Key Engineering Materials
ISSN: 1662-9795, Vol. 954, pp 125-133

Submitted: 2023-03-01
Accepted: 2023-05-02
Online: 2023-08-31

Investigation of the Impact Properties of the Material of the Isolation on the Parameters of the Loaded Cable Lines

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Keywords: cable line, current loading, line thermal resistance of the heat transfer, material of the isolation, maximum allowed current

Abstract. The thermodynamic model of work of the loaded cable line is presented. The received mathematical ratio allows to define the maximum allowed current loadings of the cable line in the form of a single-core cable product with the single-layer isolation depending on material and thickness of layer of isolation. It is constructed dependences of the maximum allowed current for a single-core wire of a certain section with one layer rubber (or polyvinilchloride) isolation from insulation layer thickness at various temperatures of the environment and the coefficients of the heat conductivity.

1 Introduction

Cable products are one of types of materials that is used for building. Cable products are an aggregate of materials and wares (power and control cables, send-offs, electric cords and others like that) that is used for a transmission and distribution of electric energy [1].

The statistical data about the fires in Ukraine [2] demonstrates that in the country there has been the unsatisfactory situations with the fires from the cable products. The problem of fire safety of electric cables has also worsened due to the increase in the number of fires at thermal power plants, nuclear power plants [3-5] and other large energy facilities [6, 7]. Fire safety of cable products is relevant for industrial electrical appliances, units, other electrical systems and is one of the criteria for the reliability of their work [8, 9]. Among the electro-technical products on fire insecurity the cable products takes first place (about 60% of the fires, 20% of the dead cases and 70% of direct loss of material property). At the production of cable products the main measures of decrease in their fire insecurity is the reduction of combustible materials masses and the use of the materials with the lowered level of inflammability, smoke - and gas emission [10]. The counted period of service of cable products is in average 30 years. On the real objects the cable products are operated much longer time. The branched cable communications are not only the carriers of a fire load, but also the guiding systems along which fire can propagate in buildings and structures [6, 11]. Therefore as a part of cable lines the cable products which were mounted at the different building constructions are operated and, respectively have to be more fire-safe in comparison with the modern cable products [12].

During the operation the properties of the insulating materials gets change: the electric resistance, heat-conducting properties and other properties decrease [13]. Owing to deterioration in the operational characteristics of the cable lines there is set, in particular, a reduction the maximum allowed current loading.

Research of time-history properties of materials of cable wares work is sanctified to [14]. The question of heat exchange between cable busses and environment is devote works [15-20]. In works [21, 22] offered approach to determination of remaining term of exploitation of building constructions. Results over of experimental researches of correlation between the dangerous factors of self-ignition of materials in apartments are brought in-process [23, 24]. In the articles [25, 26] the described methodology of study of the technical state of steel constructions, high temperatures damaged as a result of influence [27] is in particular from the fires caused by fire from cable products. In [28, 29] it is shown that the cause of catastrophic consequences and destruction is the non-compliance of the actual limit of fire resistance of building structures with regulatory requirements. In [30] the method of operative prognostication of fires is offered, in particular from cable wares. Development of method is needed for the foresight of early fire in apartments, premises [31], to take measures for prevention of their outgrowing in the phase of the out-of-control burning [32, 33]. To the timely exposure of increase of temperature, in particular round cable busses, works are devoted [34-38].

2 Unresolved Issues

The analysis of the literature references [3-38] and others data showed the absence of the accurate mathematical solution the heat exchange thermodynamic getting worse between the loaded cable line and the external space.

3 Main Part

Let's estimate the influence of the thermodynamic properties of the isolation material on the parameters of the loaded cable lines. For this purpose we will construct a thermodynamic model of the work of the loaded cable line, that is we will estimate heat exchange between the cable line and external space and we will define its maximum allowed current loadings. Let's solve for the elementary a case of the single-core cable product with single-layer isolation laid in the air. The structure that is investigated, is given on Fig.1.

