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Return voltage measurements Diagnostic interpretations based on the dielectric time constants

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Return voltage measurements of paper-oil insulations such as medium voltage cables have proven to be a reliable method to determine the actual state of degradation and/or the humidity of the insulation. As a first step, the interpretation of the measurements can be done based on the *p*-factor. This parameter is sensitive to the dielectric properties and especially the humidity of the solid part of the insulation, whereby aged or humid cables show a higher *p*-factor. The calculation of the dielectric time constants τ_1 and τ_2 of the two insulating materials oil and cellulose is unique for the return voltage method and hence exceeds the information extractable from other diagnostic methods.

Key words: *return voltage; paper-oil insulation; boundary polarization; ageing; Maxwell model; dielectric time constants*

1. Basics of the return voltage method

The principle is known for many years [1–3], the readings are reproducible and reliable, at least with regard to the collection of the data but unfortunately not always with regard to all methods of interpretation. 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., measurements of polarization and depolarization currents [4, 5].

The experimental procedure consists of the following: application of a dc voltage U_p for the time t_p, formation of a short circuit for the time t_d, and measurement of 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 U_m, the time t_m of the voltage peak and the initial incline *s* of the curve. In many cases,

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a linear dependence of the return voltage curve on the height of the poling voltage exists but in some cases a sublinear dependence may indicate some ageing. The *p*-factor defined as

$$p = \frac{U_m}{st_m} \tag{1}$$

does not depend on the height of the poling voltage U_p and is also independent of the geometric parameters of the cable. Ageing and degradation processes increase the *p*-factor.

2. Interpretation of experimental results

The analyses of time dependences of return voltage or of polarization and depolarisation currents are often done by a numerical fit based on equivalent circuits consisting of three or more RC series elements with different time constants in parallel (Fig. 1b shows only one RC-element). This equivalent circuit is physically adequate for the description of atomic polarization processes in insulating materials, namely for molecules with different polarizabilities. For other processes such as e.g., the built-up of space charges or boundary polarization processes such an equivalent circuit is just a tool for a formal mathematical fit without any correspondence to physical parameters.

3. Dielectric behaviour of a multilayer insulation

The insulation of classic power equipment such as oil filled power transformers or cables 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 different dielectrics.

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 and the necessary correlations between the electric fields at both sides of the interface.

After removal of the poling voltage, during the short circuit an instantaneous release of the charges at the external electrodes takes place and the charges accumulated at the inner boundaries 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, passes 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 of compound insulations during return voltage measurements.

4. 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 [6]. Figure 1a shows the basic equivalent circuit. This circuit is in good correspondence with a physical model discussed in the literature for power equipment with paper-oil insulation [7].

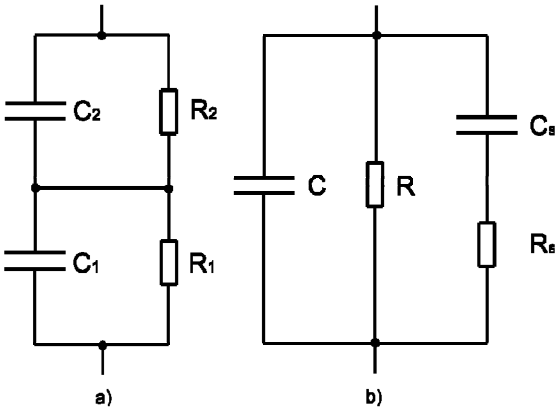

Fig. 1. Equivalent circuits to describe return voltage curves:
a) physically relevant model, b) formal equivalent circuit

The equivalent circuit in accordance to the Maxwell model can be transformed into the commonly used equivalent circuit with RC series elements that is commonly used to describe molecular polarization processes. If the measured specimen consists of two parts connected in parallel, as e.g. a cable length consisting of two parts with different properties, two Maxwell circuits in parallel must be used for the description. In the formal equivalent circuit, a second RC series element is necessary.

