Proceedings of the 5th WSEAS Int. Conf. on Power Systems and Electromagnetic Compatibility, Corfu, Greece, August 23-25, 2005 (pp514-521)

Selection of Diagnostic Parameters in Return Voltage Measurements of Medium Voltage Cables

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Abstract: The condition of service aged medium voltage cables can be assessed by measuring the dielectric response of the insulation. In time domain this can be done via return voltage or/and depolarization current measurements. The paper deals with the interpretation of experimental results of **Return Voltage Measurements** and discusses the relevance of different measurement conditions and the meaningfulness of the different diagnostic parameters chosen. Special emphasis is taken on the **p-factor**, a parameter that seems to be appropriate for all types of insulating materials.

Key words Return Voltage Method, Boundary Polarization, Maxwell-Model, Dielectric Time Constants

I. Introduction

For transformers, cables and other high voltage equipment the diagnosis of the condition of the insulating components is getting more and more important. A good method to attain this information are **Return Voltage Measurements**. The experimental procedure is the following: Application of a dc-voltage for the time $\mathbf{t_p}$, form a short circuit for the time $\mathbf{t_d}$, and measure the voltage that builds up between the external electrodes after the release of the short circuit. Commonly used parameters of the return voltage curves are the peak voltage $\mathbf{U_m}$, the time $\mathbf{t_m}$ of the voltage peak and the initial incline **s** of the curve.

The principle is known since many years [1-3], the measurements are reliable, at least with regard to the collection of the data, unfortunately not always with regard to all methods of interpretation. In addition, return voltage measurements are less sensitive to disturbances by external noise, a situation that is favourable for measurements in the field. The extractable information is comparable to that derived from other dielectric methods like e.g. the measurement of polarization and depolarization currents [4, 5].

Commercially two versions of return voltage measurements are in use, one with differently long times for polarization and short circuit [6, 7], and the other with a long polarization time and a short circuit time of 2 s [8]. The interpretation of the data is also different and unfortunately not oriented towards real physical parameters.

Molecular Processes

Polarization processes in dielectrics are well known and especially the time dependences of **molecular polarization** and **relaxation processes** have been discussed in detail in the past. Molecular **polarization processes are very quick** and occur in time scales far below the range of seconds, hence no such molecular effects can be expected to have a relevant influence on processes in the time range of tens or hundreds of seconds or more as found in return voltage measurements of commercial power equipment.

For specimens with sufficiently thick homogeneous insulations and sufficiently low conductivity (mainly organic polymers) in the **high field region** (several tens of kV/mm up to more than 100 kV/mm) time dependent currents in the time range of several minutes or even hours may be found. These are mainly due to the generation and decrease of **space charges** within the bulk (in connection with local trapping and detrapping processes of charge carrier) that influence the local field distribution and hence may produce also a current under short circuit conditions [16]. For polymeric materials and not too high electric fields usually the 'Curie-Von Schweidler law' [4, 9, 10]

$$\boldsymbol{i_p \approx i_d \sim t^{-n}}$$

with $\mathbf{n \le 1}$ is found for the 'polarization' and 'depolarization' currents.

Formal equivalent circuit

The analysis of return voltage curves or of polarization and depolarisation currents over time is often done by a numerical fit on the basis of equivalent circuits consisting of three or more **RC series-elements** with different time constants in parallel. **Fig. 1** shows such a standard circuit. This equivalent circuit is physically adequate for the description of an insulating material that contains **molecules with different polarizabilities**. For other processes such as e.g. the built-up of space charges or boundary polarization processes in such an equivalent circuit is just a tool for a mathematical fit.

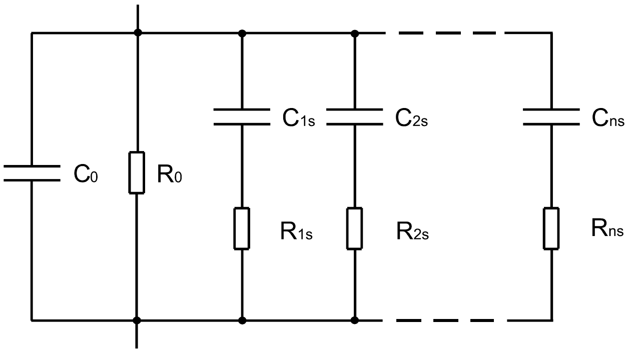

Fig. 1: Commonly used equivalent circuit of a dielectric for the description of polarization processes (after [4])

In the following some basic facts of multilayer insulations and their consequences for the interpretation of data from measurements of commercial power equipment will be discussed.