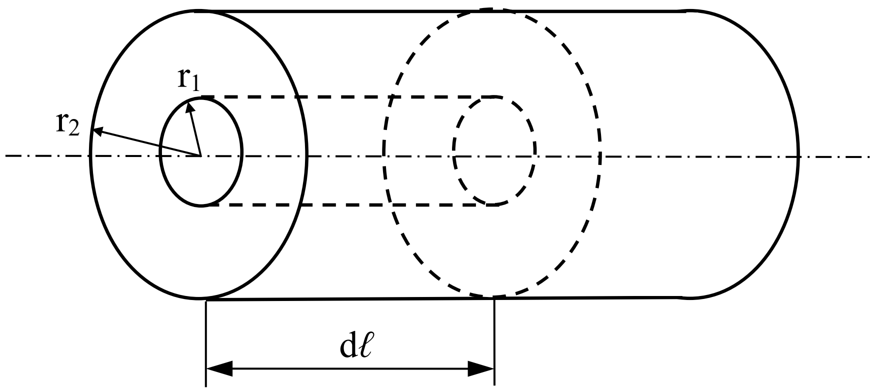

Fig. 1. A Single-core cable product with the single-layer isolation (r_1 – radius of the conducting lived, r_2 – the maximum external radius of the cable)

According to the law of Joule-Lenz [39] at the passing of the electric current force on I with the length $\mathrm{d}\ell$ in the unit of the time amount of heat is available:

$$\mathrm{d}W = I^2 \cdot \mathrm{d}R = I^2 \cdot \rho \cdot \frac{\mathrm{d}\ell}{\mathrm{S}}, \tag{1}$$

where is the

$\mathrm{d}W$ – amount of heat that is available per the unit of the time, J;

R – electrical resistance lived, Ω;

ρ – specific electrical resistance of material lived, Ω ·m;

S – the cross-sectional area of conducting lived the radius, m^2.

The cross-sectional area of conducting lived stars is connected with its radius r_1 to a formula:

$$\mathrm{S} = \pi \cdot r_1^2 . \tag{2}$$

The equation to a heat transfer for a multilayered cylindrical wall has an appearance [40, 41]:

$$\mathrm{d}Q = \frac{t_1 - t_{air}}{R_\ell} \cdot \mathrm{d}\ell , \tag{3}$$

where is the

$\mathrm{d}Q$ – a stationary heat flux through the side surface of the cable product on the site with the length $\mathrm{d}\ell$, W;

t_1 – temperature of the lived, K;

t_{air} – air temperature of the environment, K;

R_ℓ – by the permanent (stationary) thermal resistance to a heat transfer from a surface conducting lived in air, $\frac{K \cdot m}{W}$.

At the stationary thermal mode the ratio is carried out

$$\mathrm{d}W = \mathrm{d}Q . \tag{4}$$

From formulas (1), (3) and (4) we find a ratio between the current that proceeds on the cable products, and others thermodynamic to the system parameters:

$$I = \sqrt{\frac{S}{\rho} \cdot \frac{t_1 - t_{air}}{R_\ell}} . \tag{5}$$

The linear thermal R_ℓ resistance to a heat transfer from a surface conducting lived in air is determined by a formula:

$$R_\ell = R_{\lambda,\ell} + R_{\alpha,\ell} , \tag{6}$$

where is the

$R_{\lambda,\ell}$ – linear thermal resistance of heat conductivity of the cable product, $\frac{K \cdot m}{W}$;

$R_{\alpha,\ell}$ – linear thermal resistance of a convection from the outer surface of a cable product in the air, $\frac{K \cdot m}{W}$.

The linear thermal resistance $R_{\lambda,\ell}$ of the heat conductivity of a cable product is determined by a formula:

$$R_{\lambda,\ell} = \frac{1}{2\pi\lambda_2} \cdot ln\left(\frac{r_2}{r_1}\right), \tag{7}$$

where is the

λ_2 – coefficient of the heat conductivity of the insulating material of a cable product, $\frac{W}{m \cdot K}$;

Linear thermal resistance $R_{\alpha,\ell}$ of a convection from the outer surface of a cable product in the air is defined by a formula:

$$R_{\alpha,\ell} = \frac{1}{2\pi \cdot r_2 \cdot \alpha} = \frac{1}{\pi \cdot \lambda_{air} \cdot Nu} \approx \frac{1}{\pi \cdot \lambda_{air} \cdot Nu_0} , \tag{8}$$

where is the

α – thermolysis coefficient from a surface of a cable product, $\frac{W}{m \cdot K}$;

λ_{air} – value of coefficient of the heat conductivity of the air at the certain temperature, $\dfrac{W}{m \cdot K}$;

Nu_0 – Nusselt's number of process of a convection thermolysis between the air and the surface of the cable product.

Nusselt's number is defined from the criteria equation which in case of the free convection looks like:

$$Nu = C \cdot (Gr \cdot Pr)^n \ , \tag{9}$$

where is the

Gr – Grasgof's criterion;

Pr – Prandtl's criterion.

