U.P.B. Sci. Bull., Series C, Vol. 81, Iss. 1, 2019 ISSN 2286-3540

ASSESSMENT METHODS FOR CABLE CONDUCTORS HEATING AND THEIR ACCURACY SIGNIFICANCE

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The temperature value of the electrical cable conductors established using the specific thermal resistance values from Rules for Design and Construction Power Cable Network, PE 107/1995, is different versus the real one about 2 K. At the lifetime calculus, this difference leads to a years-order deviation. In this paper is proposed a more accurate computational practical method for heating determination of the electric cable conductors, by temperature measurement of the cable surface and of the environment, without making a complex calculus and particular mathematical models, to assess the power cable lifetime.

Keywords: power cables; cable lifetime; heating calculus; heat flow; Arrhenius law

1. Introduction

The cables are subjected to temperature, radiation, humidity and vibration, specific environmental condition factors. Under these factors' action are taking place physical and chemical processes into the polymeric material structure, these being ageing processes. For assessment of the electric cable lifetime is required monitoring of the working condition (temperature, radiation). Further, for the power cable, without heating due to environment is required to take into account the losses of power generated by electric current, losses converting into heat. These losses are proportional to the electric resistance of the cable wires, at the operating temperature and with long time regime current in conductors (Joule's effect). The heat is lead to the outer jacket of the cable by conduction and from there through the air by convection and radiation. The heat flowing from cable internal heat source up to air is similar to electric current flowing through finite conductivity environment, defined by the Ohm's law. By analogy, the converted heat is proportional to the difference in temperature between the wires/conductors and the environment and to inverse ratio of the thermal resistances of cable jackets and the environment.

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The energy balance between the quantity of heat generating inside the cable and the quantity of heat delivered to the environment by cable is the starting point of the heating calculus for power cables. The energy balance equation from [1] is converted such as allowing a graphical solution. Knowing the environmental temperature and thermal characteristics of the cable jacket materials are required. The Excel software is used as calculus system, in [2], to determine thermal resistance of the environment. The uncertainty inserted by the applied boundary conditions is not shown.

The determination of the cable wires heating, using the SPICE software, for a particular current, is proposed in [3]. The thermal resistance of the environment is inserted as a variable factor, dependent on the difference in temperature between the cable surface and the environment. The physical characteristics of the dry air (thermal conductivity - λ, viscosity - ϑ, thermal extension factor - β), taken from [4], are used. Knowing the thermal characteristics of the cable jackets material (specific thermal resistance) and the geometrical configuration of the cables are required.

The heating values of the electric cables determined by two calculus methods, based on the measurement of the environment temperature and temperature of the cable surface, respectively, are shown comparatively in [5]. The fluctuations due to type, the number, the material, the thermocouples arrangement and the effect of the conductors' cross section are, also, shown. The heating calculus of the high voltage cables for a dynamic condition is shown in [6]. The equation for thermal balance is written in Cartesian coordinates and are solving for a particular limit condition. For different types of cable are shown the differences between the calculated values and the measured one, at the cable temperature.

To solve the thermal balance equation is proposing in references [7] and [8] using Finite Element Method. The thermal balance equation is written in Cartesian coordinates in the reference [9], and the limit condition and an adopted hypothesis are settled for its resolution. The coefficients of heat transfer by convection and radiation from the cable surface to the environment are determined for an extensive temperature range of the air surrounding the electric cable. The values for the air characteristics are from the technical literature. For the high voltage cables, a mathematic model for determination the electric losses on the electric cable shield/sheathing, which are converted into heat, is developed in [10]. The differences between the values calculated with this model and those resulted according to IEC Standard are shown.

In this paper, is proposed a practical method to assess the power cables' lifetime, based on heating determination of the cable's conductors, by measuring of temperature on cable surface and of the environment also, without performing complex calculations or using particular mathematical models.

The structure type of the electric cable, the physical sizes and, by measurements, the temperature values of the air surrounding electric cable and of the cable surface, and the live wire current value of the electric cable, also.

