Dielectric Time Constants – the Key to the Interpretation of Return Voltage Measurements on Cellulose-Oil Insulated Power Equipment

Rainer Patsch, Johannes Menzel, Dieter Kamenka *

Institute of Materials & Diagnostics in Electrical Engineering
University of Siegen, Germany
*sebaKMT, Radeburg, Germany
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 power cables. As a consequence of misinterpretations of the results in the past, the use Return Voltage Measurements for power transformers has been reduced. Nevertheless – performing a physically meaningful interpretation of the measured curves – the application on power transformers is also very promising, especially because the geometry of the insulation system in a power transformer is closer to the conditions described by the Maxwell model for two dielectrics in series. Return Voltage curves for new or not severely aged transformers fit very well the type and shape of the voltage curve predicted by the Maxwell equivalent circuit. Ageing and degradation phenomena in the oil and the paper lead to a deviation from this behaviour.

Keywords: Dielectric time constants, Cellulose-oil insulation, boundary polarization

Introduction

For the diagnosis of insulating systems, time dependent polarization/depolarization processes can be used [1-3]. In insulating systems consisting of more than one component, boundary polarization can be considered as the dominant polarization process. This holds especially for cellulose-oil insulations that are widely used in power equipment, e.g. power cables and transformers.

In cables, the insulating paper is vacuum-impregnated with the oil. In this case, the boundaries between oil and cellulose, i.e. the boundaries between the cellulose fibres and the oil-filled space between them are more or less homogeneously distributed over the whole system, in macroscopic terms the paper-oil dielectric is “homogeneous”. So it is likely that ageing processes will usually affect both components. Thus, in most cases the ageing can be described by just one parameter, the p-factor [4, 5], that only depends on the ratio $\tau_p / \tau_0$ of paper and oil.

In transformers with pressboard-oil insulation the pressboard contains oil also, but the pressboard is also in contact with liquid oil.

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 [6]. 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 $C_O$, $R_S$, $C_S$, and $R_P$ 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 $R_O$ 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 $\sigma_i$ and the relative permittivities $\varepsilon_i$ 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.

### Cable insulation system

A paper-oil cable insulation can basically be modelled using a reduced version of the equivalent circuit shown in Fig. 2. In this case, the two dielectrics (paper and oil impregnation) are represented by $R_B$, $C_B$, $R_O$ and $C_O$. An additional a parallel conductivity ($R_S$ in Fig. 2) may result e.g. from cable joints or wet parts of the insulation. An additional capacitance ($C_S$ in Fig. 2) may represent sections of the measured cable that produce no noteworthy contribution to polarization processes, e.g. sections of a paper-oil cable that had been replaced by a solid dielectric cable. Nevertheless there is a coupling between the two dielectric time constants of the paper and the oil impregnation. In this case the boundary polarization occurs in the tiny oil filled free space of the paper.

### Transformer insulation system

In power transformers the two dielectrics are separated (the oil impregnation of the pressboard is not discussed separately) and 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 decomposition of the cellulose produces 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.

### Dielectric time constants

For an insulating material the dielectric time constant $\tau$ is proportional to the relative permittivity $\varepsilon_r$ and inversely proportional to the specific conductivity $\sigma$. Hence the time constant $\tau$ is sensitive to changes of $\sigma$ and $\varepsilon_r$, whereby for cellulose materials the specific conductivity $\sigma$ 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 $\tau = RC$ or introducing the characteristic material parameters to get rid of the actual geometric dimensions $\tau = \varepsilon_0 \varepsilon_r / \sigma$. Hence the actual time constants $\tau_B$ and $\tau_O$ of the two insulating materials cellulose and oil do not depend on the geometric dimensions of the measured test object.

### 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 (DGA). The oil can be upgraded by drying processes either continuously or in a separate offline process or the oil can be exchanged. By 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 – is much higher than in the oil.

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 measurement of the corresponding dielectric time constant of the cellulose.

### Return Voltage measurements

Water in the cellulose leads to an increase of the concentration of mobile carriers and thus to an increase of the specific conductivity $\sigma_B$ and hence a decrease of

![Fig. 3: Equivalent circuit of a paper-oil dielectric with $\tau_B = \tau_2 = R_2 C_2$ and $\tau_O = \tau_1 = R_1 C_1$ and the basic measuring circuit](image-url)
the dielectric time constant $\tau_B$. The same holds to a lower extent for a decrease of $\tau_O$ due to 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 by the evaluation of Return Voltage curves the dielectric time constants of the two dielectrics $\tau_B = R_BC_B$ and $\tau_O = R_OC_O$ can be calculated numerically. 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 bigger than the resistors $R_2$ and $R_1$ in the equivalent circuit, the Return Voltage curve $U_r(t)$ can be calculated analytically:

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

with $\tau_2 = R_2C_2$ and $\tau_1 = R_1C_1$

For Return Voltage measurements a DC voltage $U_p$ (1 or 2 kV) is applied for a certain time (e.g. $t_p = 30$ min), then the transformer is short circuited for $t_d = 2$ 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 $R_B$, $C_B$, $R_O$ and $C_O$ - 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 $U_r(t)$ allows the calculation of the dielectric time constants $\tau_2(t)$ and $\tau_1(t)$ of the two insulating materials separately [7]. The voltage $U_s$ across the two capacitors after a poling time $t_p$ and a short circuit time $t_d$ is not only influenced by the time constants $\tau_1$ and $\tau_2$, but also by the geometric dimensions of the measured system [8].