The work of criteria of Grasgof Gr and Prandtl Pr depends on properties of the air, the temperature Δt difference between the surface of the cable and the air and the radius of the cable product.

The values C and n are also permanent in the corresponding limits of change of the work $(Gr \cdot Pr)$. For example, at the air temperature t_{air}= 298 K and the temperature pressure $\Delta t = 20$ K the work profit $(Gr \cdot Pr)$ is equal:

$$Gr \cdot Pr = 1{,}4 \cdot 10^4 \cdot (\frac{r}{r_0})^3 , \tag{10}$$

where is the

$r_0 = 10^{-2}$ m – the normalizing coefficient.

If $0{,}4 < \left(\dfrac{r}{r_0}\right) < 40$, then $C = 0{,}5$, $n = 0{,}25$ [40].

If $0{,}004 < \left(\dfrac{r}{r_0}\right) < 0{,}4$, then $C = 1{,}2$, $n = 0{,}125$ [40].

Thus, the maximum allowed current I_{max} for a cable product at the temperature inhabited ($t_1 > t_{air}$) can be calculated by a formula

$$I_{max} = \sqrt{\frac{S}{\rho} \cdot \frac{t_1 - t_{air}}{R_\ell}} = \sqrt{\frac{S}{\rho} \cdot \frac{t_1 - t_{air}}{R_{\lambda,\ell} + R_{\alpha,\ell}}} = \sqrt{\frac{S}{\rho} \cdot \frac{t_1 - t_{air}}{\dfrac{1}{2\pi \cdot \lambda_2} \cdot ln\left(\dfrac{r_2}{r_1}\right) + \dfrac{1}{\pi \cdot \lambda_{air} \cdot Nu_0}}} . \tag{11}$$

Let's check the correctness of the formula (11). In [42, 43] it is given proceeded admissible currents for the new cable products depending on their design and service conditions. In particular at the temperatures lived t_1= 338 K and surrounding environments t_{air}= 298 K for the wire with rubber or polyvinylchloride isolation with a section of 10 mm^2 at an open way to laying proceeded admissible current equally $I_{possible} = 80$A (table 1.3.4 [42]). Coefficient of heat conductivity of new rubber or polyvinylchloride isolation $\lambda_2 = 0{,}16 \div 0{,}19 \dfrac{W}{m \cdot K}$, Coefficient of heat conductivity of the air $\lambda_{air} = 2{,}6 \cdot 10^{-2} \dfrac{W}{m \cdot K}$, specific electrical resistance of copper $\rho = 1{,}72 \cdot 10^{-8}\ \Omega \cdot m$ [40]. To the cross-sectional area $S = 10\ mm^2$ of a single wire there corresponds radius $r_1 = 1{,}78 \cdot 10^{-3}$m, the maximum radius of the cable r_2 is accepted equal $r_2 = 4 \cdot 10^{-3}$m, we receive: $R_{\lambda,\ell} = 0{,}716 \dfrac{K \cdot m}{W}$,

$Nu_0 = 2{,}807$, $I_{max} = 68$ A . The value I_{max} which is calculated differs from standard $I_{possible}$ for 15% that can be considered satisfactory.

On figure 2 it is given dependence of the maximum allowed current I_{max} for a copper single-core wire with one layer rubber (or polyvinylchloride) isolation from the insulation layer thickness at the various ambient temperatures.

On figure 3 it is given the dependence of the maximum allowed current I_{max} for a copper single-core wire with one layer rubber (or polyvinylchloride) isolation from the coefficient of heat conductivity of rubber or polyvinylchloride isolation at the different thickness of an insulation layer on the standard conditions it agrees [42] (temperature lived $t_1 = 338$ K , temperature surrounding environments t_{air}).