2. The calculus of the linear thermal resistances

A cross-section through three-phase cable is shown in the Fig.1. The main parts of the cable are: 1 – the conductor; 2 – the electric insulation of the conductor; 3 – the filling material; 4 – the outer jacket.

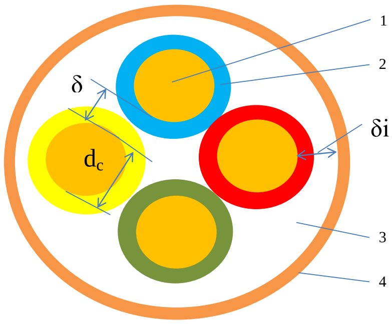

Fig. 1 - Cross section through a power cable

From the technical point of view to heat transmission resulting in cable conductors by Joule's effect we are interested of power W_1 losses and of the linear thermal resistances R_T of the power cable layers (insulation, filling material, outer jacket). Per unit length (1 m) R_T is named linear thermal resistance of the thermal circuit. The losses of power W_1 are also counted on length unit of cable and on time unit. The thermal flow transmission takes place from warm source, the cable wires, to the cold source (atmosphere) through the insulating layers of the power cable and the environment surrounding it. The linear thermal resistances R_T can be calculated using the following equations [1]:

- R_T for the conductor's insulation and the filling material:

$$R_{T1} = \frac{\rho T_1}{2\pi} \cdot G \left[\frac{\mathrm{K} \cdot \mathrm{m}}{\mathrm{W}} \right] \tag{1}$$

$$G = f\left(N, \frac{\delta}{\delta_i}, \frac{\delta_i}{d_c} \right) \tag{2}$$

where: G is the shape coefficient of the cable, d_c is the wire diameter, and ρ_{T1} is the thermal resistivity of the wire insulation material.

The G shape coefficient value, depending on the conductors' number N of the cable and the value of the ratio between the thickness of the wire cable insulation δ_i and the diameter of the wires d_c and of the ratio between filling material thickness δ and the conductor insulation thickness δ_i, is graphically described in [1].

- R_T of the second layer, the outer jacket:

$$R_{T2} = \frac{\rho T_1}{2\pi} \cdot \ln \frac{d_e}{d_{mi}} \left[\frac{\mathrm{K \cdot m}}{\mathrm{W}} \right] \tag{3}$$

where: d_e is the outer diameter of the cable jacket, d_{mi} is the inner diameter of the outer jacket and ρ_{T2} is the thermal resistivity of the cable jacket material.

In the case of a cable laid in air, the thermal flow transmission through air surrounding cable is done mainly by the convection and radiation phenomenon.

- R_T the environment thermal linear resistance can be calculate using the following relation:

$$R_{T3} = \frac{1}{\pi \cdot d_e \cdot (\alpha_{cv} + \alpha_r)} \left[\frac{\mathrm{K \cdot m}}{\mathrm{W}} \right] \tag{4}$$

where: α_{cv} and α_r are thermal convection and radiation coefficients [11]:

$$\alpha_{cv} = \frac{\lambda \cdot N_u}{d_e} \tag{5}$$

$$N_u = 0.9 \cdot (G_r \cdot P_r)^{0.2} \tag{6}$$

$$\alpha_{cv} = \frac{\lambda}{d_e} \cdot 0.9 \cdot (G_r \cdot P_r)^{0.2} \tag{7}$$

where: λ is the thermal conductivity, [W/ m·K], Nu is the Nusselt number, G_r, P_r is Grashof's criterion and Prandtl's criterion:

$$G_r = \frac{g \cdot \beta}{\vartheta^2} \cdot d_e^{\,3} \cdot \Delta\theta_s \tag{8}$$

where: ϑ is kinematic viscosity, β is the thermal coefficient of expansion of the environment, g is acceleration of gravity:

$$\beta = 1/(273.15 + \theta_{a\_med}) \tag{9}$$

$\Delta\theta s = \theta_s - \theta_a$ is the difference between cable surface temperature θ_s and air surrounding temperature θ_a; $\theta_{a\_med} = (\theta_s + \theta_a)/2 = \Delta\theta_s/2 + \theta_a$ is the average air temperature;

$$\alpha_{cv} = M \cdot d_e^{-0.4} \cdot (\theta_s - \theta_a)^{0.2} \tag{10}$$

$$M = 0.9 \cdot \lambda \cdot \left(\frac{g \cdot \Pr}{\vartheta 2 \cdot (273.15 + \theta a\_med)} \right) = 0.92784 \tag{11}$$

$$\alpha_r = \varepsilon_i \cdot K \cdot \frac{(273.15 + \theta_s)^4 - (273.15 + \theta_a)^4}{\Delta\theta_s} \qquad (12)$$

where: ε_i is the emission coefficient of the cable surface, K is the Boltzmann's constant.

Using relation (11) can be determined the coefficient *M* for an average temperature value of the air surrounding power cable. The value of coefficient *M* is shown in the Table no. 1, for θa_med value between 0 ºC and 70 ºC [4]

Table 1

The convection coefficient value depending on the physical properties of dry air

θa_med [°C]	λ [W/m·K]	$\vartheta \cdot 10^6$ [m^2/s]	*Pr*	M
0	0.0244	13.28	0.707	0.9238
10	0.0251	14.16	0.705	0.9226
20	0.0259	15.06	0.703	0.9253
30	0.0267	16.00	0.701	0.9275
40	0.0276	16.96	0.699	0.9332
50	0.0283	17.95	0.698	0.9322
60	0.0290	18.97	0.696	0.9310
70	0.0296	20.02	0.694	0.9267
Average				**0.9278**

3. The calculus of the power cable conductors electrically heated

In a steady-state regime, the boundary surface of the cable related to environment and the cable jackets surfaces become isothermal surfaces. Starting from the boundary surface (outer jacket temperature), the interior isothermal surfaces of cables have increasing temperatures, reaching a maximum value on the cable conductor's surface. By analogy between the conducting phenomenon of the heat flowing in steady state regime (Fourier law) and the electric current flowing through conductors (Ohm's law), an equivalent electric diagram [1] has established. For the case of a cable laid in air (the cable is of LV), this is shown in the figure no. 2:

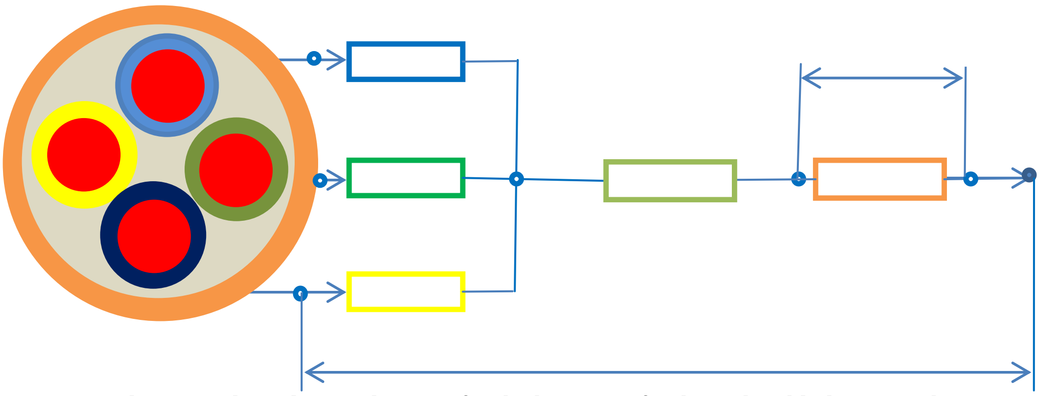

Fig. 2 .The equivalent electric diagram for the heat transfer through cable layers to the environment.

