R_1 in the equivalent circuit, the Return Voltage curve $U_r(t)$ can be calculated analytically:

$$U_r(t) = U_s \left(e^{-\frac{t}{\tau_2}} - e^{-\frac{t}{\tau_1}} \right) \qquad (1)$$

with $\tau_2 = R_2C_2$ and $\tau_1 = R_1C_1$. U_s depends also on the geometric dimensions of the insulating system, but the time constants τ_2 and τ_1 are not influenced by its value.

For Return Voltage measurements a DC voltage $\mathbf{U_p}$ (1 or 2 kV) is applied for a certain time (e.g. $\mathbf{t_p}$ = 30 min), then the transformer is short circuited for $\mathbf{t_d}$ = 2 s. After opening the short circuit, a voltage will build up across the terminals of the transformer. The equivalent circuit of a transformer insulation - i.e. its decisive elements $\mathbf{R_B}$, $\mathbf{C_B}$, $\mathbf{R_O}$ and $\mathbf{C_O}$ - corresponds very closely to a Maxwell equivalent circuit of a series connection of two RC parallel elements. The evaluation of the shape of the Return Voltage curve $\mathbf{U_r(t)}$ allows the calculation of the dielectric time constants $\boldsymbol{\tau_2}$**(t)** and $\boldsymbol{\tau_1}$**(t)** of the two insulating materials separately [4]. The voltage $\mathbf{U_s}$ across the two capacitors after a poling time $\mathbf{t_p}$ and a short circuit time $\mathbf{t_d}$ is not only influenced by the time constants τ_1 and τ_2, but also by the geometric dimensions of the measured system [7].

A curve according to eqn. (1) is exactly defined by just three data points, i.e. the **point of origin**, the peak value $\mathbf{U_m(t_m)}$ and **one additional point U(t)** of the curve. Hence the corresponding time constants τ_1**(t)** and τ_2**(t)** of the oil and the cellulose respectively can be calculated point by point from the experimentally determined curve. For the characterisation of the measured Return Voltage curve of a transformer it is interesting in how far the calculated time constants τ_1 and τ_2 are influenced by the selection of the point **U(t)**. For a Maxwell curve no such dependence exists. (All normalized curves pass per definition through (1;1), hence the use of data points around the maximum for the calculation of the dielectric time constants is not very meaningful.)

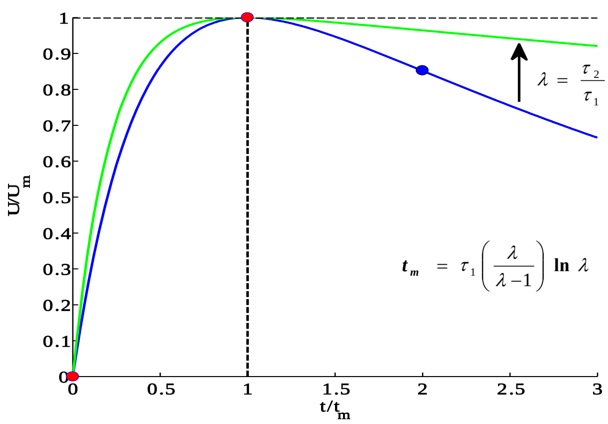

Fig. 4 Normalized Return Voltage curve and calculation of the dielectric time constants $\boldsymbol{\tau_2}$**(t)** and $\boldsymbol{\tau_1}$**(t)** from the points **(0;0)** and **(1;1)** and different points **(U;t)** of the curve.

5 MEASUREMENT RESULTS

Fig. 5 shows the dielectric time constants $\boldsymbol{\tau_2}$**(t)** of cellulose and $\boldsymbol{\tau_1}$**(t)** of oil calculated from the measured Return Voltage curve of a **non aged 31.5 MVA power transformer**. The selection of the point **U(t)** does not significantly influence the actual values of the dielectric time constants of the measured curve, thus the measured curve is nearly identical to the **Maxwell-type curve** given in eqn. (1).

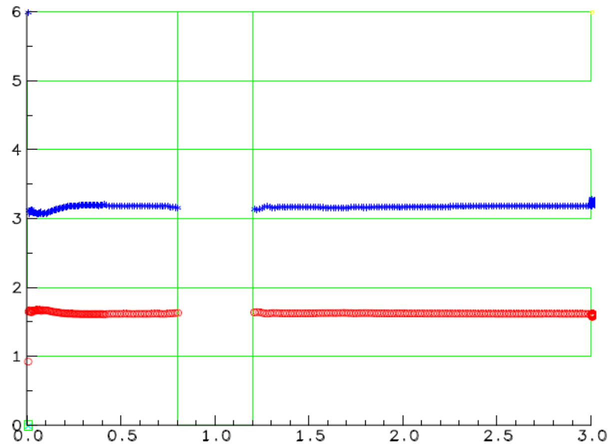

Fig. 5: Logarithms of the time constants **lg** $\boldsymbol{\tau_2}$**(t)** and **lg** $\boldsymbol{\tau_1}$**(t)** calculated from the Return Voltage curve of a **new 31.5 MVA transformer** over $\mathbf{t/t_m}$

