

The Computing of the Influence of a Steady Element on the Polarization Spectrum

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This paper describes computation of the influence of a steady current element on the current response of insulation material. The steady element is always present. When the insulation is dry, it can be neglected. When moisture is present, the steady element has to be calculated. A decision can be made after examining the spectrum.

Keywords: polarization spectrum, insulation system, current response, time of stabilization, steady element.

1 Introduction

The insulation strength of a material can be scanned only by observing the changes in the electro-physical structure of the material without destroying it. The breakdown voltage can only be determined by performing an electrical strength test. This is a destructive test on an insulation system made of solid material. This test is not suitable for service conditions [1].

The relations between the quantities are evident. Changes in material structure due to service ageing necessarily change the material properties and electrical strength. In this way the determination of quantities closely connected to an electro-physical structure requires the quality of the material to be specified [2].

Many evaluation methods can be used to determine the state of an insulation material. There is no single method at present that can provide a full description. A set of methods has to be used. Some of them involve observing the polarization spectrum. As Fig. 1 shows, the polarization spectrum is quite wide.

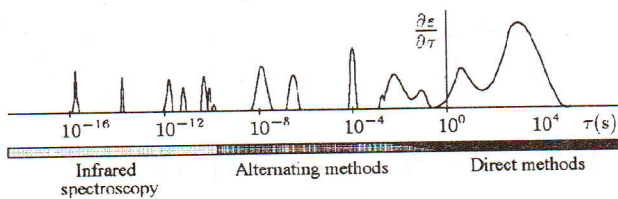


Fig. 1: Common polarization spectrum

The available methods range from infrared spectroscopy to direct methods. Most information can be found between 10^{-4} s and 10^{+5} s. This is the field where current or voltage responses can be observed mainly. There are two ways to access the polarization spectrum [3].

2 Two ways of accessing the polarization spectrum

The area of interest is in the range between 10^{-4} s and 10^{+5} s. We decided to monitor the polarization spectrum by means of current responses. Absorptive or resorptive current is a macroscopic exhibition of the polarization processes inside the material [4].

2.1 Macroscopic exhibition

Analysis of the polarization spectrum of the insulating material is nowadays based on measuring the charging and discharging processes [5].

A method based on applying direct voltage will be described below. Direct methods are based on observing current or voltage time responses. Well-known methods are polarization indices, absorptive or resorptive current analysis, recovery voltage or self-discharge analysis. There is no problem with power supply, as in the case of the alternating diagnostic method. For example, when measuring a capacitive object with a capacity of 10 nF and applied voltage 10 kV the requisite current is about 100 mA. A powerful supply is needed.

When applying external direct voltage forming an internal electrical field inside the material, the total current shown in Fig. 2 consists of the following components. While charging with direct voltage current from the geometrical capacity, absorptive and steady current are present. After some time the material is discharged, but only two currents are present – resorptive current and current from the geometrical capacity. Steady current is not present because there is no external electrical field.

$$i_t(t) = i_c(t) + i_s + i_a(t) \quad (1)$$

$i_t(t)$ total current,
 $i_c(t)$ geometrical capacity current,
 $i_a(t)$ absorption current,
 i_s steady current.

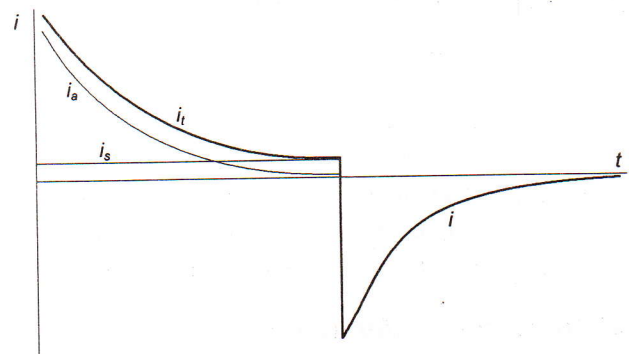


Fig. 2: Total current during charging and discharging

Geometrical capacity current is so quick (about 10^{-12} s) that it cannot be neglected. Then the total current can be described as:

$$i_t(t) = i_s + i_a(t) \quad (2)$$

For a macroscopic description of current responses the equivalent Maxwell–Wagner model can be used for dielectric materials. The equivalent model of the insulating material shown in Fig. 3 is based on n independent Debye polarization processes. Each process has its own time constant of stabilization τ_i and maximum of elementary current I_{mi} , and by observing its changes we can obtain information about the state of the insulation system.