Boundary polarization

The insulation of classic power equipment such as **oil filled cables** or **power transformers** with **paper-oil-insulation** consists of different insulating materials with different dielectric properties (ε_r and σ) and thus – in addition to molecular processes in the short time range – shows the phenomenon of **boundary polarization**, i.e. the accumulation of charge carriers at the boundaries between the different dielectrics.

An appropriate description of the dielectric situation in a hv transformer with paper-oil insulation is given by the **XY-model** [17, 18], that describes the different geometries of the different dielectric materials contained in the insulation. The potential difference between electrodes on hv potential and grounded parts is bridged by different dielectric materials, thus producing a voltage distribution that is determined by capacitive and ohmic components in the current. For a cable with paper-oil insulation the geometric situation is less complicated, because there is only one type of dielectric consisting of a mixture of cellulose and oil, there exists no area with oil only.

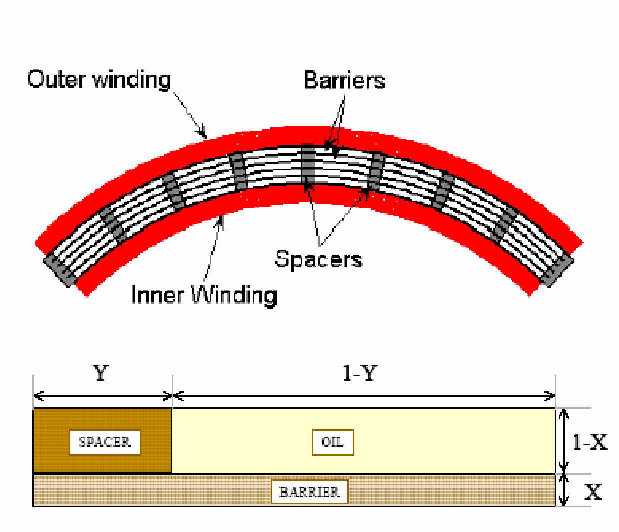

Fig. 2: Segment of transformer insulation and **XY-model** of the transformer insulation with paper-oil-dielectric (after [18])

Dielectric behaviour

If a dc-voltage is applied to the external electrodes of such a system, starting with a **capacitive voltage distribution**, a continuous change into a **resistive voltage distribution** occurs. Electric charges move within the different dielectrics and in part accumulate at the **interfaces**, where they generate local electric fields that are necessary to fulfil the **continuity equation** for the current density. During this time interval a current with a time dependence similar to the 'Curie-Von Schweidler law' occurs. In some cases a current without time dependence is superimposed.

After removal of the poling voltage, during the **short circuit** a release of the charges at the external electrodes takes place and the **locally accumulated charges move** within the dielectric materials, thus producing a **discharge current**.

After the release of the short circuit this current generates a **voltage difference between the two external electrodes**, that first increases, surpasses a maximum and decreases again, thus producing the **Return Voltage Curve**. In so far no single molecular polarization or depolarization processes are responsible for the experimentally found behaviour during return voltage measurements. Hence it seems to be necessary to question the meaningfulness of the application of the equivalent circuit shown in Fig. 1, although it is obvious that any curve with the time dependence described can be fitted with this equivalent circuit, but the question is, if there is any real physical meaning in the fit coefficients.

II. Maxwell Model

For **boundary polarization** – and this is the relevant process in power equipment with paper-oil insulation – another equivalent circuit, the **Maxwell-Model** with two **RC parallel-circuits in series**, is more appropriate, because it closely **reproduces the physical reality**. **Fig. 3** shows the basic equivalent circuit. This circuit is in good correspondence with the model shown in Fig. 2 that is discussed in the literature for transformers [7].

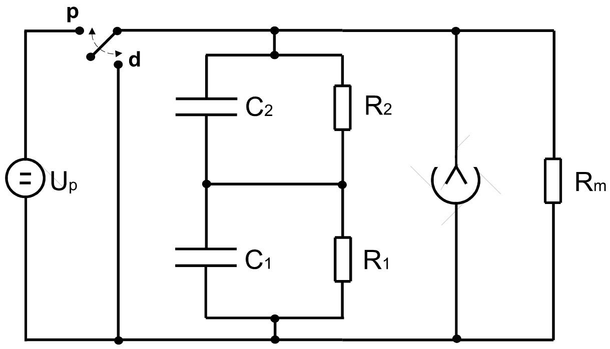

Fig. 3: Equivalent circuit of a paper-oil-dielectric and basic measuring circuit

The time constants $\tau_2 = R_2C_2$ and $\tau_1 = R_1C_1$ of the two **RC-parallel elements** correspond to the dielectric time constants of the two dielectrics cellulose and oil and R_m is the resistance of the measuring circuit, hence there is a physical relevance.

