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Research of the Replacement Schemes for Multilayer Insulation of Power Cables with Impregnated Paper Insulation to Determine the Optimal Number of Layers

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***Abstract*— The paper calculates the parameters of mathematical models and analyzes the two-layer, three-layer and four-layer equivalent insulation circuits of the power cable with IPI (impregnated paper insulation) according to self-discharge voltage and return voltage, obtained from tests of existing cables in power electrical installations. The results are presented in the form of graphs and simulated processes in the integrated package MathCad. The optimal number of insulation layers was determined when assessing the technical condition and life of cables with IPI**

***Keywords*— cable insulation, cable with impregnated paper insulation, equivalent circuit, insulation model, integration constants, mathematical model, return voltage, self-discharge voltage, time constants**

I. INTRODUCTION

The reliability of the power supply of agricultural and industrial consumers affects the efficiency of their work. The decrease in the quality of the electricity supplied and the overall reliability of the power supply is due to the deterioration of the technical condition of the equipment being operated and cable lines.

The reliability of cable lines largely depends on the quality of maintenance and timely repair. The technical condition of high-voltage power cable lines is estimated primarily by the state of their isolation. For a reliable assessment of the technical condition of the insulation, it is necessary to know the processes occurring in it, its mathematical model and diagnostic parameters. To date, many methods and devices have been developed for monitoring the insulation condition of cable lines. Non-destructive testing methods are becoming more common, they include: measurement of insulation resistance; measurement of capacitance and dielectric loss tangent of insulation; partial discharge measurement; absorption coefficient measurement; thermal imaging control over the entire length of the cable line; return voltage method; voltage self-discharge method; removal of cable echograms by pulse method (e.g. [1]).

Such scientists as M. A. Boev, A. P. Dolin, S. V. Serebryannikov, S. D. Kholodny, A. I. Kononenko, V. A. Kaniskin, A. I. Tadjibaev, M. Yu. Shuvalov, E. Gulski, J. J. Smit, P. P. Seitz, C. Weindl and many others made a great contribution to the study of the development of insulation resource, cable line failures, development and implementation of diagnostic methods (e.g. [1]–[11]).

II. MATERIALS AND METHODS

Studies have shown that the analysis of absorption processes in insulation provides more information about its state. The character of absorption processes can be judged by the dependences of the insulation resistance, self-discharge voltage, and return voltage on the time.

Insulation of high-voltage cable lines is heterogeneous, consists of several layers. Each layer is distinguished by its physical properties, and therefore it has different values of electrical capacitance and resistance. A multilayer insulation model of power cables with impregnated paper insulation can be represented by a diagram (Fig. 1).

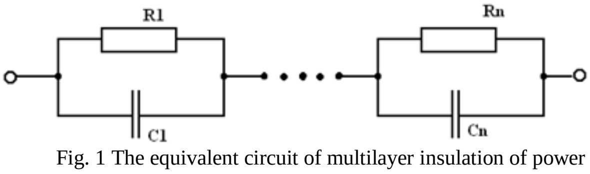


Fig. 1 The equivalent circuit of multilayer insulation of power cables with IPI

Using the automated device for diagnosing electrical insulation “UDEI-1”, developed at the Department of Electrification and Automation by Serebryakov A. S. and Semenov D. A. [12], insulation characteristics were measured: resistance, self-discharge voltage, return voltage. Further, they determine the parameters of the mathematical model of isolation and its equivalent circuit. If we assume that the resistance of a voltmeter is infinite, then the mathematical model of multilayer insulation for self-discharge voltage u_s and return voltage u_r can be represented as a sum of decaying exponents with different values of time constants (e.g. [13]-[15]):

$$u_s(t) = \sum_{i=1}^{n} A_i \cdot e^{-\frac{t}{T_i}}, \quad u_r(t) = \sum_{i=1}^{n} A_i \cdot e^{-\frac{t}{T_i}},$$

where n – number of layers in the insulation replacement circuit, A_i – constant value for the *i*-th layer, equal to the voltage on the *i*-th layer at the initial moment of time of the self-discharge process, $T_i = R_i C_i$ – time constant of the self-discharge of the *i*-th layer, equal to the product of the resistance of the *i*-th layer and the electric capacitance of this layer, t is the current time.