Using the symbols from equivalent electric diagram can be writing the following system of equations:

$$3 \cdot W_1 \cdot \left(\frac{R_{T1}}{3} + R_{T2} + R_{T3} \right) = \theta_c - \theta_a = \Delta\theta_c \tag{13}$$

$$3 \cdot W_1 \cdot R_{T3} = \theta_s - \theta_a = \Delta\theta_s \tag{14}$$

For determination of the electrical cable conductors heating, θ_c, have to calculate the linear thermal resistances values, R_{T1} and R_{T2}, of the cable components and the environmental thermal resistance R_{T3}.

As resulted from relations (1) ÷ (3), for the thermal resistances determination of the cable components $R_{T1} \div R_{T3}$ are required the cable jackets diameters and thermal resistivity ρ_T of the insulating materials from which the cable jackets are made of. These data (ρ_T) are not always specified by the manufacturer. The diameters of cable jackets can be measured if there are cable samples to be analysed. The thermal resistance R_{T3} can be determine using equations (4) ÷ (11).

According to [1], the losses of energy W_1 generated by Joule effect in cable conductors are calculated by following relation:

$$W_1 = R_{cca} \cdot I^2 \tag{15}$$

where: I is the electric current through conductor in permanent regime, on A, R_{cca} is the alternating current linear resistance, on the conductor's length unit, at θ_c temperature, in Ω/m, [1].

$$R_{cca} = R_{20} \cdot \left[1 + \alpha_{20} \cdot \left(\theta_c - 20\right)\right] \tag{16}$$

where: R_{20} is electric resistance at 20°C, α_{20} [1/grd] is the temperature coefficient of resistance related to temperature of 20°C;

$$R_{20} = \frac{\rho_{20} \cdot l}{s} \tag{17}$$

where: ρ_{20} is the resistivity of the material at temperature of 20°C, measured in direct current, in (Ω mm^2)/m, *l* –is the conductor length, *s* is the conductor cross section.

The equation for the conductor's temperature determination, θ_c, is resulting from relations 13÷17:

$$\theta_c = \frac{\left(\frac{\pi \cdot d_e \cdot (\theta s - \theta a) \cdot (\alpha_{cv} + \alpha_r)}{I^2 \cdot R_{20} \cdot} - 1\right)}{\alpha_{20}} + 20 \tag{18}$$

Knowing the cable surface temperature, θs, and those of the environment, θa, of the current *I*, passing through cable conductors and of the environment resistance R_{T3}, the conductor’s temperature can be determined from equation (18).

4. Results

The analysed cable was of low voltage cable, 06/1kV, typ (N) HXH FE 180 E90, 3x25 mm^2 +16 mm^2, the outer diameter d_e = 0.0281 m, the inner diameter of the outer jacket d_{mi} = 0.0237 m, the insulating thickness δ_i = 0.0024 m, the filling material thickness δ = 0.0028m, the wire diameter d_c = 0.0059 m and the cable jacket thickness δinv = 0.0022m. According to [1] for δ_i/δ = 1 (the up curve) and δ_i/d_c = 0.4, results G = 1.4 (G_1), as shown in Fig. 3 (curves -¨-, for cables with four conductors).

For the polyethylene, a material similar to the material HXH FE 180 E90, the specific resistance according to [12] has the value: ρ_{T1}=3.5 W/m·K and according to (1) and (2), results: R_{T1}=0.78 K·m/W, R_{T2}=0.095 K·m/W. For the electrical conductors’ heating determination of low voltage cables, mathematically simulated by equations (1)÷(18), the SIMULINK application has been used. The thermal resistance values of the cable component parts R_{T1} and R_{T2}, the environmental temperature θ_a, and the current *I*, passing through cable conductors have been considered as input data.