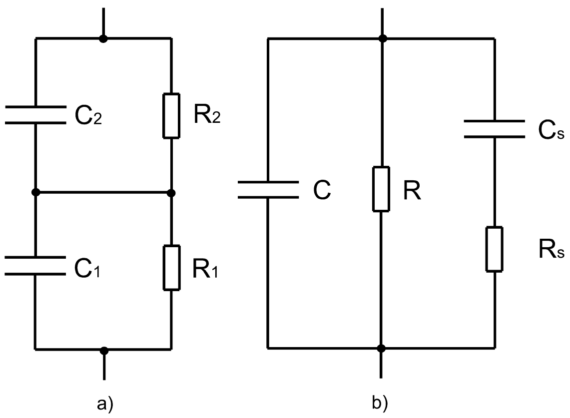

Fig. 4: Correlation between the two basic equivalent circuits for a paper-oil-dielectric: a) the Maxwell circuit and b) the corresponding formal equivalent circuit

As mentioned already, for a purely formal description also an equivalent circuit with the RC series-elements is possible [11]. **Fig. 4** shows the two corresponding circuits.

The numerical values of the elements in Fig. 4b) are correlated to the RC parallel-elements in the Maxwell-Model, but the physical meaning is lost. For the numerical values of the formal equivalent circuit we find:

$$C = \frac{C_1 C_2}{C_1 + C_2}, \qquad R = R_1 + R_2,$$

$$C_s = \frac{(R_2C_2 - R_1C_1)^2}{(R_1+R_2)^2 (C_1 + C_2)},$$

$$R_s = \frac{R_1R_2 (R_1 + R_2)(C_1 + C_2)^2}{(R_2C_2 - R_1C_1)^2},$$

$$\tau_s = \frac{R_1R_2(C_1 + C_2)}{R_1 + R_2}$$

It is worth mentioning that the possibility of a formal fit of the data with the circuit shown in **Fig. 4b)** does not mean that the description is a direct representation of a real physically process. The time constants τ_1 and τ_2 in the circuit shown in **Fig. 4a)** correspond to the **physical dielectric time constants** of the two dielectrics**.** There is no direct physical correspondence in the elements R_s, C_s and τ_s of the RC series-circuit with regard to the different dielectric materials paper and oil, and it is hard to derive any conclusions from their numerical values. Especially the **physically relevant dielectric time constants τ_1 and τ_2** of the insulating materials cannot be calculated from the RC series elements.

To have more possibilities for a numerical fit, usually formal equivalent circuits with three or more RC series elements in parallel are used. The physical correspondence would be two or more Maxwell circuits with different time constants in parallel. This might be necessary for a more sophisticated analysis for the interpretation of measurements performed in **network circuits containing different cables** or joints that behave different. In this case the absolute values of the capacitors in the parallel Maxwell circuits determine the 'dominant' values of the time constants.

Proceedings of the 5th WSEAS Int. Conf. on Power Systems and Electromagnetic Compatibility, Corfu, Greece, August 23-25, 2005 (pp514-521)

Numerical simulations with two Maxwell equivalent circuits in parallel showed the possibility to simulate experimentally found return voltage curves by choosing appropriate numerical values of the elements of the circuits.

Evaluation of the Maxwell equivalent circuit

As a first step the analysis of the results of return voltage measurements can be done on the basis of just one **Maxwell-Model**. After the application of a dc-voltage, the system starts with a capacitive voltage division of the poling voltage $\mathbf{U_p}$ between $\mathbf{U_1}$ and $\mathbf{U_2}$, that gradually changes into an ohmic division in accordance to $\mathbf{R_1}$ and $\mathbf{R_2}$. During the short circuit, charges are exchanged between the two capacitors until the voltages across the capacitors $\mathbf{C_1}$ and $\mathbf{C_2}$ are identical. During short circuit conditions this voltage decreases simultaneously for both capacitors with a time constant τ. After the release of the short circuit the voltages at both capacitors decrease independently with the time constants τ_1 and τ_2. **Fig. 5** shows the voltage changes over time for the different time intervals during the return voltage measurement.