On the basis that a curve according to eqn. (1) is exactly defined by just three data points, i.e. the point of origin, the peak value $U_m(t_m)$ and one additional point $U(t)$ of the curve the time constants $\tau_1$ and $\tau_2$ of the oil and the cellulose respectively can be calculated point by point due to the curve. For the characterisation of the measured curve it is interesting in how far the calculated time constants are influenced by the selection of the point $U(t)$. For a Maxwell curve no such dependence exists.
Measurement results

Fig. 4 shows the dielectric time constants of oil ($\tau_1$) and cellulose ($\tau_2$) calculated from the measured Return Voltage curve of a 31.5 MVA power transformer. The time constants calculated from different data points $U(t)$ of the measured curve are nearly identical, thus the measured curve is nearly identical to the Maxwell-type curve given in eqn. (1).

Fig. 5 shows the measured Return Voltage curve and the computed Maxwell-type curve (according to eqn. (1)) using the dielectric time constants calculated for the point $U(2t_m)$ and the difference between the two curves. Obviously there is almost no difference. With regard to the Return Voltage curve (and the underlying conduction and polarisation processes) the transformer insulation behaves nearly like an ideal Maxwell equivalent circuit. The insulation system shows no indication of ageing.

Measurements performed on differently aged 630 kVA transformers show additional short time polarisation processes in the initial part of the curve that lead to different dielectric time constants for different measurement times, an indication for different amount of ageing [7].

Figs. 6 and 7 show the corresponding data for a seriously aged 100 MVA transformer that was decommissioned 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. The effects might be caused by chemical changes in the insulation components due to ageing 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. With increasing time of the measurement the influence of these processes decreases and the shape of the measured Return Voltage curve approaches the Maxwell-type behaviour.
Influence of oil drying

The best way to see the influence of the condition of the insulating system on the Return Voltage curve and especially the aforementioned diagnostic parameters is to perform measurements before and after repair, drying or an oil exchange. Measurements performed on a 250 MVA power transformer before (Figs. 8 and 9) and after oil drying (Figs. 10 and 11) clearly show the differences.

The deviation of the Return Voltage curve from the ideal Maxwell-type behaviour has become much less prominent than before oil drying. Water and ageing products that were responsible for the short time behaviour had been removed to a high degree from the oil by the drying process. The value of $\tau_1$ 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. The corresponding value of $\tau_2$ 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.

Temperature dependence

Fig. 12 shows the dependence of the calculated dielectric time constants on temperature for measurements of two differently aged 50 kVA transformers at different temperatures in the lab. For both transformers the plots show almost straight lines, an indication that – under the assumption of thermally activated conduction processes, the Maxwell model describes the processes well [9]. For Tr1 there is an influence of $R_m$ that generates the deviation of $\tau_2$ at low temperatures.

Fig. 13 shows the corresponding data for a core of a heavily aged PILC cable that was measured over a smaller temperature range. For better comparability the diagrams are in the same scale as those in Fig. 12.

Repetitive measurements on cables

On some cables in the field repetitive measurements were performed in different seasons of the year. Table 1 shows the p-factors, Fig. 14 the dielectric time constants calculated from the values $U_{im}$, $t_m$ and $s$ of the Return Voltage curves [7]. In one of the cables (GER6) the increase of the p-factor and the decrease of $\tau_2$ due to ageing processes (different for the three cores) is obvious and can be separated from the influence from different measurement temperatures of the cable in different seasons of the year.
Conclusions

It is possible to calculate the dielectric time constants of the components in the two-component insulation system of power transformers or paper-oil insulated cables by means of Return Voltage measurements using the Maxwell equivalent circuit as a model. This allows to monitor the condition of each component separately.

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 in that part of the curve leads to smaller values of $\tau_1$ and higher values of $\tau_2$. 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 has almost no influence after the peak of the curve.

The analysis of measurements on differently aged power transformers or on a transformer before and after oil drying showed that 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.

Measurements of cables showed different p-factors, indicating different degree of ageing. Repetitive measurements of cables showed for some cables an increase of the p-factor, indicating additional ageing since the preceding measurement, or no change for others.

References