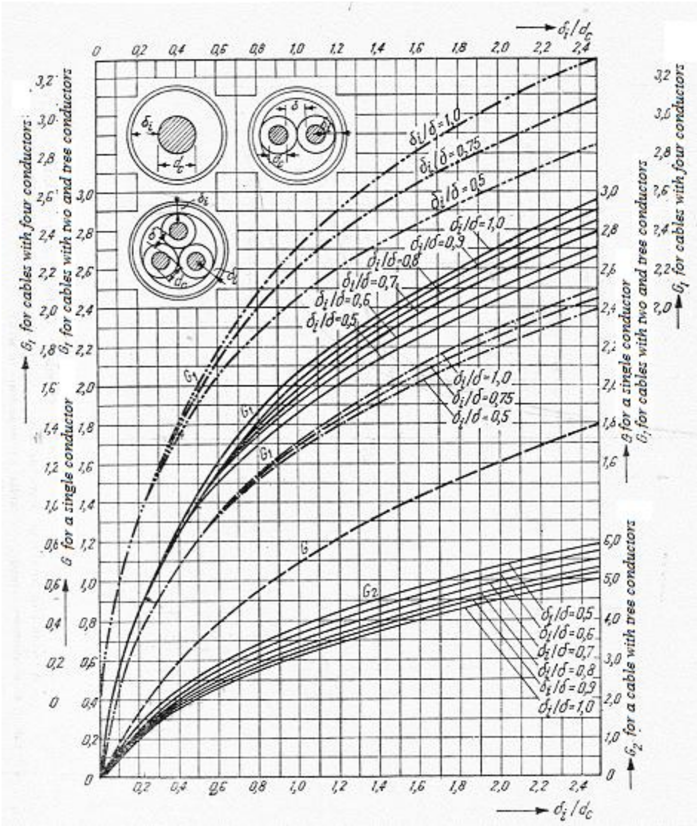

Fig. 3 – The variation of G shape coefficient factor versus δi/δ and δi/dc for cables, [1].

The block diagram of the calculus programme for the cable conductors' heating and the simulation programme results are shown in Fig. 4, the temperature θc being of 58.7°C.

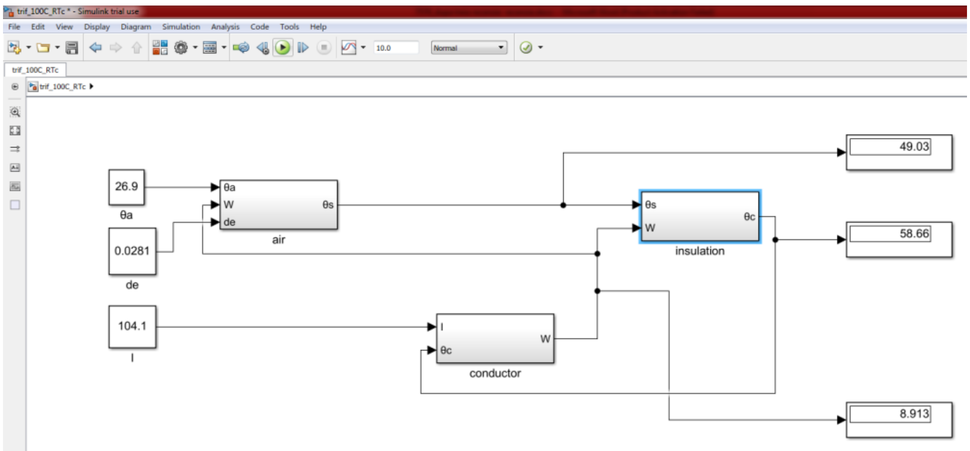

Fig. 4 - SIMULINK application block diagram – the temperature value for ρ_T = 3.5 K·m/W.

The measured temperature value of the cable conductors was of 55.5ºC. To develop alternatively a more accurate assessment methods for cable's conductors temperature being analysed, have measured and recorded the environmental temperature values θ_a and of the cable surface θ_s, using a data acquisition system. For instance, the working screen is shown in the Fig.5 and the measured values for about 15 minutes of monitoring time are given in the Table 2.