$$i_t(t) = i_s + \sum_{i=1}^n I_{mi} \exp\left(\frac{-t}{\tau_i}\right) \quad (3)$$

The values of the R and C elements of the model are calculated from the observed absorptive or resorptive currents. They represent time independent elements – steady current i_s and time dependent polarization element $i_a(t)$. The principle of analysis is described by following equations:

$$i_s = \frac{U_0}{R_0} \quad (4)$$

$$I_{mi} = \frac{U_i}{R_i} \quad (5)$$

$$\tau_i = R_i \cdot C_i \quad (6)$$

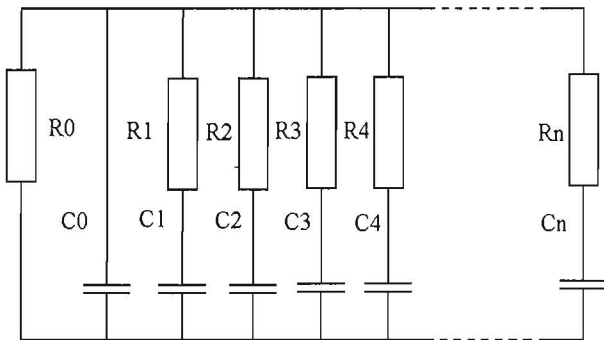


Fig. 3: Maxwell–Wagner equivalent model for dielectric materials

In the past the polarization spectrum of an insulation material was scanned only by polarization indices. These are described very easily as a ratio of observing absorptive or resorptive currents at a determined time. One-minute and 10-minute polarization indices are normally used.

$$p_1 = \frac{I_{15}}{I_{60}} \quad (7)$$

$$p_{10} = \frac{I_{60}}{I_{600}}, \quad (8)$$

where I_{15} magnitude of observing current at 15 s,
 I_{60} magnitude of observing current at 60 s,
 I_{600} magnitude of observing current at 600 s.

2.2 Microscopic exhibition

Basic background information can be found in works of Simmons, Tamm and Ewers [6]. The probability of the emis-

sion of negative charges from the trapping level with activation energy

$$W_T = W_L - W_H \quad (9)$$

W_L energy of low conduction level,

W_T activation energy for charge emission from trapping level,

W_H energy of trapping level.

The observing current for a surface unit is

$$i_N(t) \cdot t = \frac{q \cdot d \cdot k \cdot T}{2} \cdot \Gamma(W) \cdot V(W) \quad (10)$$

$\Gamma(W)$ initialization of occupation of trapping level,

$V(W)$ energy spectrum of trapping levels,

q charge,

d thickness of sample,

k Boltzmann's constant,

T temperature.

W_H is time dependent because while occupying the energy level it retreats from the conducting level. $W_T(t)$ is directly proportional to time.

$$W_T = W_L - W_H = k \cdot T \cdot \ln(v \cdot t) \quad (11)$$

$$\Gamma(W) \cdot V(W) = \frac{2}{q \cdot d \cdot k \cdot T} \cdot t \cdot \left[I_0 + \sum_{i=1}^n a_i \cdot e^{-\frac{t}{\tau_i}} \right] \quad (12)$$

As we can see, the result is equation (12) with the steady state element in brackets I_0 that represents the steady current i_s from equation (3) or element $\frac{U_0}{R_0}$ from equation (4). Ele-

ment $\sum_{i=1}^n a_i \cdot e^{-\frac{t}{\tau_i}}$ represents the absorption current $i_a(t)$ from equation (2) or it is identical with the element from equation (3).