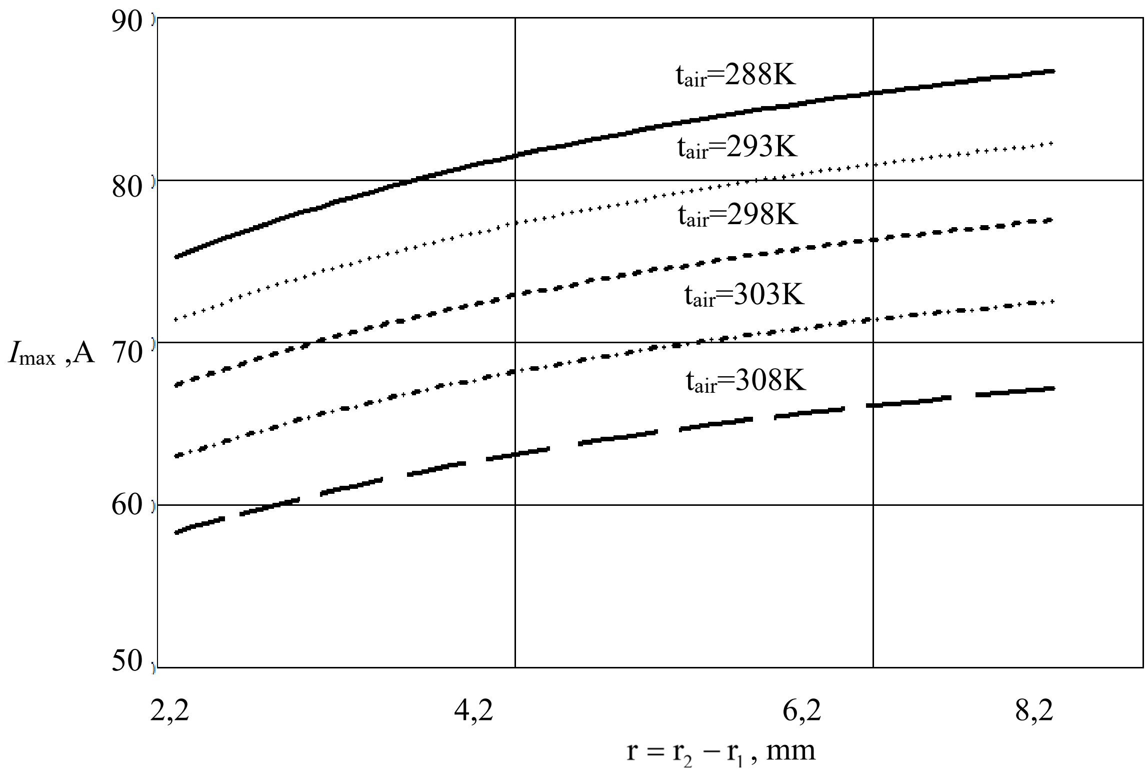

Fig. 2. The dependence of the maximum allowable current I_{max} for a copper single-core wire with a single layer of rubber (or polyvinyl chloride) insulation on the coefficient of thermal conductivity of rubber or polyvinyl chloride insulation at different ambient temperatures