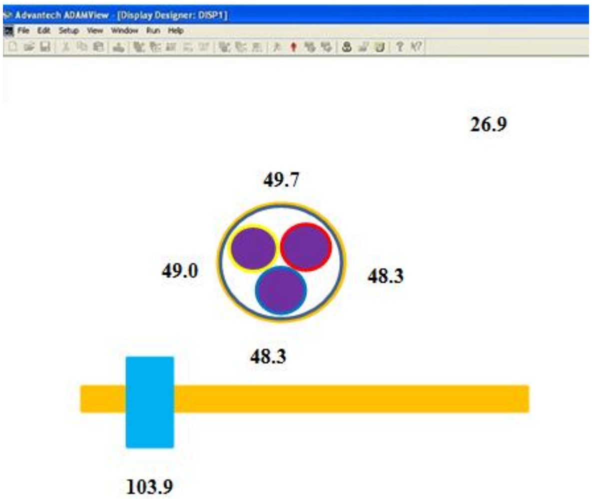

Fig. 5. The working display for cable surface temperature using DAQ system.

Table 2

The temperature values of the cable component parts using DAQ system

θ_a (°C)	θ_{s_down} (°C)	θ_{s_right} (°C)	θ_{s_left} (°C)	θ_{s_top} (°C)	$\theta_{s\_average}$ (°C)	I (A)
26.8	48.4	48.3	49.1	49.8	48.9	104.3
26.8	48.2	48.6	49.0	49.7	48.9	104.4
27.1	48.0	48.5	49.0	49.6	48.8	104.4
27.1	48.1	48.7	49.0	49.7	48.9	104.2
27.2	48.2	48.7	49.2	49.6	48.9	104.0
27.0	48.1	48.4	49.0	49.7	48.8	103.9
27.0	48.3	48.3	49.3	49.7	48.9	103.9
26.9	48.3	48.3	49.0	49.7	48.8	103.9
26.8	48.1	48.2	48.9	49.6	48.7	104.0
26.9	48.0	48.4	49.0	49.5	48.7	103.9
26.8	48.0	48.2	48.8	49.6	48.6	104.0
26.8	47.9	48.1	48.8	49.6	48.6	103.8
26.9	48.1	48.3	48.9	49.6	48.7	103.9
26.8	48.0	48.4	48.9	49.6	48.7	104.2
26.9	**48.1**	**48.4**	**49.0**	**49.6**	**48.8**	**104.1**

For the measurement of the cable surface temperature θ_s and of the environment temperature θ_a are using thermocouples and for the current measurement through conductors, *I*, a transducer having output current of 4 - 20 mA. For the electrically conductors heating determination of low voltage cables the SIMULINK application was used. The environmental temperature θ_a, the average cable surface temperature θ_s, and the current *I*, passing through cable conductors have considered as input data. The block diagram of the calculus programme for the cable conductors heating is shown in the Fig.6.

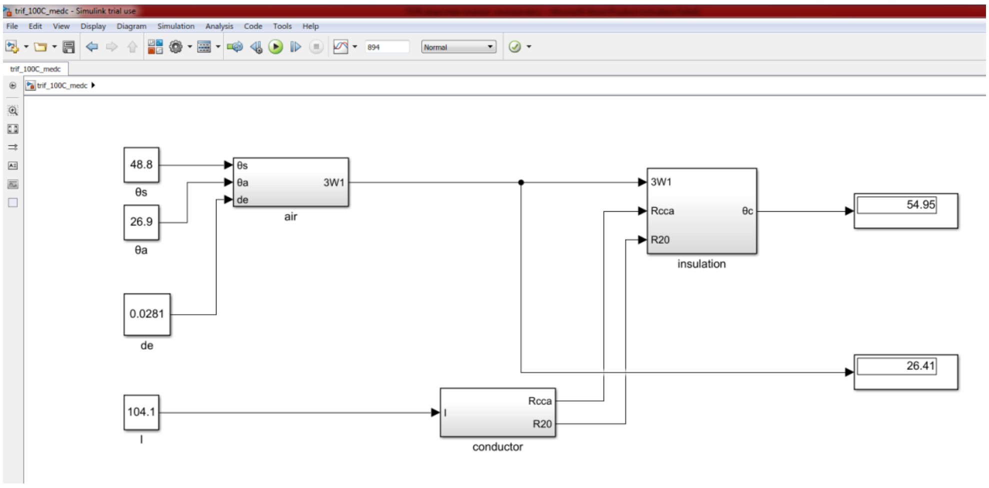

Fig. 6. SIMULINK application block diagram – the conductor's temperature value

The calculated temperature values of the cable conductors was of 55 °C, for a current of 104.1 A, at the air temperature of 26.9°C and for a cable surface temperature of 48.8 °C.

