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Model of the PVDF Material Electrical Properties Dependence on Temperature Regarding the Influence of Fractional Elements

Abstract. *The paper presents how electrical properties of a PVDF material is influenced by a change of temperature when not subjected to a mechanical stress The results of PVDF cables behavior during frequency testing are presented. The fractional derivatives method was used to interpret the findings as well as to verify the model proposed earlier. Experimental data taken for PVDF cables made in Wroclaw Division of Electrotechnical Institute, after subjecting them for frequency testing at temperatures ranging from-50 ^{o}C to +50 ^{o}C proved that the model proposed by the authors correctly describes the changes taking place in PVDF material under temperature. An eletrical equivalent model was derrived and its parameters at different temperature points were identified. The premise was to describe the changes in electrical properties of the test material against the temperature. The proposed modeling does not include the influence of the power conection leads and plates, which affect the outcome of the measurements*

Streszczenie. *Prezentowana praca zawiera wyniki badań częstotliwościowych przewodów PVDF wyprodukowanych w IEL i poddanych działaniu temperatury w zakresie od –50C do +50C. Do interpretacji wyników pomiarów częstotliwościowych i jednoczesnej weryfikacji wcześniej zaproponowanego modelu zastosowano metodę pochodnych ułamkowych. Na podstawie przeprowadzonej weryfikacji i interpretacji badań eksperymentalnych stwierdzono, że zaproponowany przez autorów model dobrze opisuje zmiany parametrów układu poddanego działaniu temperatury w zakresie od –50C do +50V. (**Temperaturowy model elektryczny materiału PVDF uwzględniający wpływ elementów ułamkowych**)*

Keywords: PVDF, temperature ageing, electric model.
Słowa kluczowe: PVDF, starzenie termiczne, model elektryczny.

Introduction

The structure of the material under discussion has been already described in previous work [1-6]. It was assumed that the model consists of resistances and capacitances connected in parallel as well as of a fractional element as illustrated in Figure 3. The presence of such an element results in a simpler model equation which is easier to interpret physically, which proves to be crutial in achieving desired material parameters during the process of material manufacturing. This also applies that models of this type have a practical application.

Experimental

The study was conducted for temperatures ranging from -50^{o}C to +50^{o}C in a climatic chamber, which allowed to continously change the temperature in the range from -60 ^{o}C to +80^{o}C. As shown by previous research [1,3,5] the material gradually loses its properties in temperatures below -50^{o}C and above +50^{o}C i.e. deformation, loss of flexibility and problems with the conduction in both the internal and the external layer occur. The measurment system was described in the article [5]. The sample was tested using a LCR HP4284A impedance spectrometer.
The investigation was conducted on several samples. The measurments have been conducted for temperature values increasing from -50^{o}C to + 50°C, and then decreasing from +50^{o}C to - 50°C, with a pressure force of 0 N. The results presented are averaged for easier presentation of the problem under consideration.

Results and discussion

The invesitgated material was manufactured in Wroclaw Division of Electrotechnical Institute [1-5] and its structure is highly porous and is similar to the structure of PVDF material manufactured by the Prismedical Corporation [7]. The structures are shown in Figures 1a and b.
The frequency response of the system for temperatures from -50C to +50 C is shown in Figures 2a and b.

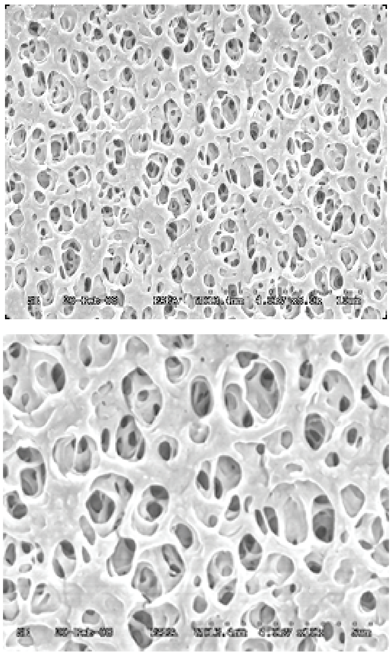

Fig.1 PVDF surface: a) magnified by 5000 times; b) magnified by 10000 times

Basing on results presented in Figures 2a and b it can be concluded that:
1.The effect of temperature is most apparent during the phase φ changing as a function of frequency.There are substantial changes of frequency occuring with the increase of temperature.
2. The change of temperature causes only a parallel shift toward smaller values in the curves characterising module |Z| as a function of frequency .When temperature increases the module decreases proportionally.
Basing on the other work [8-13] and the carried out measurements, an electric model of the PVDF material was assumed (not including leads resistance).The model is shown in Fig 3. [6].