Both equivalent circuits shown in Fig. 1 are able to describe the return voltage curves. They can be transformed into each other [8]

$$C = \frac{C_1 C_2}{C_1 + C_2}, \qquad R = R_1 + R_2 \tag{2}$$

$$C_s = \frac{(R_2 C_2 - R_1 C_1)^2}{(R_1 + R_2)^2 (C_1 + C_2)} \tag{3}$$

$$R_s = \frac{R_1 R_2 (R_1 + R_2)(C_1 + C_2)^2}{(R_2 C_2 - R_1 C_1)^2} \tag{4}$$

$$\tau_s = \frac{R_1 R_2 (C_1 + C_2)}{R_1 + R_2} \tag{5}$$

The two equivalent circuits can be used for basic discussions, e.g. with regard to the influence of the measuring resistance R_m or the influence of a parallel capacitance C_m. The time constant τ_s of the RC series element equals the time constant τ of the Maxwell equivalent circuit during polarization or under short circuit conditions.

According to the Maxwell model, the shape of the return voltage curve $U_r(t)$ can be calculated analytically and (neglecting the influence of R_m at the moment) is given by

$$U_r(t) = U_s \left(\mathrm{e}^{-t/\tau_2} - \mathrm{e}^{-t/\tau_1} \right) \tag{6}$$

U_s is the voltage over C_1 and C_2 immediately after the release of the short circuit being influenced by the polarization voltage U_p, the elements R_1, R_2, C_1 and C_2 of the equivalent circuit the time of polarization t_p and the time of short circuit

$$U_s = \frac{\lambda - 1}{1 + \lambda + \frac{R_2}{R_1} + \frac{C_2}{C_1}}, \qquad U_p \left(1 - \mathrm{e}^{-t_p/\tau} \right) \mathrm{e}^{-t_d/\tau} \tag{7}$$

with

$$\tau = \frac{\tau_2 R_1 + \tau_1 R_2}{R_1 + R_2} \tag{8}$$

The time constants $\tau_2 = R_2 C_2$ and $\tau_1 = R_1 C_1$ of the two RC parallel elements in the equivalent circuit correspond to the physical dielectric time constants $\tau_i = \rho_i \varepsilon_i \varepsilon_0$ of the two dielectrics cellulose ($i = 2$) and oil ($i = 1$) [9] and R_m is the resistance of the measuring circuit. The correspondence of the elements in the equivalent circuit and the physical properties of the real dielectric in the measured object is obvious. The inner resistance R_p of the insulation or any other parasitic resistances at splices or terminations behave in the same way.

5. Parameters used for RVM evaluation

The three basic parameters used for the evaluation of return voltage measurements can be calculated analytically. The diagnostic parameters s and U_m contain U_s as a factor and are consequently influenced by the geometric dimensions of the object under test. The time t_m of the voltage maximum depends only on the ratio $\lambda = \tau_2/\tau_1$ and the time constant τ_1

$$U_m = U_s \left(\lambda^{1/(1-\lambda)} - \lambda^{\lambda/(1-\lambda)}\right) \tag{9}$$

$$s = \frac{U_s}{\tau_1}\left(\frac{\lambda-1}{\lambda}\right) \tag{10}$$

$$t_m = \tau_1\left(\frac{\lambda}{\lambda-1}\right)\ln\lambda \tag{11}$$

The ratio U_m/s does not depend on U_s but only on τ_1 and the ratio $\lambda = \tau_2/\tau_1$

$$\frac{U_m}{s} = \tau_1\frac{\lambda}{\lambda-1}\left(\lambda^{1/(1-\lambda)} - \lambda^{\lambda/(1-\lambda)}\right) \tag{12}$$

In addition to the use of the standard plots of U_r over t as a first documentation of the results measurements, a more effective characterization of the results of return voltage measurements can be made by the analysis of the dependence between the two parameters U_m/s and 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 λ [10].

The p-factor defined as

$$p = \frac{U_m}{st_m} = \frac{\lambda^{1/(1-\lambda)} - \lambda^{\lambda/(1-\lambda)}}{\ln\lambda} \tag{13}$$

eliminates not only the factor U_s but also τ_1, since s is inversely and t_m is directly proportional to τ_1. p depends only on the ratio $\lambda = \tau_2/\tau_1$ of the two time constants instead of R_1, C_1, R_2 and 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 [11]. In addition the p-factor is also independent of the height of the polarization voltage, because both, s and U_m are proportional to U_p. On the other hand, if p changes with the polarization voltage this is an indication of field dependent conductivities in the dielectrics, possibly as a consequence of ageing processes.