The conclusion is that macroscopic and microscopic views of the polarization processes when applying direct voltage lead to the same results.

3 Influence of steady current

Calculating the stabilization times of Debye independent polarization processes is one way to test the state of the insulation system. Another way to observe the polarization spectrum is transform the current response to the frequency domain.

The idea was to observe the influence of the steady element in the polarization current on two occasions. First, there were the modeling data. If the data is prepared in an artificial mode, the exact value of any element from equation (3) is known. This enables a correct comparison of the results obtained from calculations with the artificial input data [7]. The data sets were prepared with and without the steady element, and the calculations were also done with two modes – calculation when the steady elements were present and also when they were not present.

Table 1 shows the components of the artificial data. Seven elements were selected on the basis of our knowledge. For one set the steady element was added.

Table 1: Components of artificial data

		<i>i</i> -th element	steady	1	2	3	4	5	6	7
Model 0	without steady	τ_i [s]		0.1	0.5	1	5	10	50	100
		I_{mi} [pA]	0	100000	50000	10000	5000	1000	500	100
Model 1	with steady	τ_i [s]		0.1	0.5	1	5	10	50	100
		I_{mi} [pA]	10	100000	50000	10000	5000	1000	500	100

As is shown in Table 1, model 1 is the same as model 0, except that the steady element is added for amplitude 10 pA. This allows a very strict distinction of differences between the two models as the influence of the DC component.

Both models were analyzed with two modes of calculation. First, without the presence of the DC component (model 0 and model 1) two data sets were achieved. Then the same mode of calculation was performed, but with the presence of the DC component.

It is not easy to perform the calculation. It is virtually impossible to calculate seven elements directly. The computation process is very unstable and it is very sensitive to the initial conditions. A better way is to compute only one element first. This means that the total current will be replaced by a single polarization process. This process is represented by one element from equation (3), where parameter $n = 1$. DC elements may or may not be present. Then another element is added and the calculation is repeated. The result

replaces the total current with two elementary polarization processes (in the macroscopic mode there are two elementary current responses). Then more elements are added until all seven elements are used in the calculation.

The results are shown in Fig. 4. It shows the data for model 0 and also the artificial data. There is only one elementary process in the calculation. The calculation is done without the steady element. There are large differences between them. Fig. 5 shows the same situation, except that the seven polarization processes are present in the computation. It is hard to distinguish between the artificial data and the data achieved from modeling according to equation (3).

The situation is practically the same when the steady element is present in the calculation.

For one element the error is large, and for seven elements the calculation and the artificial data are the same. The conclusion is evident and no more results are needed.