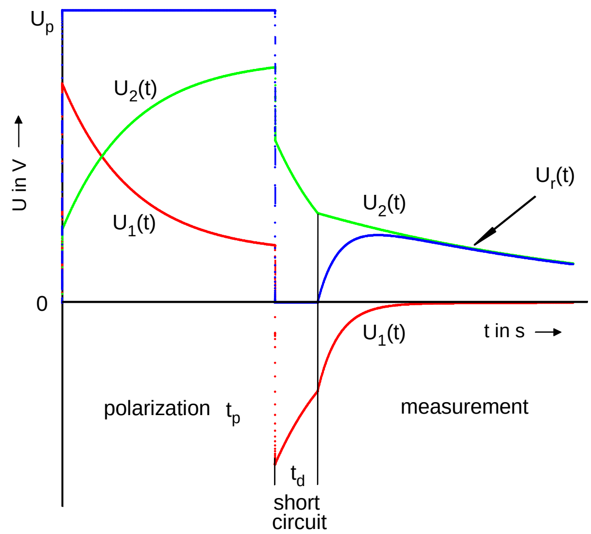

Fig. 5: Voltages across the capacitors $\mathbf{C_1}$ and $\mathbf{C_2}$ during polarization, short circuit and return voltage measurement for $\tau_1 < \tau_2$

The important point for a **meaningful interpretation** of the measured data is the selection of the parameters used for the diagnosis. As mentioned already the parameters usually taken for the diagnosis are the initial incline **s** of the return voltage curve, the maximum $\mathbf{U_m}$ of the return voltage and the time $\mathbf{t_m}$ of this maximum or the dependence of these parameters on the height of the poling voltage $\mathbf{U_p}$.

Empirically a large variation of these parameters is found without a 'straight forward correlation' like a monotonous tendency of the parameters with ageing.

Under the assumption that the resistance $\mathbf{R_m}$ of the voltage measurement system is significantly higher than the resistors $\mathbf{R_1}$ and $\mathbf{R_2}$, the maximum $\mathbf{U_m}$, the initial incline **s** and the time $\mathbf{t_m}$ of the maximum can be easily calculated analytically [13]. For the equivalent circuit shown in Fig. 3 we find:

$$U_r(t) = U_1(t) + U_2(t) = U_s\left(e^{-\frac{t}{\tau_2}} - e^{-\frac{t}{\tau_1}}\right)$$

with $\tau_1 = R_1 C_1,\quad \tau_2 = R_2 C_2$ and $\lambda = \tau_2 / \tau_1$

If $\mathbf{R_m}$ is not considerably larger than $\mathbf{R_1}$ and $\mathbf{R_2}$, the shape of the return voltage curve is also the **sum of two exponential functions**, but – as a consequence of the coupling of the two RC-elements via $\mathbf{R_m}$ – the time constants τ_1' and τ_2' are different from the values $\mathbf{R_1C_1}$ and $\mathbf{R_2C_2}$ [19].

For the voltage across the two capacitors after a poling time $\mathbf{t_p}$ and a short circuit time $\mathbf{t_d}$ we find:

$$U_s = \frac{\lambda - 1}{1 + \lambda + \frac{R_2}{R_1} + \frac{C_2}{C_1}} U_p\left(1 - e^{-t_p/\tau}\right) e^{-t_d/\tau} \quad \text{with}$$

$$\tau = \frac{\tau_2 R_1 + \tau_1 R_2}{R_1 + R_2}$$

τ is the time constant of the system and identical with τ_s in Fig. 4b). Obviously $\mathbf{U_s}$ depends in a complex manner on the elements of the equivalent circuit that are determined by the actual geometry and the dielectric properties of the insulating materials used.

Starting from the **physical ageing processes** in paper-oil dielectrics, due to the chemical degradation processes a decrease of the dielectric time constants τ_1 and τ_2 will occur. Especially τ_2, the time constant of the cellulose, will decrease, because water is generated as a **by-product of the degradation of paper** and accumulated in the cellulose. This leads to a marked decrease of the conductivity and hence the dielectric time constant τ_2 of the paper. Some of the water will be diluted in the oil, but the amount is far less than the amount in the paper. For the equilibrium distribution and further details see [12].