When solving a general problem, the results of solving (1) cannot be uniquely determined through the coefficients of a system of nonlinear equations. However, in the case of solving the problem related to the insulation of power cables, it can be assumed that the number of terms in the form of an exponential function will be no more than three, and the parameters of these functions will be different. According to the physical meaning of the problem, the speed of striving of all three exponents to 0 will be different. Thus, it is possible to formulate a general principle of the algorithm for calculating the values of the coefficients of the function being studied – for sufficiently large time values, the graph of the common function will tend to the simple exponent graph, which makes it possible to determine the parameters of the expression that is a component of the common function, after which the values of a certain exponent are subtracted from the initial values after which the algorithm is repeated until all unknown coefficients are determined (e.g. [16], [17]).

The exact values of the parameters A_i and T_i can be determined using the integrated MathCAD package, solving a system of nonlinear equations of the form:

$$\sum_{k=1}^{2n}\left(\sum_{i=1}^{n} A_i \cdot e^{-\frac{t_k}{T_i}} = u_{sk}\right),$$

u_{sk} – self-discharge voltage at the *k*-th point, t_k – time at the *k*-th point.

Since according to the equivalent circuit, there are two parameters for each layer: a time constant and an integration constant, in the mathematical model the number of points for finding the parameters is equal to twice the number of layers. For example, to find the parameters of the mathematical model of a two-layer equivalent circuit (Fig. 1), it is necessary to create a system of four equations:

$$A_1 \cdot e^{-\frac{t1}{T1}} + A_2 \cdot e^{-\frac{t1}{T2}} = u_{s1};$$

$$A_1 \cdot e^{-\frac{t2}{T1}} + A_2 \cdot e^{-\frac{t2}{T2}} = u_{s2};$$

$$A_1 \cdot e^{-\frac{t3}{T1}} + A_2 \cdot e^{-\frac{t3}{T2}} = u_{s3};$$

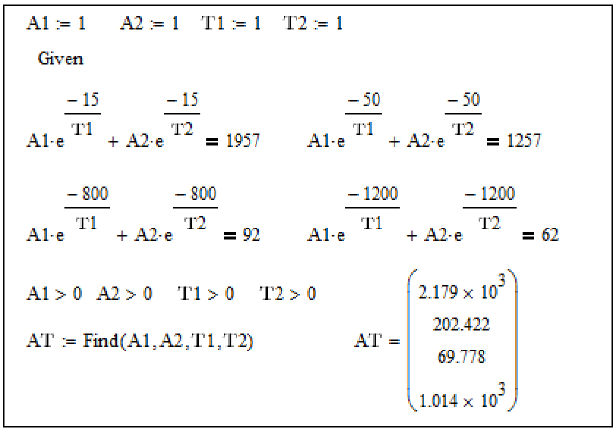
$$A_1 \cdot e^{-\frac{t4}{T1}} + A_2 \cdot e^{-\frac{t4}{T2}} = u_{s4}.$$

And for a three-layer equivalent scheme, it is necessary to create a system of six equations (Fig. 5).

III. RESULTS AND DISCUSSION

We will analyze single-layer, two-layer, three-layer, four-layer insulation replacement circuits according to experimental data of the “AAShV-3× 95” power cable, having three aluminum cores with impregnated paper insulation and aluminum sheath covered by PVC.

We define the parameters of the mathematical model for the two-layer insulation replacement scheme in the integrated MATHCAD package using the standard Find and Minerr comands. The solution of the system of four equations is presented in Figure 2. For clarity, the solution of the desired values of the time constants (T1, T2) and the module of the exponents (A1, A2) is equal to 1, since their real values are several orders of magnitude smaller.