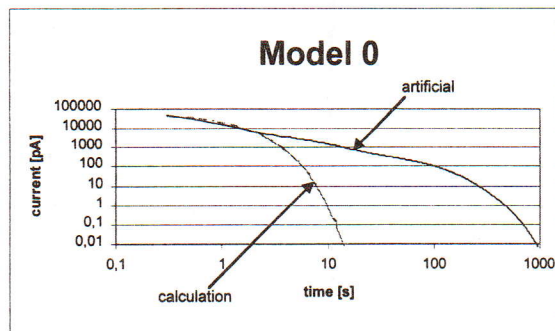


Fig. 4: One element

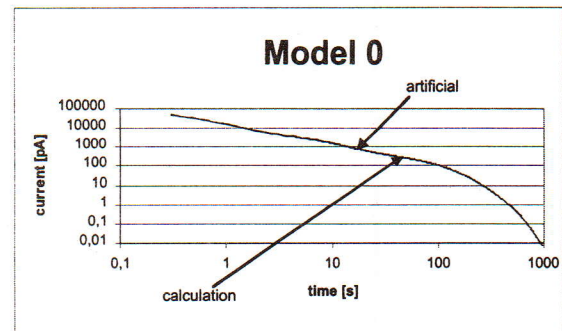


Fig. 5: Seven elements

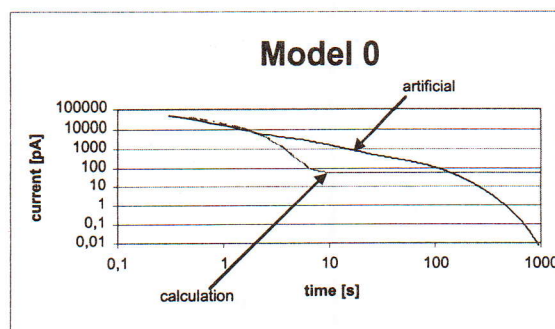


Fig. 6: One element

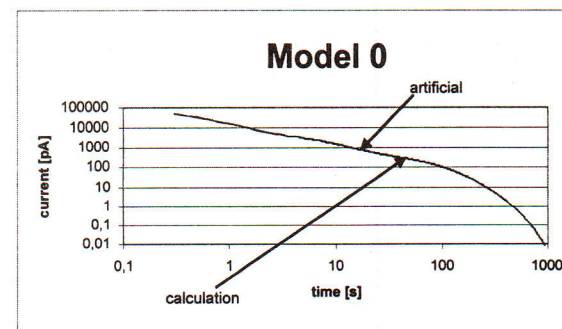


Fig. 7: Seven elements

Table 2: Results of the computation

No. of elements	Element	Model 0		Model 1		Real cable	
		With steady	Without steady	With steady	Without steady	With steady	Without steady
1	I_{m1}	59408	59239	59408	59207	891.00	290
	I_0	54		64		223.00	
	τ_1	0.87	0.88	0.87	0.88	13.56	2281.65
2	I_{m1}	69528	69441	69528	69401	1112.00	922
	I_{m2}	6030	5927	6030	5880	406.00	241
	I_0	22		32		220.00	
	τ_1	0.53	0.54	0.53	0.54	2.78	11.86
	τ_2	8.06	8.33	8.06	8.47	30.66	7112.8
3	I_{m1}	70462	70461	70462	70454	1094.00	1110
	I_{m2}	7861	7841	7861	7775	443.00	427
	I_{m3}	876	857	876	800	63.00	228
	I_0	3		13		218.00	
	τ_1	0.48	0.48	0.48	0.48	2.26	2.59
	τ_2	4.26	4.3	4.26	4.43	20.04	27.43
	τ_3	43.13	44.64	43.13	49.88	97.41	16979.8
4	I_{m1}	48763	48748	48763	48740	1016.00	1066
	I_{m2}	45562	45411	45562	44182	316.00	380
	I_{m3}	5996	5987	5996	5915	303.00	178
	I_{m4}	659	653	659	609	20.00	224
	I_0	1		11		217.00	
	τ_1	0.2	0.2	0.2	0.21	1.89	2.06
	τ_2	0.66	0.66	0.66	0.67	8.74	13.93
	τ_3	5.6	5.63	5.6	5.8	31.48	46.24
	τ_4	53.81	54.7	53.81	61.87	233.06	27466.08
5	I_{m1}	58560	57487	58560	48829	908.00	1018
	I_{m2}	52723	52505	52723	46075	319.00	278
	I_{m3}	3778	3882	3778	6025	320.00	311
	I_{m4}	4010	3759	4010	677	113.00	39
	I_{m5}	580	571	580	21	13.00	222
	I_0	1		11		216.00	
	τ_1	0.14	0.14	0.14	0.2	1.71	1.91
	τ_2	0.58	0.58	0.58	0.65	5.01	8.35
	τ_3	2.63	2.82	2.63	5.52	20.18	27.41
	τ_4	7.02	7.23	7.02	50.3	49.53	94.51
	τ_5	58.82	59.8	58.82	965.32	389.13	39793.24