6. Evaluation of τ_1 and τ_2

A very interesting and unique possibility of the interpretation of the experimental results based on the Maxwell model is the possibility to use the dependence of U_m/s on

t_m to calculate the time constants τ_1 and τ_2 of the two RC elements of the equivalent circuit in Fig. 2. These time constants are characteristic of the two dielectrics paper and oil in the cable, and – important for application of the method in the field – they do not depend on the actual geometry of the specimen, i.e. neither the cable length nor the cross section of the conductor or the insulation thickness are of importance.

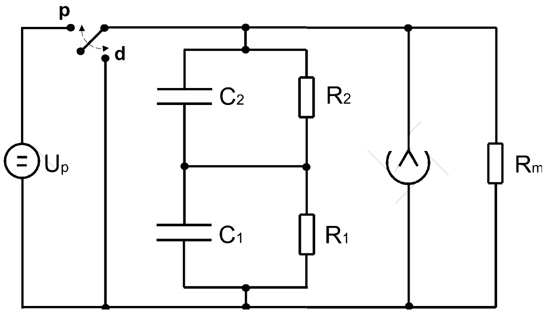

Fig. 2. Equivalent circuit of a paper-oil-dielectric with $\tau_2 = R_2C_2$ and $\tau_1 = R_1C_1$ and a basic measuring circuit

For an insulating material, the dielectric time constant τ is proportional to $\rho\varepsilon$, the product of the specific resistance ρ and the relative permittivity ε. The time constant is sensitive to changes of ρ and ε, whereby for cellulose materials the specific resistance ρ is very sensitive to the content of water. In the case of paper-oil insulations, one of the main parameters in the ageing process is the water content 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 τ_2.

By use of the Eqs. (13) and (11) it is possible to calculate the time constants τ_2 and τ_1 directly from the experimental parameters U_m, t_m and s. The time constants are per definition independent of the specimen geometry and thus characterize directly the dielectric properties of the two insulating materials – paper and oil.

7. Influence of the measuring resistor

For short lengths of cables in very good condition a complication may arise. This is the case if the input resistance R_m of the measuring system is of the same size as the leakage resistance of the measured object, or – in terms of the equivalent circuit – comes into the region of values of the resistors R_1 and R_2. In this case, the influence of the additional resistor R_m cannot be neglected. The analysis shows that in this case the type of the return voltage curve indicated in Eq. (1) remains, but the time constants τ_1 and τ_2 are changed. Instead of τ_1 and τ_2, effective time constants τ_1' and τ_2' must be used and also different elements in the equivalent circuit.

The resistor R_m influences τ_1 and τ_2 but not U_s. The quantitative influence of this resistance can be calculated analytically. Equations (14)–(17) show the correlations

$$U_r(t) = U_s\left(\mathrm{e}^{-t/\tau_2'} - \mathrm{e}^{-t/\tau_1'}\right) \tag{14}$$

$$\tau_2' = \left(\alpha - \sqrt{\alpha^2 - \beta}\right)^{-1}$$
$$\tau_1' = \left(\alpha + \sqrt{\alpha^2 - \beta}\right)^{-1} \tag{15}$$

$$\alpha = \frac{1}{2}\left[\frac{\tau_1(R_2 + R_m) + \tau_2(R_1 + R_m)}{\tau_1\tau_2 R_m}\right] \tag{16}$$

$$\beta = \frac{(R_1 + R_2 + R_m)}{\tau_1\tau_2 R_m} \tag{17}$$

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

8. Measurements in the field

In dependence on the actual structure of the distribution network, various lengths of cable segments are to be measured and hence the capacitance C_p and the resistance R_p of the measured cable sections are different.

In principle, the return voltage curve does not depend on the length of a measured cable, because every part of the cable contributes with a certain amount of current from the depolarization processes, whereby the current per length of the cable is constant. This current charges the cable and since the capacitance C_p of the measured cable is also proportional to its length, no dependence of the return voltage curve on the length of the cable should occur.

The measurement resistor R_m of the measurement system leads to a discharge of the cable capacitance C_p and hence may influence the real return voltage curve. A characteristic parameter to describe this influence is the time constant $\tau_m = C_pR_m$ of the system. If this time constant is significantly higher than the time t_m at which the maximum of the return voltage occurs, the influence of R_m can be neglected.