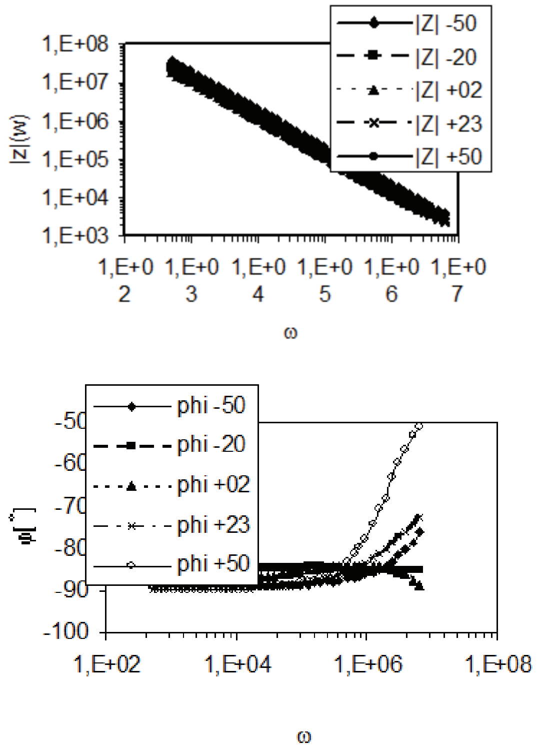

Fig.2 .Dependence of a) module | Z | and b) phase of (ω) for temperatures: -50, -20, 02, 23, 50 ° C

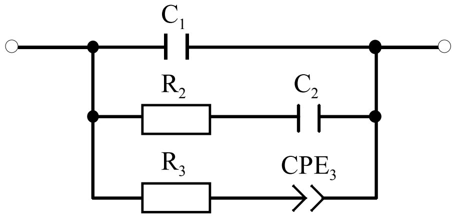

Fig.3. Equivalent model of a PVDF cable.

It should be noted that the proposed model of the PVDF material under investigation is simple and based on suggestions from literature regarding similar types of materials [8,9,11]. It proves to be correct for various temperatures and as shown in [5] for different pressure forces. After assuming that the given model is appropriate for this type of material, the authors focused on the identification of its R, L, C, parameters [6].

Thus, transmittance of the material PVDF takes the form:

$$Z(\omega)=\cfrac{1}{C_1 j\omega+\cfrac{1}{R_2+\cfrac{1}{C_2 j\omega}}+\cfrac{1}{R_3+\cfrac{1}{T(j\omega)^{\varphi}}}} \qquad (1)$$

$$Z2(\omega)=C_2 j\omega(R_3T(j\omega)^{\varphi}+1)$$

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Transforming the equation (1) it can be shown that:

$$Z(\omega)=\cfrac{1}{C_1 j\omega+\cfrac{C_2 j\omega}{1+R_2C_2 j\omega}+\cfrac{T(j\omega)^{\varphi}}{1+R_3T(j\omega)^{\varphi}}} \qquad (2)$$

And then from equation (2):

$$Z(\omega)=\frac{(R_2C_2 j\omega+1)(R_3T(j\omega)^{\varphi}+1)}{Z1(j\omega)+Z2(j\omega)+Z3(j\omega)} \qquad (3)$$

where:

$$(4)\quad Z1(\omega)=C_1 j\omega(R_2C_2 j\omega+1)(R_3T(j\omega)^{\varphi}+1)$$

$$(5)\quad Z2(\omega)=C_2 j\omega(R_3T(j\omega)^{\varphi}+1)$$

$$(6)\quad Z1(\omega)=T(j\omega)^{\varphi}(R_2C_2 j\omega+1)$$

A substitution can be applied in order to simplify the notation. Let then:

$$Z(\omega)=\frac{a_n j\omega}{b_n j\omega} \qquad (7)$$

Then after multiplication of the numerator and denominator from equation (2) and using notation from equation (1)it can be written:

$$Z(\omega)=\frac{a_1(j\omega)^{\varphi+1}+a_2 j\omega+a_3(j\omega)^{\varphi}+a_4}{b_1(j\omega)^{\varphi+2}+b_2(j\omega)^2+b_3(j\omega)^{\varphi+1}+b_4 j\omega+b_5(j\omega)^{\varphi}} \qquad (8)$$

where:

$$(9)\quad \begin{cases} a_1=R_2R_3C_2T \\ a_2=R_2C_2 \\ a_3=R_3T \\ a_4=1 \end{cases} \qquad \begin{cases} b_1=R_2R_3C_1C_2T \\ b_2=R_2C_2C_1 \\ b_3=R_3C_1T+R_3C_2T+R_2C_2T \\ b_4=C_1+C_2 \\ b_5=T \end{cases}$$

Identification was performed utilizing the Fourier transformation [5,6]. This process allowed to identify values of resistance, capacitance and phase angle φ as shown in Table 1. In Tables 2 and 3 values of model parameters and $a_{1\text{-}4}$ i $b_{1\text{-}5}$ derrived from formula (9) are presented.

Table 1. The values of resistance, capacitance and phase angle φ

Temp [C]	**C1** **[F]**	**R2** **[Ω]**	**C2** **[F]**	**R3** **[Ω]**	**T** **[F]**	φ
-50	1.59-11	2155	2.88-11	359260	2.33-11	0.87
-20	4.84-11	44019	9.65-12	641530	5.98-11	0.87
02	6.25-11	80046	1.78-11	137420	2.68-10	0.65
23	4.51-11	161320	6.98-12	4238	4.99-11	0.98
50	2.32-11	5845	5.52-11	8574	4.07-11	0.97

Table 2. The values of parameters a and phase angle φ

Temp [°C]	a_1	a_2	a_3	a_4	φ
-50	5.18E-13	6.20E-8	8.36E-6	1	0.87
-20	1.63E-11	4.25E-7	3.84E-5	1	0.87
+02	5.25E-11	1.43E-6	3.68E-5	1	0.65
+23	2.38E-13	1.13E-6	2.12E-7	1	0.98
+50	1.12E-13	3.23E-7	3.49E-7	1	0.97

Table 3. The values of parameters b

Temp [°C]	b_1	b_2	b_3	b_4	b_5
-50	8.24E-24	9.86E-19	3.75E-16	4.47E-11	2.33E-11
-20	7.88E-22	2.05E-17	2.25E-15	5.80E-11	5.98E-11
+02	3.28E-21	8.92E-17	3.34E-15	8.03E-11	2.68E-10
+23	1.08E-23	5.08E-17	6.73E-17	5.21E-11	4.99E-11
+50	2.61E-24	7.48E-18	4.04E-17	7.84E-11	4.07E-11

The established mathematical model will have the same form at any temperature, and only the parameters will vary, where D is a differential operator of a given degree, and φ is a non-integer value from the (0, 1) interval.

$$L(b_nD)y(t)=P(a_nD)u(t) \qquad (10)$$

(11) $$P(a_nD)=\left[5.18\cdot10^{-13}D^{1.87}+6.20\cdot10^{-8}D+8.36\cdot10^{-6}D^{0.87}+1\right]$$

(12) $$L(b_nD)=\left[\begin{array}{l}8.24\cdot10^{-24}D^{2.87}+9.86\cdot10^{-19}D^{2}+3.75\cdot10^{-16}D^{1.87}\\+4.47\cdot10^{-11}D+2.33\cdot10^{-11}D^{0.87}\end{array}\right.$$

Figures 4-8 present the responses of the real object along with those of an assumed model for temperatures: -50 ^{C,} - 20 ° C, 02 ° C, 23 ° C 50 ° C.