$A1 := 1 \quad A2 := 1 \quad T1 := 1 \quad T2 := 1$

Given

$$A1 \cdot e^{\frac{-15}{T1}} + A2 \cdot e^{\frac{-15}{T2}} = 1957 \qquad A1 \cdot e^{\frac{-50}{T1}} + A2 \cdot e^{\frac{-50}{T2}} = 1257$$

$$A1 \cdot e^{\frac{-800}{T1}} + A2 \cdot e^{\frac{-800}{T2}} = 92 \qquad A1 \cdot e^{\frac{-1200}{T1}} + A2 \cdot e^{\frac{-1200}{T2}} = 62$$

$A1 > 0 \quad A2 > 0 \quad T1 > 0 \quad T2 > 0$

$AT := \mathrm{Find}(A1, A2, T1, T2) \qquad AT = \begin{pmatrix} 2.179 \times 10^3 \\ 202.422 \\ 69.778 \\ 1.014 \times 10^3 \end{pmatrix}$

Fig. 2 The program of determining the parameters of a two-layer mathematical model

When determining the parameters of the two-layer insulation model in the system of four equations, the values of the self-discharge voltage measured at t=15, 50, 800 and 1200 seconds are taken. In Figure 2 the values of time constants (T_1, T_2) and integration constants (A_1, A_2) were obtained in the matrix column AT.

The resulting parameters and measurement results were used to plot the voltage curves of the self-discharge (Figure 3). In Figure 3, the *Us* curve is plotted from measurements of the self-discharge voltage of the cable under study, the curves $u0(t)$ and $u1(t)$ correspond to the exponents of the 1st and 2nd layer, the curve $u(t)$ is the result of their addition $u(t) = u0(t) + u1(t)$.

As can be seen from Figure 3, the curve $u(t)$ does not coincide with the curve Us, which means that the considered two-layer model does not fully describe the process. We come to the same conclusion when analyzing the return voltage curves for the two-layer insulation model (Figure 4).

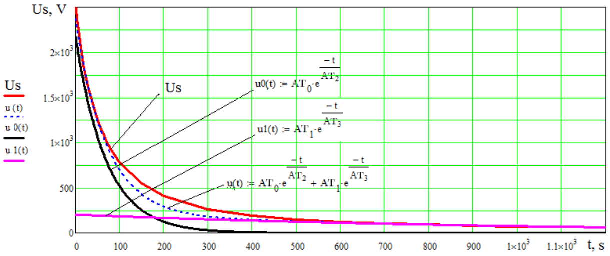


Fig. 3 Voltage curves of self-discharge of power cable with IPI for a two-layer insulation model

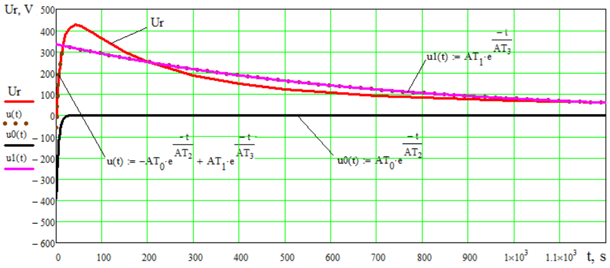
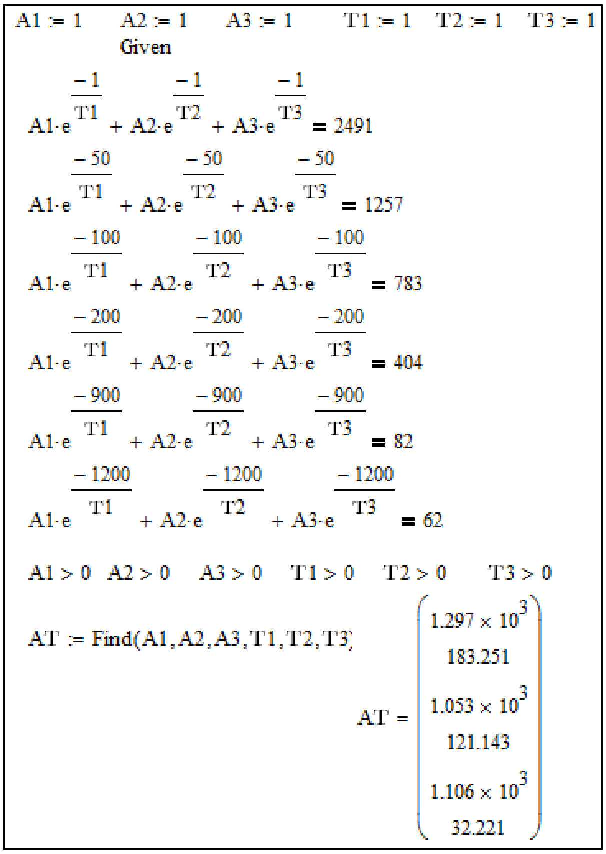