If the time constant $\tau_m = C_pR_m$ is in the same region or smaller than the time constants τ_1 and τ_2 in Figure 2 there is an influence of the measurement procedure on the experimentally found return voltage curve. It is obvious that the shorter the cable is, the more pronounced the influence of R_m may be. Hence the p-factor calculated from the return voltage curve may be higher as a consequence of the measurement resistor, thus indicating a higher degradation of the cable.

To evaluate the influence of the measurement resistor R_m, experiments were performed with cables of various lengths and with various measurement resistors. The results show that the explanation given is relevant. In one set of experiments, three cores L1, L2 and L3 of a cable of 150 m long were measured with measuring resistors of 12 and 42 GΩ. In some measurements, two or three cores of the cable were measured in parallel, thus forming specimens with different lengths. The results are shown in Fig. 3. The curves from the three cores are very similar. The measurement of core L1 alone with 42 GΩ generates nearly the same curve as the measurement of L1 || L2 || L3 with 12 GΩ, a result that verifies the influence of the time constant $\tau_m = C_pR_m$. Cores L2 and L3 in parallel show a slightly higher return voltage curve. In this case even with a measurement resistor of 42 GΩ a small dependence on the length of the measured object exists.

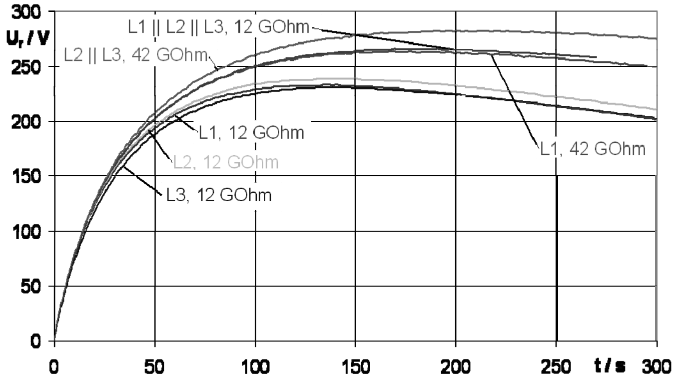

Fig. 3. Return voltage curves from measurements of three cores L1, L2 and L3 of a 150 m long cable (GA9) with various measuring resistors

Another set of measurements was performed with a cable 1300 m long. This cable was measured with resistors of 2 and 12 GΩ. Also in this case single cores or two or three cores in parallel were measured. The results are shown in Fig. 4. The dependence found is similar as the aforementioned.

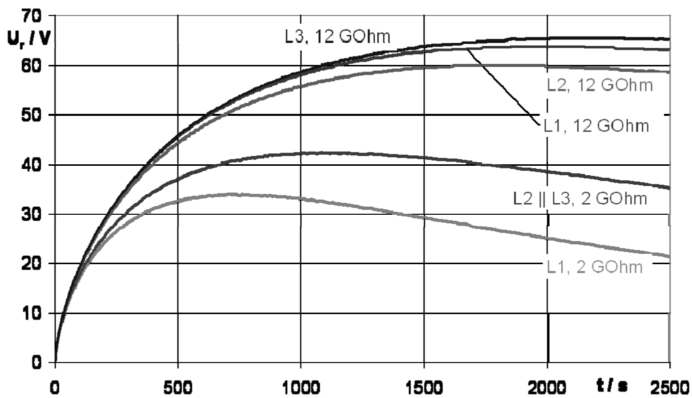

Fig. 4. Return voltage curves from measurements of three cores L1, L2 and L3 of a 1300 m long cable (TOR) with various measuring resistors

For another cable with the length of 330 m (HEI) measurements were performed using measuring resistors of 12 and 62 GΩ. Due to the influence of the measurement resistor, in the measurement with 12 GΩ a slightly higher *p*-factors were found.

The measurements with 62 GΩ showed no length dependence of the *p*-factors and the calculated dielectric time constants. The comparison of the measurements of L1, L1 || L2 and all three cores in parallel showed values that were to be expected with respect to the separate measurements of the three cores. Table 1 shows the *p*-factors and the dielectric time constants calculated from the aforementioned measurement data.