III. Diagnostic parameters

U_m/s over t_m and the p-factor

The classical diagnostic parameters $\mathbf{U_m}$ and **s** contain U_s as a factor and a function of the ratio $\lambda = \tau_2/\tau_1$. The time $\mathbf{t_m}$ of the voltage maximum depends on τ_1 and a function of the factor $\lambda = \tau_2/\tau_1$.

$$U_m = U_s \left(\lambda^{1/(1-\lambda)} - \lambda^{\lambda/(1-\lambda)}\right)$$

$$s = \frac{U_s}{\tau_1}\left(\frac{\lambda-1}{\lambda}\right)$$

$$t_m = \tau_1\left(\frac{\lambda}{\lambda-1}\right)\ln\lambda$$

The ratio $\mathbf{U_m/s}$ does not depend on U_s but only on τ_1 and a function of the factor $\lambda = \tau_2/\tau_1$ Hence geometric influences on the diagnostic parameters disappear.

$$\frac{U_m}{s} = \tau_1 \frac{\lambda}{\lambda-1}\left(\lambda^{1/(1-\lambda)} - \lambda^{\lambda/(1-\lambda)}\right)$$

In addition to the use of the standard plots of $\mathbf{U_r}$ over **t** as a first documentation of the measurement result, a more effective characterization of the results of return voltage measurements can be made by the analysis of the dependence between the two parameters $\mathbf{U_m/s}$ and $\mathbf{t_m}$. Both parameters contain τ_1 and depend only on the ratio $\lambda = \tau_2/\tau_1$. The ratio between the two parameters can be taken as a new parameter **p** [14].

The **p-factor** defined as

$$p = \frac{U_m}{s\,t_m} = \frac{\lambda^{1/(1-\lambda)} - \lambda^{\lambda/(1-\lambda)}}{\ln\lambda}$$

eliminates not only the factor U_s – since **s** is inversely and $\mathbf{t_m}$ is directly proportional to τ_1 – but depends only on the ratio $\lambda = \tau_2/\tau_1$ of the two time constants instead on $\mathbf{R_1}$, $\mathbf{C_1}$, $\mathbf{R_2}$ and $\mathbf{C_2}$ separately. Hence the **p-factor** is not only independent of the geometric dimensions of the two dielectrics but also independent of all parameter changes that influence τ_1 and τ_2 in the same way. This holds - at least in first approximation - e.g. for the influence of the temperature of the measured object. This may be important if measurements performed in different seasons of the year are compared. In addition the **p-factor** is also independent of the height of the poling voltage, because both, **s** and $\mathbf{U_m}$ are proportional to $\mathbf{U_p}$.

Evaluation of the time constants τ_1 and τ_2

A very interesting and unique possibility of the interpretation of the experimental results on the basis of the **Maxwell-Model** is the possibility to use the dependence of $\mathbf{U_m/s}$ on $\mathbf{t_m}$ to calculate the conductivity the **time constants** τ_1 and τ_2 of the two dielectrics in the elements of the equivalent circuit. These time constants are proportional to ε_r / σ (the ratio of the dielectric constant and the specific conductivity) of the dielectrics and are sensitive on changes of the dielectric constant ε_r and σ, whereby for cellulose materials the specific conductivity σ is very sensitive on the contents of water. In the case of paper-oil-insulations one of the main parameters in the ageing process is the **water contents of the paper**, that on one hand **accelerates ageing** and on the other hand **appears as a degradation product**. Hence the ageing process significantly influences the corresponding dielectric time constant.

IV. Analysis of the influence of different parameters

Influence of the ambient temperature

It is known that - like other dielectric measurements - return voltage curves are influenced by the temperature of the measured object, an effect that must be taken care of [15]. **Figs. 6** to **8** show results from three measurements of a cable in different seasons of the year and possibilities for the evaluation of the experimental data. **Fig. 5** shows that the return voltage curve (shown for one core only) was significantly higher in the measurement that was performed in summer. The two curves from the measurements in winter are nearly identical.