Fig. 4 Power cable return voltage curves for a two-layer insulation model

Similarly, we analyzed the model of a three-layer equivalent circuit. Figure 5 and 6 show the program for determining the parameters of the mathematical model in the integrated MathCAD package for self-discharge voltage (Figure 5) and return voltage (Figure 6).



A1 := 1 A2 := 1 A3 := 1 T1 := 1 T2 := 1 T3 := 1

Given

$$A1 \cdot e^{\frac{-1}{T1}} + A2 \cdot e^{\frac{-1}{T2}} + A3 \cdot e^{\frac{-1}{T3}} = 2491$$

$$A1 \cdot e^{\frac{-50}{T1}} + A2 \cdot e^{\frac{-50}{T2}} + A3 \cdot e^{\frac{-50}{T3}} = 1257$$

$$A1 \cdot e^{\frac{-100}{T1}} + A2 \cdot e^{\frac{-100}{T2}} + A3 \cdot e^{\frac{-100}{T3}} = 783$$

$$A1 \cdot e^{\frac{-200}{T1}} + A2 \cdot e^{\frac{-200}{T2}} + A3 \cdot e^{\frac{-200}{T3}} = 404$$

$$A1 \cdot e^{\frac{-900}{T1}} + A2 \cdot e^{\frac{-900}{T2}} + A3 \cdot e^{\frac{-900}{T3}} = 82$$

$$A1 \cdot e^{\frac{-1200}{T1}} + A2 \cdot e^{\frac{-1200}{T2}} + A3 \cdot e^{\frac{-1200}{T3}} = 62$$

A1 > 0 A2 > 0 A3 > 0 T1 > 0 T2 > 0 T3 > 0

AT := Find(A1, A2, A3, T1, T2, T3)

$$AT = \begin{pmatrix} 1.297 \times 10^3 \\ 183.251 \\ 1.053 \times 10^3 \\ 121.143 \\ 1.106 \times 10^3 \\ 32.221 \end{pmatrix}$$

Fig. 5 The program for determining the parameters of the mathematical model of three-layer insulation for self-discharge voltage

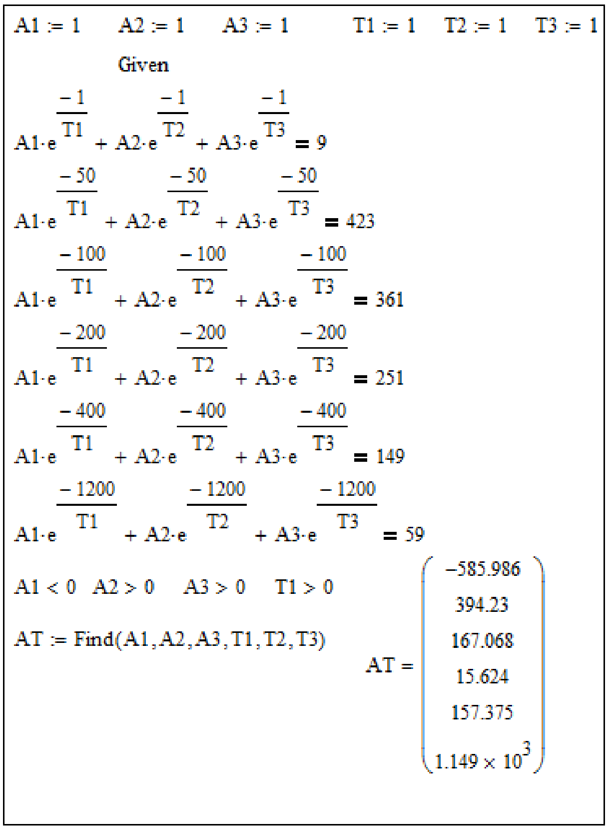
The parameters of the three-layer insulation model are calculated by solving a system of six nonlinear equations. The voltage equation of self-discharge for a three-layer model of the cable under consideration will take the form:

$$u_s = 1297 e^{-\frac{t}{121{,}143}} + 183{,}251 e^{-\frac{t}{1106}} + 1053 e^{-\frac{t}{32.221}}$$

where A_1=1297 [V], A_2=183,251 [V] и A_3=1053 [V] are the integration constants.

According to the resulting equation and experimental data, we construct a curve of the dependence of the self-discharge voltage on time (Figure 7).

The $u(t)$ curve constructed from the six equations coincides with the *Us* curve constructed from the experimental data (Figure 7). The individual components of the self-discharge voltage $u0(t)$, $u1(t)$ and $u2(t)$ are also shown.



A1 := 1 A2 := 1 A3 := 1 T1 := 1 T2 := 1 T3 := 1

Given

$$A1 \cdot e^{\frac{-1}{T1}} + A2 \cdot e^{\frac{-1}{T2}} + A3 \cdot e^{\frac{-1}{T3}} = 9$$

$$A1 \cdot e^{\frac{-50}{T1}} + A2 \cdot e^{\frac{-50}{T2}} + A3 \cdot e^{\frac{-50}{T3}} = 423$$

$$A1 \cdot e^{\frac{-100}{T1}} + A2 \cdot e^{\frac{-100}{T2}} + A3 \cdot e^{\frac{-100}{T3}} = 361$$

$$A1 \cdot e^{\frac{-200}{T1}} + A2 \cdot e^{\frac{-200}{T2}} + A3 \cdot e^{\frac{-200}{T3}} = 251$$

$$A1 \cdot e^{\frac{-400}{T1}} + A2 \cdot e^{\frac{-400}{T2}} + A3 \cdot e^{\frac{-400}{T3}} = 149$$

$$A1 \cdot e^{\frac{-1200}{T1}} + A2 \cdot e^{\frac{-1200}{T2}} + A3 \cdot e^{\frac{-1200}{T3}} = 59$$

A1 < 0 A2 > 0 A3 > 0 T1 > 0

AT := Find(A1, A2, A3, T1, T2, T3)

$$AT = \begin{pmatrix} -585.986 \\ 394.23 \\ 167.068 \\ 15.624 \\ 157.375 \\ 1.149 \times 10^3 \end{pmatrix}$$

Fig. 6 The program for determining the parameters of the mathematical model of three-layer insulation for the return voltage

Comparing them with the curves $u0(t)$ and $u1(t)$ shown in Figure 3, we conclude that the parameters of the 1st and 2nd layers for the three-layer and two-layer insulation models are close to each other. But in the three-layer model, another exponent appears with a smaller time constant T_3 = 32.221 s, taking into account which, we obtain new information in comparison with the two-layer model.

Studies have also shown that the three-layer insulation model describes not only the process of self-discharge, but also the process for measuring the return voltage (Fig. 8).

Similarly, the calculation of the four-layer insulation model was made (Fig. 9).