No. of elements	Element	Model 0		Model 1		Real cable	
		With steady	Without steady	With steady	Without steady	With steady	Without steady
6	I_{m1}	127229	84099	127229	58626		
	I_{m2}	50355	52594	50355	52742		
	I_{m3}	10631	6551	10631	3764		
	I_{m4}	5532	5425	5532	4043		
	I_{m5}	451	400	451	581		
	I_{m6}	460	407	460	11		
	I_0	0		10			
	τ_1	0.09	0.11	0.09	0.14		
	τ_2	0.49	0.52	0.49	0.58		
	τ_3	1.01	1.23	1.01	2.61		
	τ_4	5.44	5.66	5.44	6.99		
	τ_5	19.46	24.84	19.46	58.58		
	τ_6	66.14	69.64	66.14	18579.76		
7	I_{m1}	98535	100003	98535	91222		
	I_{m2}	50309	50000	50309	52003		
	I_{m3}	9625	10000	9625	8415		
	I_{m4}	5074	5000	5074	5434		
	I_{m5}	895	1000	895	577		
	I_{m6}	496	500	496	104		
	I_{m7}	102	100	102	10		
	I_0	0		10			
	τ_1	0.1	0.1	0.1	0.1		
	τ_2	0.5	0.5	0.5	0.51		
	τ_3	1.02	1	1.02	1.16		
	τ_4	5.07	5	5.07	5.89		
	τ_5	10.36	10	10.36	44.92		
	τ_6	50.12	50	50.12	107.03		
τ_7	99.5	100	99.5	268880			

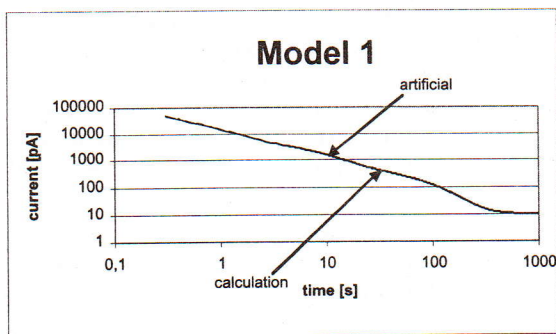


Fig. 8: Calculation without steady element

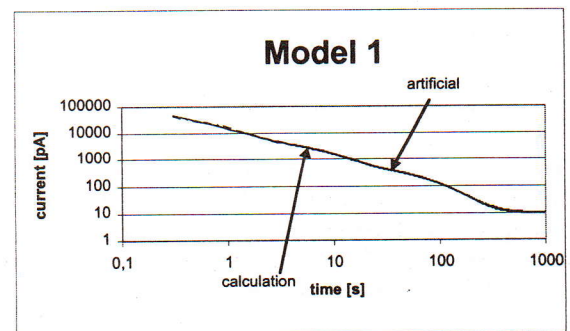


Fig. 9: Calculation with steady element

Let us have a look at model 0 and the force calculation with the steady element (the first two columns of data) with expansion to seven elementary polarization processes (number of elements – 7). It can be seen that the calculation is quite successful. Only small differences appear between the artificial and calculated data. When the calculation was done without the steady component, the results exactly match with the artificial data. The conclusion is that the calculation really reveals the presence of the steady element, and its value can also be defined.

In the case of model 1 (artificial data with a steady element of magnitude 10 pA), the calculation with obligatory presence of the steady component is also successful. In the third column of data with 7 expansion elements can be seen that the calculation exactly revealed steady element I_0 and determined its value. The fourth column belongs to calculation without forced of steady component. The results are completely wrong. The time constants and amplitudes of the elementary polarization processes have large errors. This leads to the conclusion that if the steady element is present and the calculation does not require it, the result is completely wrong.

This situation was as expected. The calculation can reveal the steady element, and it is recommended to required calculation with it. If the element is present, the calculation reveals it. If the element is not present and the calculation is required to compute it, the result is a steady element with a magnitude of 0.