Fig. 6 shows the corresponding data for a **seriously aged 100 MVA transformer** that had been taken out of service due to a fault. The deviation from the Maxwell-type behaviour can be explained by **additional polarization** or conduction processes with time constants in the range of up to a few 10 seconds. Those effects can be described by additional RC series elements in parallel to the Maxwell circuit. Numerical simulations with a computer program on the basis of this assumption show a similar behaviour [7].

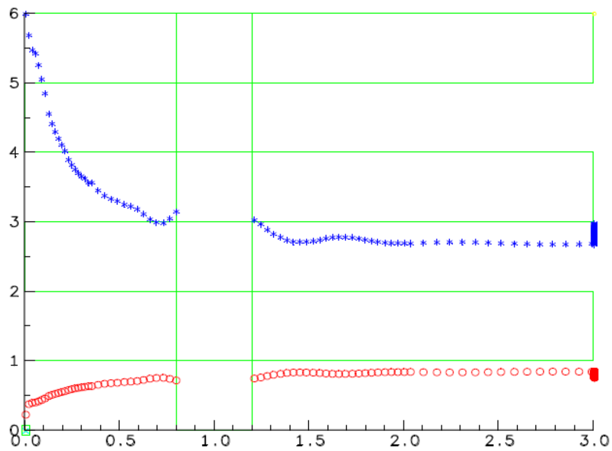

Fig. 6: Logarithms of the time constants **lg** $\boldsymbol{\tau_2}$**(t)** and **lg** $\boldsymbol{\tau_1}$**(t)** calculated from the Return Voltage curve of a **seriously aged 100 MVA transformer** over $\mathbf{t/t_m}$

The effects are be caused by **chemical changes** in the insulation components **due to ageing and degradation processes**. These changes do not only lead to an increased conductivity, but also generate polar molecules within the insulation. The depolarisation of these components leads to a steeper incline of the Return Voltage curve and to higher ratios τ_2/τ_1 as indicated in Fig. 4. With increasing time of the measurement the influence of these processes decreases and the shape of the measured Return Voltage curve approachs the Maxwell-type behaviour. Nevertheless compared to the data from a new transformer (Fig. 5) the values of the time constants are lower.

For diagnostic purposes the data from **t > t_m** are a measure for the DC-conductivities of the dielectrics, while the data from **t** < **t_m** are more influenced by additional, predominantly polar ageing and degradation products. Measurements of transformers at different temperatures in the range between **15** and **55 °C** show for **t > t_m** a temperature dependence of the dielectric time constants as expected from **thermally activated conduction processes** [6, 7], a proof for the validity of the concept of the interpretation of Return Voltage measurements on power transformers on the basis of the Maxwell-model.

5.1 Influence of oil drying

A good way to check the reliability of the **diagnostic parameters** gained from a Return Voltage curve for the description of the **condition of an insulating system** is a measurement before and after drying, oil exchange or a repair. Measurements performed on a **250 MVA power transformer before** (**Fig. 7**) and **after oil drying** (**Fig. 8**) show the changes.

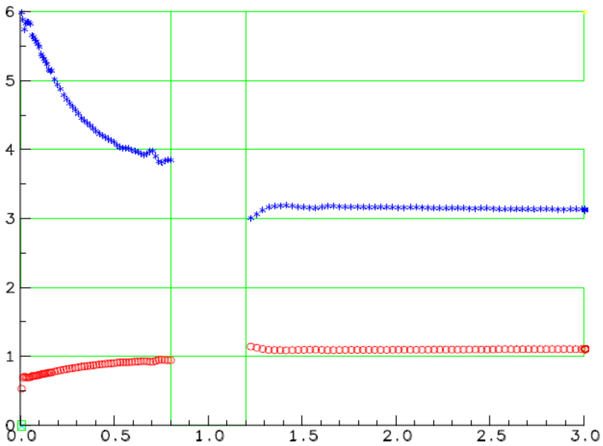

Fig. 7: Logarithms of the time constants **lg τ_2(t)** and **lg τ_1(t)** calculated from Return Voltage curves of an **aged 250 MVA** transformer **before oil drying**

The deviation of the Return Voltage curve from the ideal Maxwell-type behaviour - indicated by the dependence of the dielectric time constants τ_i on the selection of the point **U(t)** - has become much less prominent by the drying process. Water and ageing products that were responsible for the behaviour at **t** < **t_m** had been removed to a high degree from the oil by the drying process. The value of τ_1 around **2 t_m** or later has more than **tripled**, because oil drying decreases the oil conductivity and, along with that, increases the dielectric time constant.