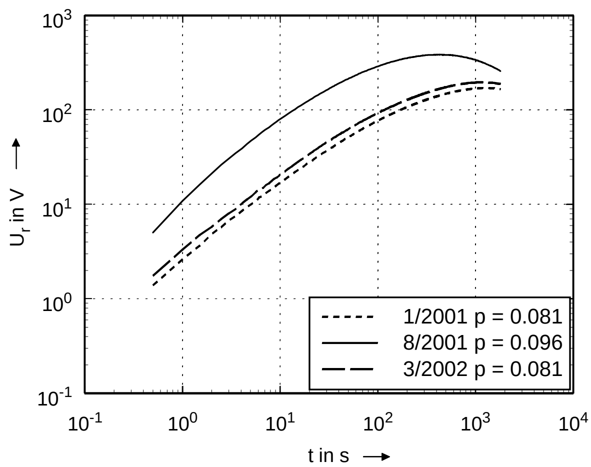

Fig. 6: Return voltage curves of cable DYR for measurements in different seasons of the year

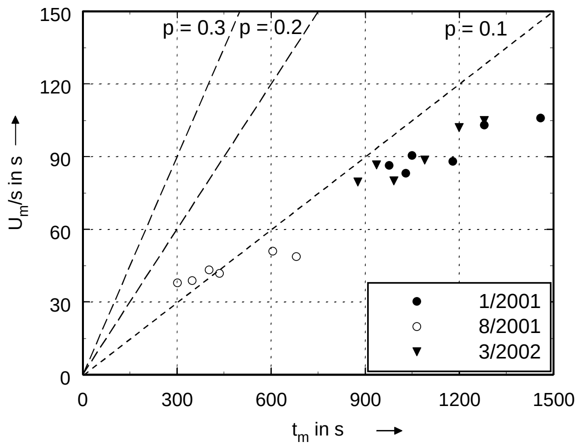

Fig. 7: Dependence of $\mathbf{U_m/s}$ on $\mathbf{t_m}$ for cable DYR measured in different seasons of the year

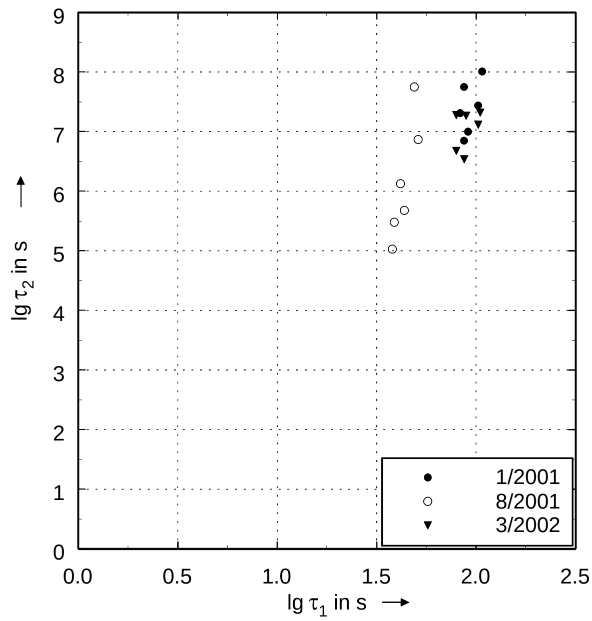

Fig. 8: Time constants τ_1 and τ_2 for cable DYR measured in different seasons of the year (calculated from the data shown in Fig. 6)

The **p-factor** for the measurement in summer was only insignificantly higher than those found in the measurements during the cold season of the year.

Figs. 7 and **8** show the calculated new diagnostic parameters $\mathbf{U_m/s}$, $\mathbf{t_m}$, τ_1 and τ_2 for all three cores. As a result of the higher temperature during summer the dielectric time constants are lower. The comparison of the two winter measurements shows that the time constants had not changed, an indication that during the time interval between the two measurements apparently no ageing had occurred.

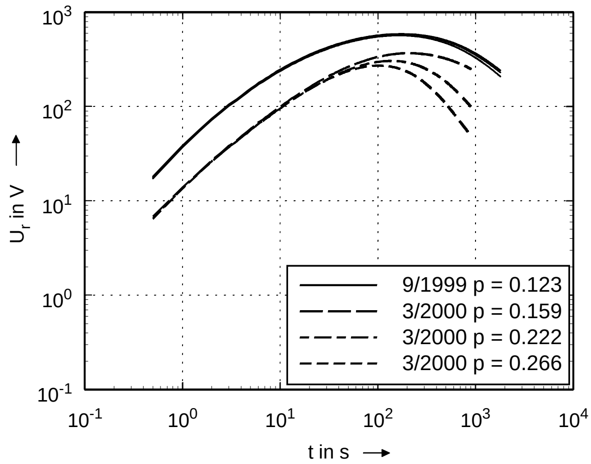

Fig. 9: Return voltage curves of cable GER6 for measurements in different seasons of the year