The final situation was examined by measuring of real object. The cable was examined after accelerated thermal stress for a period of 7000 hours at a temperature of 100 °C. The cable was made from XPLE and for a 22 kV voltage operating level. The cable was charged with direct voltage at 100 V and the current response was observed for a period of 1000 s. The observing time was selected to have the same time window of polarization processes as in the artificial data for model 0 and model 1. Fig. 10 shows the measuring set.

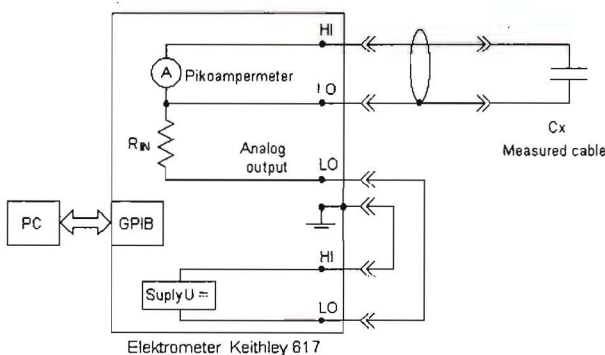


Fig. 10: Measured equipment for cable

The electrometer can measure currents down to 10^{-16} A and it is suitable for our purposes. Fig. 11 shows the measured cable response and the calculation without required steady element. The values of the data are given in the fifth column of data in Table 2. Fig. 12 shows the same situation but without a required steady component. The situations in the data values are completely changed. Although the data in graphic form seems to be the same, the magnitudes are different. The

charging time was 1000 s and for this reason the observing time constant τ , cannot be higher than 10-times. The reason for this is based on the physical background. If the charging lasts 1000 s, polarization processes with a level no higher than 10-times the time duration can be excited. Nevertheless the calculations only to five elementary processes were successful. No polarizations with a higher time constant were started.

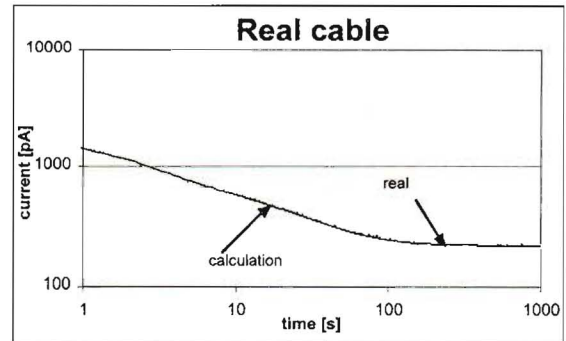


Fig. 11: Calculation without steady element

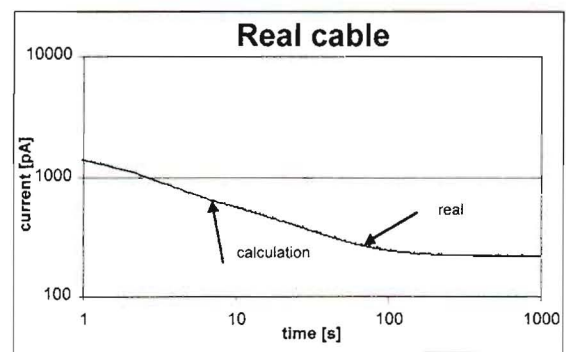


Fig. 12: Calculation with steady element

4 Conclusion

This paper deals with calculating elements of equivalent models for dielectric materials. The basic principles of the methods were described, together with the magnitudes of the elementary polarization currents and the time constant of their stabilization. First of all, the artificial data was verified. The calculation was to the presence of a steady element.

Then the approximation of real data was carried out successfully. It was demonstrated, that graphical fitting alone does not allow to claim that a model of a real object has been achieved. The magnitudes of the observing elements have to be investigated with their electro-physical background. Although higher values were calculated and graphical fitting confirmed them, the physical processes did not start and they did not really exist.

The real object has a direct element because it is at the end of its life after long-term accelerated thermal stress [8]. This is evident from graphical representation of real measured data. For this reason calculation with a required steady element must always be made, whether this steady component really exists or not.

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