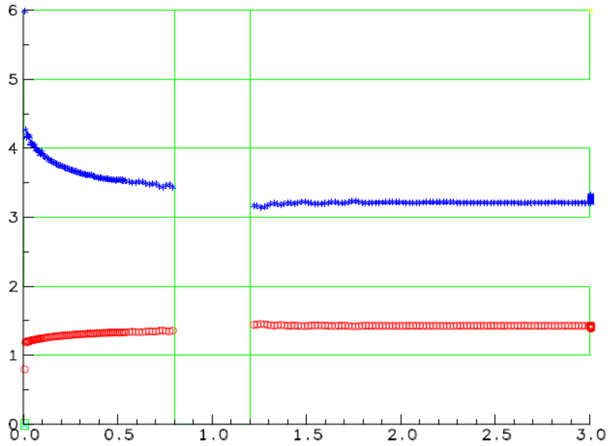

Fig. 8: Logarithms of the time constants **lg τ_2(t)** and **lg τ_1(t)** calculated from Return Voltage curves of an **aged 250 MVA** transformer **after oil drying**

The corresponding value of τ_2 did not change significantly. Nevertheless the **removal of ageing and degradation products from the oil** has a beneficial influence on the further life of the cellulose, although to be effective, a repetitive or better a continuous removal should be preferred.

6 CORRELATION PLOT τ_2(t) OVER τ_1(t)

As discussed in the previous chapter the dependence **τ_1(t)** and **τ_2(t)** characterizes the degree of ageing and degradation of the insulation system of a power transformer. A step forward is the plot of **τ_2(t)** over **τ_1(t)** with the time **t** as an implicit parameter. **Fig. 9** shows a corresponding plot of the data presented in Figs. 5 to 8. The differences are obvious. For better characterization of the curves, a set of different hyperbolas characterizing lines of constant products of **lg τ_2** and **lg τ_1** is displayed.

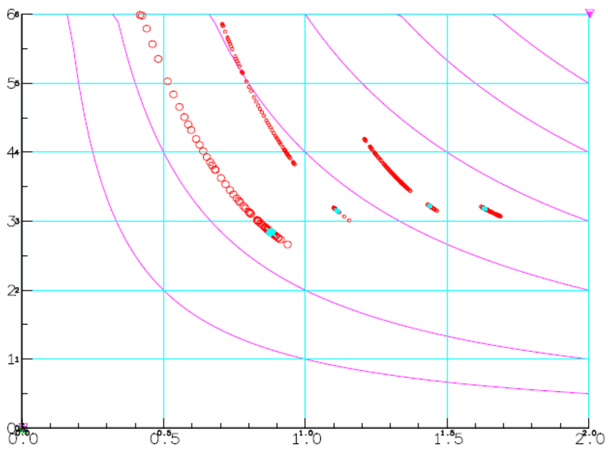

Fig. 9: Correlation plots of the logarithms of the time constants **lg τ_2(t)** over **lg τ_1(t)** for three power transformers, from left to right: a **seriously aged 100 MVA** transformer (Fig. 6), an **aged 250 MVA** transformer **before** and **after oil drying** (Figs. 7 and 8), and a **new 31.5 MVA transformer** (Fig. 5)

7 RELYABILITY FACTOR r

For the application of the diagnostic method in practice, starting from Fig. 9 a newly defined parameter, the **r - factor** can be used.

$$r = \lg \tau_2 \times \lg \tau_1$$

For the **non aged transformer r > 5** is found and there is nearly no change in the time constant τ_1. For the **seriously aged transformer r ≈ 2.5** is found, and a large change in τ_1 occurs.

Figs. 10 and **11** show diagrams of the **r- factor** over **lg** τ_1 for the data from Fig. 9. For a more detailed analysis the **r - factor** is displayed in two separate graphs : for **t** < t_m (Fig. 10) and for **t** > t_m (Fig. 11).

For **t >** t_m (Fig. 11) also for aged transformers the **r - factor** is nearly constant as well as the time constant τ_1, an indication that in this time region the Return Voltage curve is shaped like expected from the Maxwell model. The data from this time region mainly represent the "DC-conductivities of the two dielectrics in the insulation system without a relevant influence of polarization den depolarization effects. As a first step from this graph the **r - factor** can be taken as a **single numerical value** for **diagnostic characterization**

The short time region **t** < t_m (Fig. 10) may show additional differences due to the degree of ageing and degradation. They are mainly a result of specific polarization and depolarization processes and hence sensitive on **polar ageing and degradation products**. The detailed analysis of this region in more detail reveals further information about the actual situation of the insulation system.