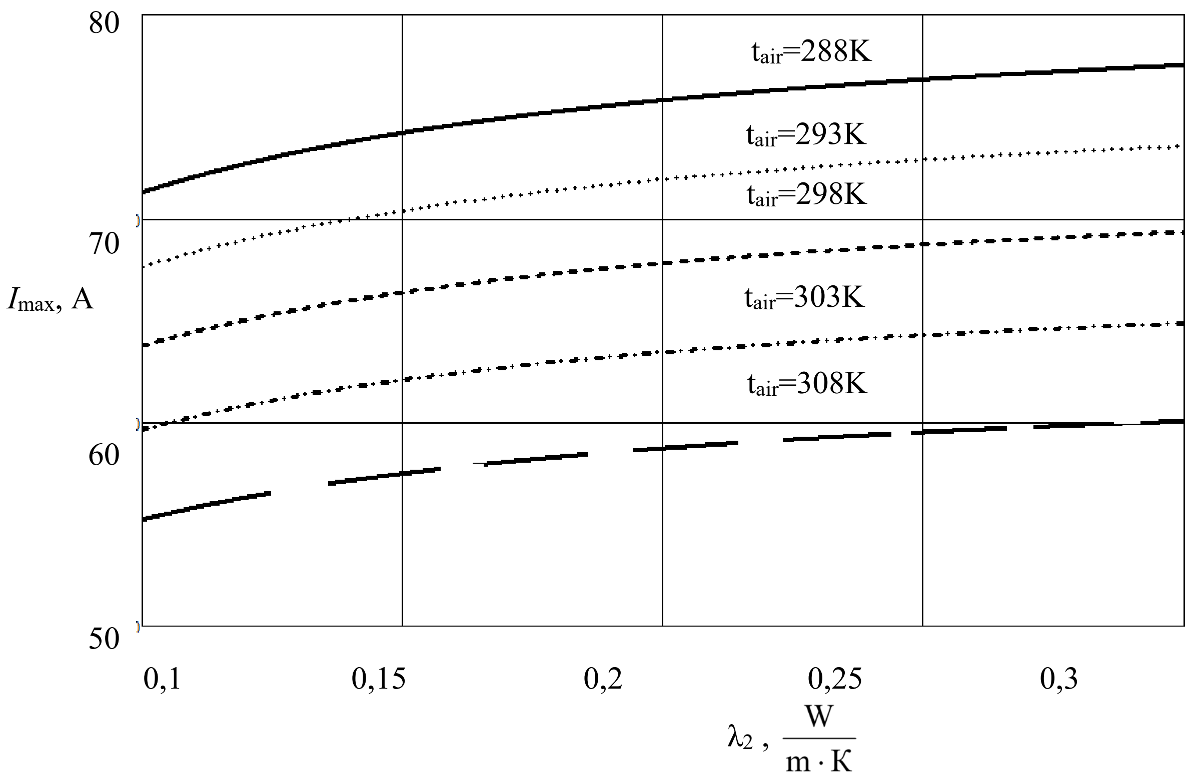

Fig. 3. The dependence of the maximum allowed current I_{max} for a copper single-core wire with one layer rubber (or polyvinylchloride) isolation from coefficient of heat conductivity of rubber or polyvinylchloride isolation at various ambient temperatures

4 Conclusion

The analysis of dependence of the maximum allowed current I_{max} for the copper single-core wire with one layer rubber (or polyvinylchloride) as material of isolation from insulation layer thickness at various ambient temperatures allows to draw the following conclusions:

- the value of the maximum allowed current significantly depends on insulation layer thickness, at the same time growth I_{max} corresponds to the growth of the thickness $r = r_2 - r_1$ - it is caused by the fact that the growth of thickness of the isolation provides the decrease in the heat exchange with the environment;

- the environment temperature also affects the value of the maximum allowed current: Its growth causes decrease I_{max}: so at r=4,2 mm growth of the temperature on 5^0C causes to the decrease I_{max} approximately on 5 A in the certain conditions;

- in the conditions of identical ambient the temperature increases in value with the growth I_{max} of the thickness of the isolation happens not linearly: at $t_{air} = 288$ K change of value r from 2,8 mm to 5,5 mm causes growth from I_{max} 76,9 A to 86,7 A; at $t_{air} = 298$ K change of value r from 2,8 mm to 5.5 mm causes growth from I_{max} 68,8 A to 72,5 A; at $t_{air} = 308$ K change of value r from 2,8 mm to 5,5 mm causes growth from I_{max} 59,6 A to 67,1 A.

The analysis of graphic dependences of the maximum allowed current I_{max} for the copper single-core wire with one layer rubber (or polyvinylchloride) as material of isolation from coefficient of the heat conductivity rubber or polychlorinated isolation at the various ambient temperatures confirms the following:

- the value of the maximum allowed current depends on coefficient of heat conductivity of isolation not linearly, at the same time growth I_{max} corresponds to growth of coefficient λ_2 - it is defined by the fact that growth of coefficient of heat conductivity causes reduction of value of linear thermal resistance of a convection thermolysis from an outer surface of the wire in the air;

- temperature the environment similarly previous case affects value of the maximum allowed current I_{max}: its growth causes decrease: so at λ_2 = 0,2 growth of temperature on 5^0C a reason to decrease I_{max} approximately on 5 A in certain conditions;

- in the conditions of identical ambient temperature increase I_{max} in value with a growth of coefficient of heat conductivity of isolation happens as follows: at t_{air}=288К change of value λ_2 from 0,1 mm to 0,3 mm causes growth I_{max} from 71,3 A to 77,5 A; at t_{air}=298К change of value λ_2 from 0,1 mm to 0.3 mm - growth I_{max} with 63,6 A to 69,3 A; at t_{air}= 308 K change of value λ_2 from 0,1 mm to 0,3 mm – growth I_{max} with 55,2 A to 60,1 A.

Received graphic dependences of the maximum allowed current for a copper single-core wire with one insulation layer from heat conductivity coefficient at various ambient temperatures in a complex to schedules of dependences of the maximum allowed current for the copper single-core wire with one insulation layer from insulation layer thickness at the various ambient temperatures allow to develop recommendations in relation to exploitation of cable products under various conditions in accordance with composition of material of isolation of her thickness and thermophysical descriptions of material.

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