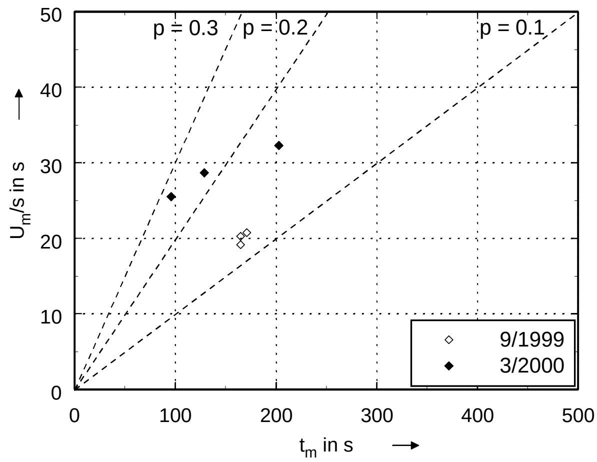

Fig. 10: Dependence of U_m/s on t_m for cable GER6 for measurements in different seasons of the year

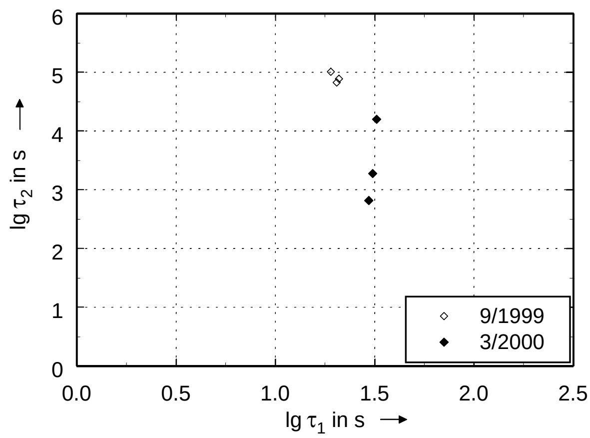

Fig. 11: Time constants τ_1 and τ_2 calculated from the data presented in Fig. 8

Proceedings of the 5th WSEAS Int. Conf. on Power Systems and Electromagnetic Compatibility, Corfu, Greece, August 23-25, 2005 (pp514-521)

Influence of ageing

For another cable the effect of ageing was clearly visible. In the first measurement the three cores showed identical return voltage curves. 6 months later the curves were different (see **Fig. 9**). Additional measurements showed that for two of the three cores the resistance had decreased below **1 GΩ.** The **p-factor had increased** significantly and especially the time constant τ_2 of the 'solid part' of the insulation (the cellulose material) had decreased. **Figs. 10** and **11** show the corresponding data. Interestingly the time constant τ_1 (correlated to the oil) had not changed, while the time constant τ_2 (correlated to the paper) had decreased significantly but differently for the three cores.

Influence of the measurement resistor R_m

As long as the resistance $\mathbf{R_m}$ of the voltage measurement system is significantly higher than the inner resistances of the measured object - symbolized by the resistors $\mathbf{R_1}$ and $\mathbf{R_2}$ in the equivalent circuit - the return voltage curve can be calculated analytically and described as the sum of two exponential functions. If this assumption is not true, $\mathbf{R_m}$ leads to a coupling of the voltages across the two capacitors $\mathbf{C_1}$ and $\mathbf{C_2}$. The initial incline **s** of the voltage curve is not influenced by this effect, but the further shape. Lower resistances $\mathbf{R_m}$ tend to decrease the maximum of the return voltage curve and to shift it to earlier times. **Fig. 12** shows results from measurements of return voltage curves one core of a paper-oil-insulated cable with different measuring resistors $\mathbf{R_m}$ **= 10 GΩ, 5 GΩ** and **2 GΩ**. **Fig. 12** shows the corresponding graph of for the $\mathbf{U_m/s}$ over $\mathbf{t_m}$ plot for all three cores. Interestingly the data points lie on a monotonously increasing curve. **Fig. 14** shows the graph of τ_2 over τ_1. τ_1 is unchanged, τ_2 decreases with decreasing $\mathbf{R_m}$.

Influence of the polarization time

In order to examine the influence of the polarization time on the values of the diagnostic parameters, the measurements displayed in **Fig. 13** and **Fig. 14** have been made with **600**, **900** and **1200 s** polarization time respectively.