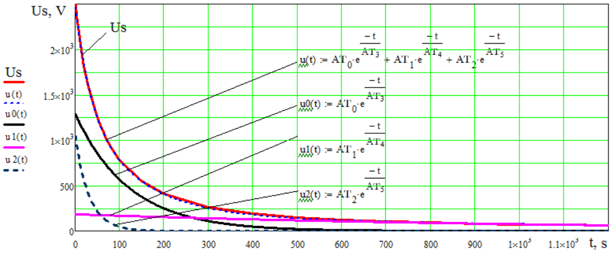


Fig. 7 Self-discharge voltage curve of a power cable for a three-layer insulation model

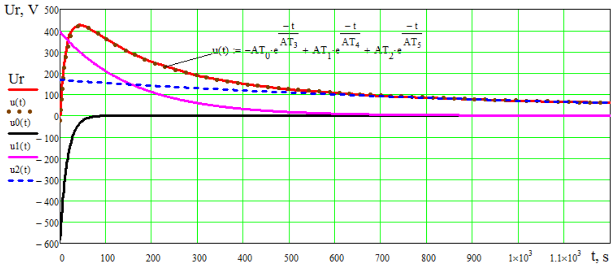
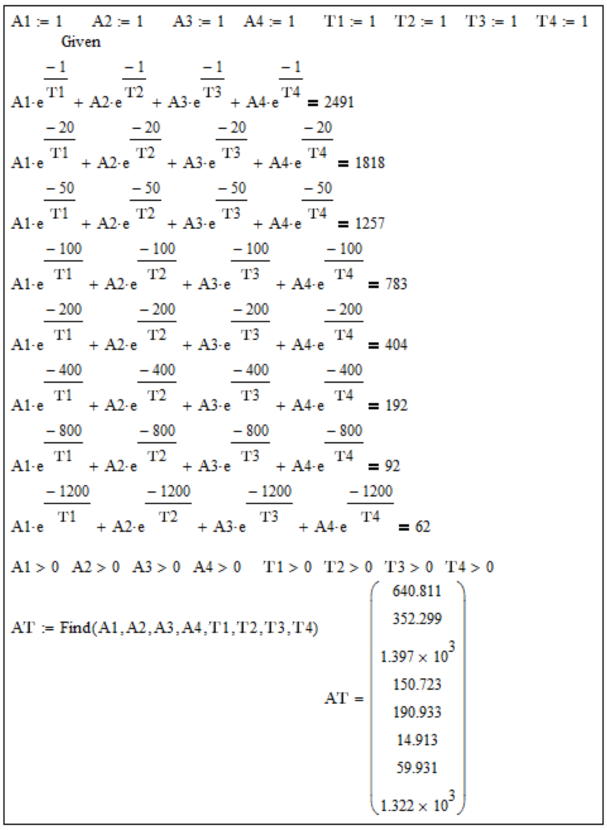


Fig. 8 Power cable return voltage curve for three-layer insulation model



$A1 := 1 \quad A2 := 1 \quad A3 := 1 \quad A4 := 1 \quad T1 := 1 \quad T2 := 1 \quad T3 := 1 \quad T4 := 1$

Given

$$A1 \cdot e^{\frac{-1}{T1}} + A2 \cdot e^{\frac{-1}{T2}} + A3 \cdot e^{\frac{-1}{T3}} + A4 \cdot e^{\frac{-1}{T4}} = 2491$$

$$A1 \cdot e^{\frac{-20}{T1}} + A2 \cdot e^{\frac{-20}{T2}} + A3 \cdot e^{\frac{-20}{T3}} + A4 \cdot e^{\frac{-20}{T4}} = 1818$$

$$A1 \cdot e^{\frac{-50}{T1}} + A2 \cdot e^{\frac{-50}{T2}} + A3 \cdot e^{\frac{-50}{T3}} + A4 \cdot e^{\frac{-50}{T4}} = 1257$$

$$A1 \cdot e^{\frac{-100}{T1}} + A2 \cdot e^{\frac{-100}{T2}} + A3 \cdot e^{\frac{-100}{T3}} + A4 \cdot e^{\frac{-100}{T4}} = 783$$