Table 1. *p*-Factors and electric permittivities for the measurements of cable HEI (3 cores of 330 m each) with various measuring resistors and for various circuits

12 GΩ	L1	L2	L3
U_m [*V*]	35.6	36.86	47.39
t_m [s]	312	331	325
s [V/s]	0.672	0.725	0.771
p	0.170	0.154	0.189
lg τ_2 [s]	4.24	4.50	4.01
lg τ_1 [s]	1.73	1.71	1.80
62 GΩ	L1	L2	L3
U_m [V]	33.0	38.2	60.5
t_m [s]	329	405	405
s [V [s]	0.671	0.759	0.892
p	0.150	0.124	0.167
lg τ_2 [s]	4.56	5.19	4.38
lg τ_1 [s]	1.70	1.70	1.84
62 GΩ	L1 || L2	L3	L1 || L2 || L3
U_m [V]	36.8	57.6	41.4
t_m [s]	371	417	373
s [V/s]	0.701	0.908	0.717
p	0.142	0.152	0.155
lg τ_2 [s]	4.77	4.63	4.53
lg τ_1 [s]	1.72	1.81	1.77

The time constants τ_1 were about 50 s in all cases. For the measurements of one, two or three cores with 62 GΩ no length dependence was found. The measurements of parallel circuits showed dielectric time constants compatible to the results of single measurements of the cores. Figure 5 shows the calculated dielectric time constants τ_1 and τ_2 for the measurements of different parallel circuits of the three cores with 62 GΩ.

Whether the measurement resistor R_m has an influence on the measured results depends on the 'quality' of the measured object. If the measurement resistor is significantly higher than the over all resistance R_p of the insulation of the measured cable (including all splices, terminations, etc.) the return voltage curve is not significantly influenced.

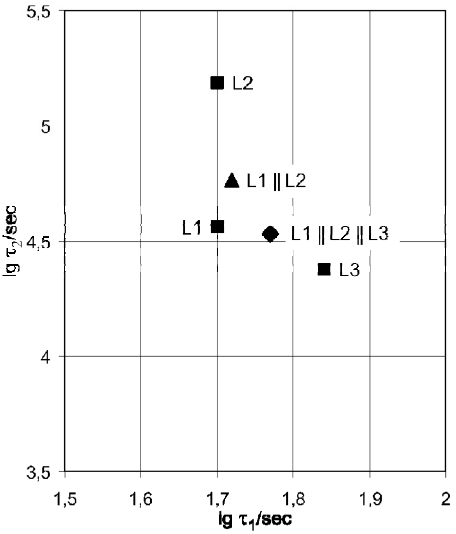

Fig. 5. Dielectric time constants τ_1 and τ_2 for the measurements with 62 GΩ (selection from Table 1)

In general shorter cable lengths tend to show higher p-factors and lower time constants τ_2, but this is not always the case. Different cables of similar lengths often show different p-factors and different time constants τ_2 thus allowing a relative ranking.

Measurements of cables in one utility showed no influence of the cable lengths at all. In this case, it showed up that the cables in general showed a high degree of degradation, so – even for low lengths of the cables – the inner resistances R_p of the cables were significantly smaller than the measuring resistor R_m.

9. Further experience from the field

Similar to other diagnostic methods, return voltage measurements in various seasons of the year may show different results. Figure 6 and Table 2 show the results from three measurements within 14 months. Compared to the measurement in winter, as a consequence of the higher temperature of the soil around the cable, the measurement in summer resulted in lower dielectric time constants for paper and oil. The second measurement in the cold season showed that no ageing had occurred, the dielectric time constants were the same as 14 months before.

The ageing processes in a cable in general lead to a decrease of the resistance of the cellulose. The same holds for an uptake of water in the cellulose, whereby water on one hand accelerates the degradation of the cellulose and on the other hand it also occurs as a degradation product. Thus ageing will result in a decrease of the time constant τ_2 of the cellulose. The time constant τ_1 of the oil will be influenced only to a less extent.

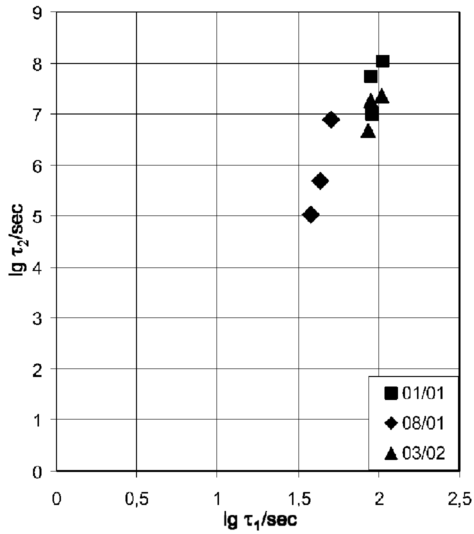

Fig. 6. Dielectric time constants for measurements of cable DYR in various seasons of the year (see Table 2)