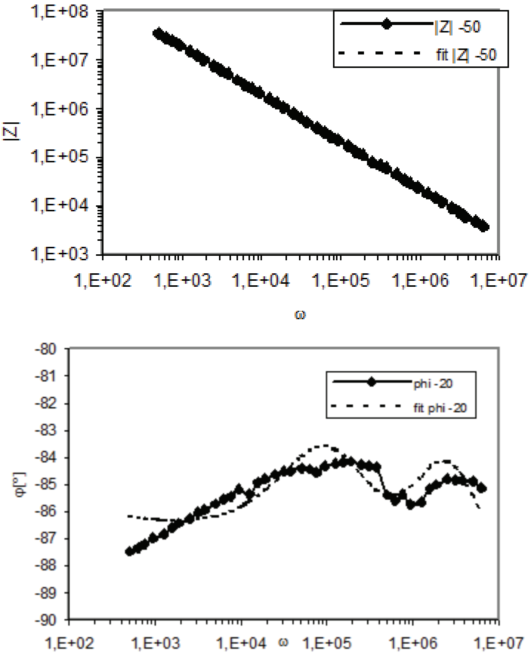

Fig.4 .Dependence of a) module | Z |□ and b) phase of (ω) for temperature -50° C; 1) –•– the actual results of the measurements, and 2) – – – response of the adopted model

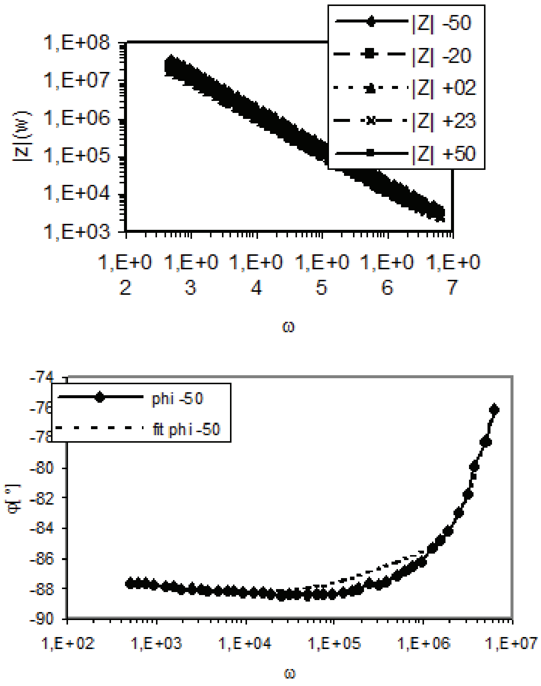

Fig.5 .Dependence of a) module | Z | □ and b) phase of (ω) for temperature -23° C; 1) the actual results of the measurements, and 2) response of the adopted model

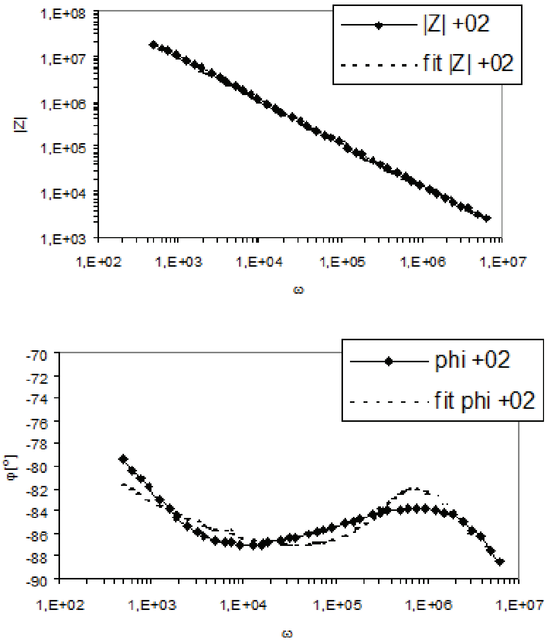

Fig.6 .Dependence of a) module | Z | and b) phase of (ω) for temperature 02° C; 1) –•– the actual results of the measurements, and 2) response of the adopted model