Arrhenius law is often used as a physical model for lifetime prediction due of thermal ageing. It assumes that the rate of thermal ageing mechanism of polymers material decreases with the inverse of the temperature, [13].

According to Arrhenius law for the temperature values of the cable's conductors determined above (T_1), the equation of constant rate is the following:

$$k_1 = A \cdot e^{-\frac{E}{R \cdot T_1}}. \tag{19}$$

For the temperature values of the cable's conductors T_2, the equation of constant rate is the following:

$$k_2 = A \cdot e^{-\frac{E}{R \cdot T_2}}. \tag{20}$$

where: T_2 is the temperature (K) of the thermal accelerated ageing cable insulation, E = 110 kJ/mol is the activation energy of a thermal oxidation reaction, for temperatures greater than 100 °C, E =79.1 kJ/mol – is the activation energy of a thermal oxidation reaction, for the temperatures smaller than 100 °C, A is constant for the material being tested, R=8.314 J/K·mol is the universal gas constant.

The lifetime (D_1=1/k_1) for a power cable in the long-term regulated service regime with a specific temperature (T_1) is calculated with following equation:

$$D_1 = D_2 \cdot e^{-\frac{E}{R}\cdot\frac{T_1 - T_2}{T_1 \cdot T_2}} \tag{21}$$

where: D_2 is the time for accelerated thermal ageing condition for which the elongation at breaking was 50 % of initial elongation.

The results are shown in the Table 3.

Table 3

The lifetime values of the cable materials for the temperature values fitted

For calculated values D_1 with temperature values T1:	T_1 (K)	T_2 (K)	D_2 (years)	D_1 (years)
T_1 real	273+55.5	379.3	0.67	37.86
T_1 calculated with (RT_1)	273+58.7	379.3	0.67	28.74
T_1 calculated with (θ_S)	273+55.0	379.3	0.67	39.56
The difference: D_1 (RT_1)–D_1 (real)				**9.1**
The difference D_1 (θ_s) –D_1(real)				**1.7**

An 81 % $\left(\frac{9.1-1.7}{9.1}\cdot 100\right)$ error decreasing is found out in the case of temperature determination of cable's conductor by cable surface temperature measurement, using a data acquisition system.

5. Conclusions

In the case of cable laid in air, the heat flow is conducting to the outer jacket of the cable by conduction and from there, by convection and radiation to the environment. In a steady-state regime, the boundary surface of the cable become the isothermal surfaces. Beginning from the outer jacket temperature, the interior isothermal surfaces of cables have the temperatures increasing, reaching a maximum value on the cable conductor's surface. The conductor temperature depends of power losses inside of cable, the linear thermal resistances of the cable jackets and those of the environment.

The manufacturer does not always specify the thermal specific resistances of the materials. If those from the technical literature are used, the cable conductors heating value is different from the real one. The difference is between 2 ÷ 6 °C. At the lifetime calculus, this difference leads to a years-order deviation. For determination, the electrical heating of the cable laid in air with an increased accuracy, can be used a data acquisition system for the measurement of the cable surface temperature, the environment temperature and of the current passing through cable. The working in variable operating conditions could be more or less severe and impact on cable components ageing may remain unknown. Consequently, the service life cannot by accuaratelу predicted. The results are useful for detection and management of the ageing phenomenon for the NPP power cables' materials. Those cables works in steady service condition and under a constant environmental temperature. There is an issue to provide the non-aged initial samples of power cable manufactured many years ago for laboratory tests.

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