Table 2. p-Factors and electric permittivities for various measurements of the three cores of cable DYR

	L1	L2	L3
1 January			
U_m [V]	171	192	167
t_m [s]	1178	1463	1052
s [V/s]	1.94	1.82	1.84
p	0.075	0.073	0.086
$\lg \tau_2$ [s]	7.74	8.03	7.01
$\lg \tau_1$ [s]	1.95	2.02	1.96
1 August			
U_m [V]	387	449	343
t_m [s]	403	606	302
s [V/s]	8.96	8.82	9.04
p	0.107	0.084	0.126
$\lg \tau_2$ [s]	5.68	6.88	5.03
$\lg \tau_1$ [s]	1.64	1.71	1.58
1 March			
U_m/V	197	220	181
t_m [s]	1087	1283	937
s [V/s]	2.22	2.10	2.10
p	0.082	0.082	0.092
$\lg \tau_2$ [s]	7.27	7.36	6.69
$\lg \tau_1$ [s]	1.95	2.02	1.94

The described ageing processes have been found also in practice. Figure 7 shows the results of two measurements of a cable in different seasons of the year. In this case the first measurement was performed in summer. The measurement 6 months later expectedly showed higher time constants τ_1 of the oil. Interestingly the time constants τ_2 of the cellulose had decreased. The ageing of the cores during the time interval between the two measurements was different (see Table 3). The *p*-factors showed corresponding changes.

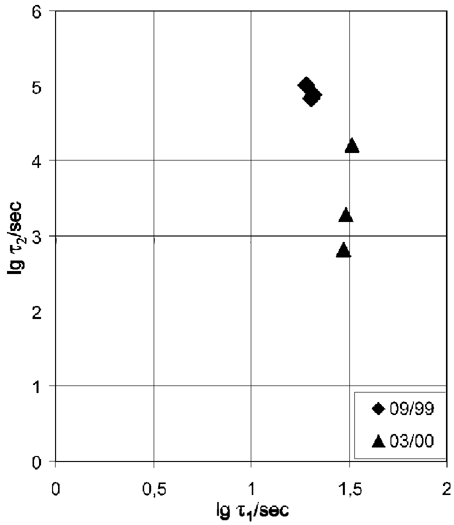

Fig. 7. Change of the dielectric time constants as a consequence of ageing during 6 months (Table 3)

Table 3. *p*-Factors and electric permittivities for the measurements of three cores of cable GER6 in various seasons of the year

	L1	L2	L3
September 1999			
U_m [V]	569	590	590
t_m [s]	165	165	171
s [V/s]	29.7	29.1	28.4
p	0.116	0.123	0.121
$\lg\tau_2$ [s]	5.02	4.83	4.89
$\lg\tau_1$ [s]	1.28	1.31	1.32
March 2000			
U_m [V]	306	273	370
t_m [s]	129	96	203
s [V/s]	10.7	10.7	11.5
p	0.222	0.266	0.159
$\lg\tau_2$ [s]	3.29	2.82	4.21
$\lg\tau_1$ [s]	1.49	1.47	1.51

In a set of measurements in one utility, the cables measured showed the general tendency that – for cables of lengths below a few hundred meters – the *p*-factors increased with decreasing lengths. But nevertheless even in this dataset, cables of nearly identical lengths showed significantly different p-factors, indicating different degradations. Measurements of cables in another utility showed no influence of the cable lengths. For these cables with a higher degree of degradation the influence of the measuring resistor was not relevant even for lengths of about 100 m [12].

10. Summary

In dependence on the actual condition of a cable examined with the return voltage method the diagnostic result may be influenced by the actual length of the cable. The calculated p-factor of short cable lengths may be higher than representative for the degree of degradation, indicating a more severe degree of ageing. This influence can be overcome by the use of higher measuring resistors or by an appropriate correction of the measured data.

Based on the Maxwell model, an appropriate concept for the description of the phenomena that occur in a paper-oil insulation, return voltage curves can be used to calculate the dielectric time constants τ_1 and τ_2 of the two dielectrics oil and paper. Ageing and degradation of the insulation significantly reduces the time constant τ_2 of the cellulose.

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