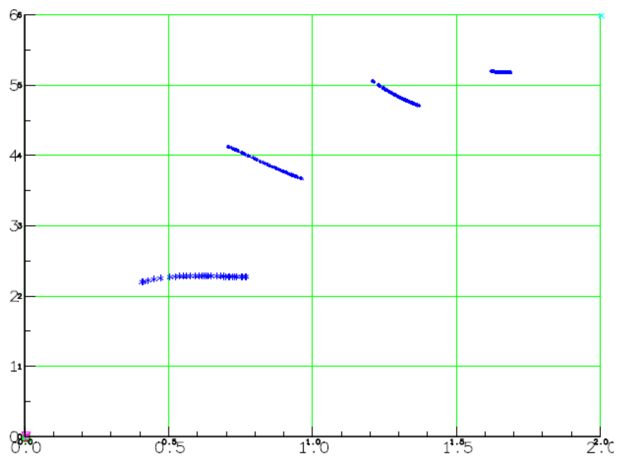

Fig. 10: r- factor over **lg** τ_1 for **t <** t_m for three power transformers, from left to right: a **seriously aged 100 MVA** transformer (Fig. 6), an **aged 250 MVA** transformer **before** and **after oil drying** (Figs. 7 and 8), and a **new 31.5 MVA transformer** (Fig. 5).

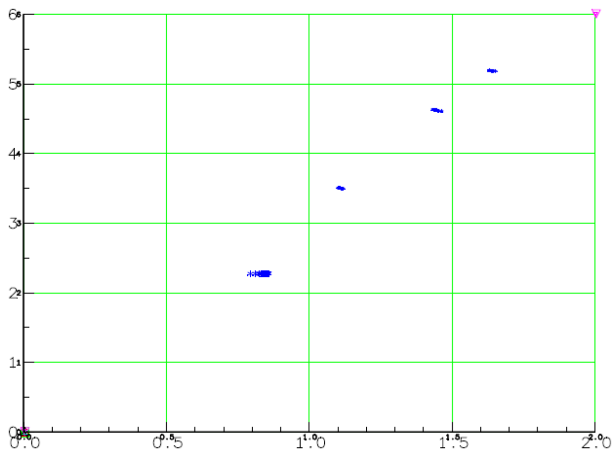

Fig. 11: r- factor over **lg** τ_1 for **t >** t_m for three power transformers, from left to right: a **seriously aged 100 MVA** transformer (Fig. 6), an **aged 250 MVA** transformer **before** and **after oil drying** (Figs. 7 and 8), and a **new 31.5 MVA transformer** (Fig. 5).

8 CONCLUSIONS

It is possible to calculate the **dielectric time constants** of the components in the **two-component insulation system** of power transformers by means of **Return Voltage** measurements using the **Maxwell equivalent circuit** as a model. This allows to monitor the condition of each component separately, without being influenced by the size and geometry of the insulation of the transformer.

For **aged** insulation systems marked **deviations from the ideal Maxwell model** can be found. Especially the initial incline of the Return Voltage curve is often very steep. A fit for **t** < t_m leads to smaller values of τ_1 and higher values of τ_2. This is due to degradation products that lead to additional conduction and polarisation processes in the range of up to a few 10 seconds. The influence of these effects on the shape of the curve decreases with time and for **t** > t_m i.e. after the peak of the curve **nearly no time dependence** exists – the system behaves as predicted from the **Maxwell-model**.

In general: The analysis of measurements on differently degraded or aged power transformers or of transformers **before and after oil drying** or a **repair** showed that less ageing and degradation i.e. a better condition of the insulation system leads to a smaller deviation of the shape of the Return Voltage curve from the ideal curve predicted by the Maxwell model. Hence this deviation as well as the numerical values of the time constants $\tau_B = \tau_2$ and $\tau_O = \tau_1$ can be used as a diagnostic parameter for ageing and degradation.

The plot of the logarithms of the time constants **lg τ_2(t)** over **lg τ_1(t)** with the time **t** as implicit parameter shows **significant differentiations between differently aged and degraded power transformers**. For the numerical characterization of the degree of ageing and degradation of power transformers the **r-factor** is introduced as a meaningful parameter. As a first step the **r-factor** should be taken for **t** > $\mathbf{t_m}$, for a more detailed analysis the data for **t** < $\mathbf{t_m}$ should be used also.

The comparison of the **r-factor** with e.g. the **humidity of the oil** – data from several measurements of different power transformers not presented in this paper – shows a good correlation.

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