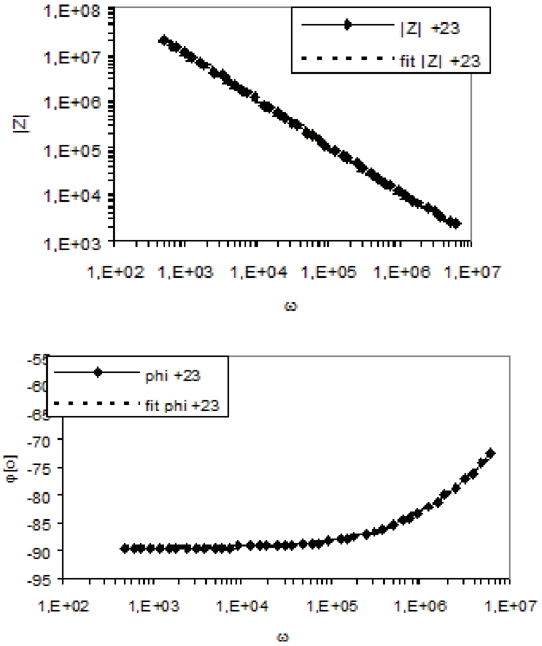

Fig.7 .Dependence of a) module | Z |□ and b) phase of (ω) for temperature 23° C; 1) – • – the actual results of the measurements, and 2) – – – response of the adopted mode

The obtained results show that the proposed electrical model described by the transmittance (1) describes the behavior of the material reasonably well .It is depicted in Figures 4-8, where the calculated responses of the adopted model are shown along with the measured ones. A greater dispersion occurs in the phase part of the model at temperatures of 0 and 20 degrees. This may be caused by humidity as the deviation disperses at the temperature of 50 degrees.The humidity and its impact on electric model were not investigated, however, it is an important research question, as considering the structure of the material it may be significant at temperatures from -5 to 20 degrees C .It should be noted that the inner and outer electrode are made from different material than the PVDF structure. This can cause water to accumulate on the contact area during the transition from positive to negative temperatures.This behavior can be also a result of expansion or compression of the material.

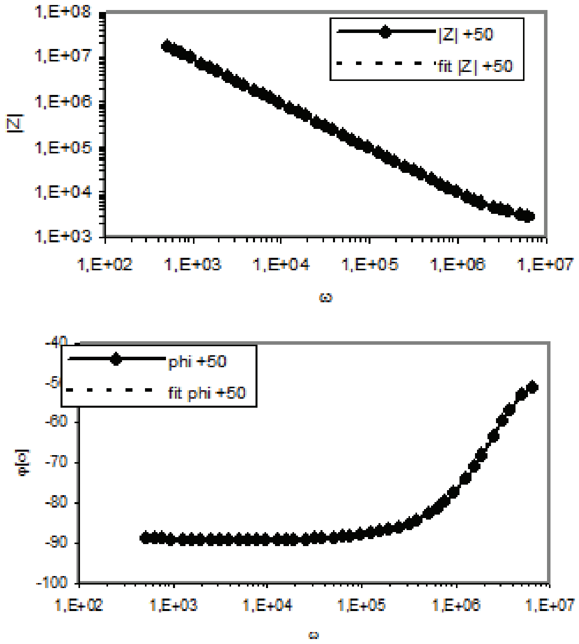

Fig.8 .Dependence of a) module | Z | □ and b) phase of (ω) for temperature 50° C; 1) – •– the actual results of the measurements, and 2) – – – response of the adopted model

As mentioned, the study was carried out on several cycles of cooling and heating. A more detailed description will be presented in subsequent articles.

Summary

The aim of this study was to investigate the influence of temperature on the PVDF material in its nominal range, establishing its electrical model as well as identifying the parameters of such a model.

Basing on the analysis of experimental results it was concluded that:

1.The model proposed by the authors for materials under external mechanical stress at room temperature is also suitable for dipicting the changes in material structure under the impact of temperatures ranging from of-50°C to +50°C.

2.The proposed model, containing a fractional component, is simple, most satisfactory for anticipating material parameters and easy to interpret.

3.A sample subjected to temperature changes can be described using this model with other values of electrical parameters.

Concluding one can say that signals identifying methods allow to formulate more complex alternative models, illustrating the properties of the PVDF material more accurately. It must be stated however, that any large-scale model must be correlated with the actual properties of the object in question. The work presented here-in , as well as the other ones dealing with materials for devices such as ion sensors and varistors [6, 11-14] will be helpful when it comes to manfacturing of the PVDF materials within their specifications. Due to it PVDF materials would be used in a wider spectrum of applications, not only to test the speed and weight of vehicles, as in their flexibility and adaptibility and in the fact that they can withstand a wide range of temperatures lies a great potential.

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