The polarization time influences the different parameters differently. The initial incline **s** shows only a minor change, while the voltage maximum $\mathbf{U_m}$ and the time of the maximum $\mathbf{t_m}$ clearly increase with the polarization time $\mathbf{t_p}$. The calculated time constants τ_1 and τ_2 show a negligible influence for τ_1 and a small increase of τ_2 with $\mathbf{t_p}$. In most cases the p-factor shows a small decrease with increasing polarization time.

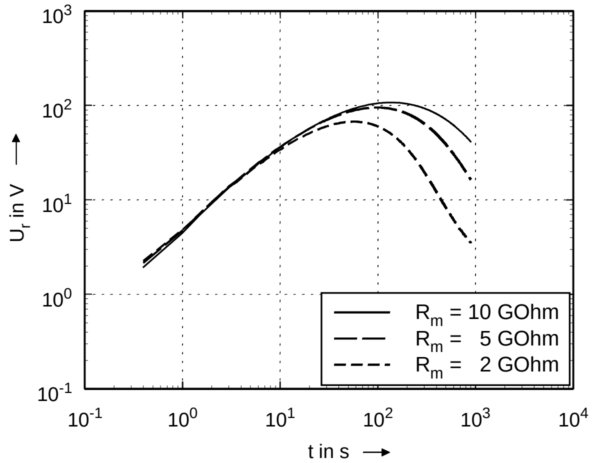

Fig. 12: Return voltage curves of cable S2 for measurements with different measurement resistors

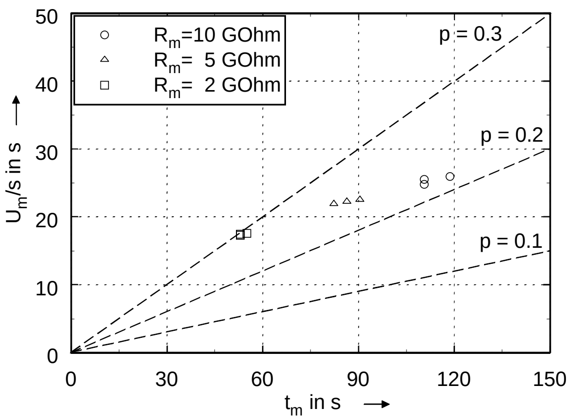

Fig. 13: Dependence of U_m/s on t_m for cable S2 for measurements with different measurement resistances

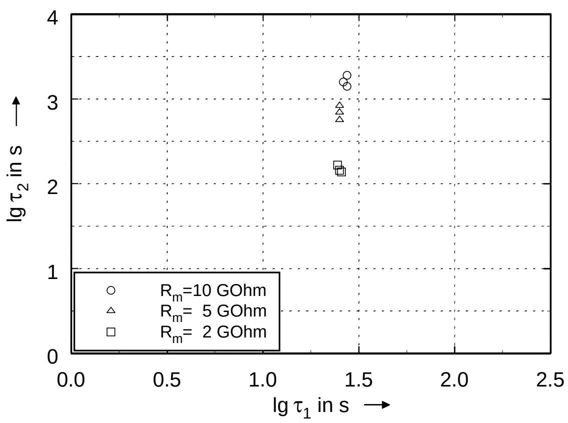

Fig. 14: Time constants τ_1 and τ_2 calculated from data shown in Fig. 12

A practical consequence of the observed minor dependence of relevant parameters on the polarization time is that the total time of the measurement necessary to assess the condition of the cable insulation can be reduced. Practical results show that **15 min** are sufficient in most cases. The changes compared to $\mathbf{t_p = 30}$ **min** are not very significant.

V. Conclusions

The **Return Voltage Method** is capable of detecting changes in the dielectric properties of composite insulations and hence ageing processes in paper-oil insulated medium voltage cables or transformers can be monitored. The application of the Return Voltage Method is possible for all multi layer systems that include insulations with different dielectric properties, and that show the phenomenon of **boundary polarization.** The evaluation of the data on the basis of the Maxwell-Model allows a meaningful interpretation.
The **p-factor** has proven to be a reliable parameter to characterize the ageing of paper-oil insulations. In contrast to other parameters, by the temperature of the measured object the p-factor is only slightly influenced. The evaluation of the correlation between $\mathbf{U_m/s}$ and $\mathbf{t_m}$ can be used to calculate the **dielectric time constants** τ_1 and τ_2 of the insulation materials that are a good indicator for ageing processes or the contents of water in the dielectrics.

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