$$A1 \cdot e^{\frac{-200}{T1}} + A2 \cdot e^{\frac{-200}{T2}} + A3 \cdot e^{\frac{-200}{T3}} + A4 \cdot e^{\frac{-200}{T4}} = 404$$

$$A1 \cdot e^{\frac{-400}{T1}} + A2 \cdot e^{\frac{-400}{T2}} + A3 \cdot e^{\frac{-400}{T3}} + A4 \cdot e^{\frac{-400}{T4}} = 192$$

$$A1 \cdot e^{\frac{-800}{T1}} + A2 \cdot e^{\frac{-800}{T2}} + A3 \cdot e^{\frac{-800}{T3}} + A4 \cdot e^{\frac{-800}{T4}} = 92$$

$$A1 \cdot e^{\frac{-1200}{T1}} + A2 \cdot e^{\frac{-1200}{T2}} + A3 \cdot e^{\frac{-1200}{T3}} + A4 \cdot e^{\frac{-1200}{T4}} = 62$$

$A1 > 0 \quad A2 > 0 \quad A3 > 0 \quad A4 > 0 \quad T1 > 0 \quad T2 > 0 \quad T3 > 0 \quad T4 > 0$

$AT := \mathrm{Find}(A1, A2, A3, A4, T1, T2, T3, T4)$

$$AT = \begin{pmatrix} 640.811 \\ 352.299 \\ 1.397 \times 10^3 \\ 150.723 \\ 190.933 \\ 14.913 \\ 59.931 \\ 1.322 \times 10^3 \end{pmatrix}$$

Fig. 9 The program for determining the parameters of the mathematical model of four-layer isolation

Analysing the graphs in Figure 10 shows that the new information does not work, since the two exponents of the expansion of the return voltage curve of the four-layer insulation model with time constants close in value when added completely coincide with one of the three-layer exponential models (Fig. 11).

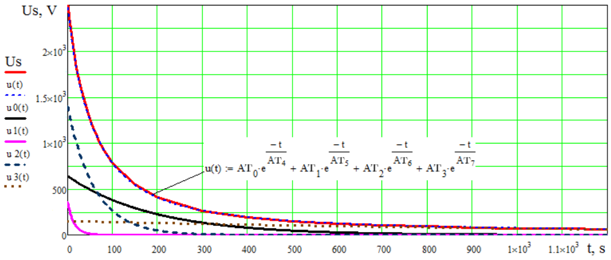


Fig. 10 Voltage curve of self-discharge of power cable for four-layer insulation model

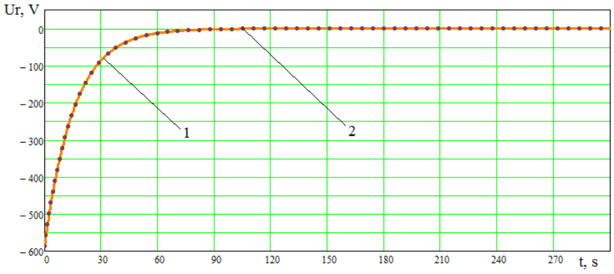


Fig. 11 Return voltage curve – fast return voltage exponent in a three-layer insulation model (1) and the sum of two fast exponents, shown by dots in four-layer insulation (2)

In the analysis of the five-layer isolation model, as studies showed, no new information was obtained.

IV. CONCLUSIONS

Investigating the two-layer, three-layer and four-layer equivalent insulation schemes of a power cable with IPI, according to self-discharge voltage and return voltage, it was concluded that it is advisable to consider a three-layer insulation model. The fact that is most suitable for the insulation replacement circuit is a three-layer model can also be explained from a physical point of view, since three components are involved in isolation. It is the presence of the three components that confirms the fact that the parameters for the fourth layer are not found for the four-layer model. The fourth layer is obtained as part of the third layer in the three-layer model. Consequently, it is the three-layer model that should be used to analyze the processes in isolation, in its diagnosis, and in assessing the technical condition and life of cables with IPI.

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