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Investigation the Intensity of Heating of the Isolation Material of an Electrical Wire

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Abstract. The intensity of heating of the insulation material of loaded electric wires was investigated. Calculations were made for insulation materials made of polyvinyl chloride plastic and rubber, and copper and aluminum wires. The dependences of the heating temperature of the wires on the time of their operation at load currents smaller, close to and larger than the maximum allowable ones are plotted. The time during which you spend heated to critical temperatures, is individual for each brand-size. For wires with a copper core, heating occurs more slowly compared to wires with an aluminum core. Wires with polyvinyl chloride core insulation heat up more slowly than wires with rubber core insulation. In all cases, addiction temperature of the wires from the time of operation at different load currents has a logarithmic form.

1 Introduction

The thermal effect of electric current is the main dangerous manifestation during the operation of cable products (hereinafter referred to as CP) from the point of view of fire hazard. If an electric current flows through the cable product, the value of which is greater than the value for which it is designed, then the insulation and the current-carrying core are heated. Heating can lead to ignition of the insulation, which can disable the cable line or cause a fire [1, 2]. Their operation in emergency modes and the formation of ignition sources in these modes lead to the occurrence and development of HF fires [3, 4]. Ignition of CP can occur under the influence of internal and external sources of ignition. External sources of ignition for CP are open flames formed during ignition of objects located near them and excessive heat emitted from heat-generating installations and burning products [5, 6]. Of course, the influence of external sources of ignition on CP causes their short circuit, which can also contribute to the acceleration of the fire development process from them [7, 8]. Insulated wires and cables also potentially contribute to the development of fire [9,10]. The spread of flame along long cable lines, including through unsealed passages of partitions and ceilings, and the involvement of other objects placed next to them in this process, leads to the fire covering a significant surface of buildings and structures [11, 12]. Such fires are not always detected in the early stages, which leads to their more intensive development, increases the extinguishing time, and therefore the damage caused to the environment [13, 14]. Most often, emergency conditions do not allow to relieve the tension in the area covered by fire, especially since the situation requires emergency measures and quick solutions [15, 16].

In general, the temperature of the cable product depends on:
- the strength of the current flowing through its veins;
- ambient temperature;
- core cross-section and insulation thickness;
- conditions of heat exchange with the environment;
- specific resistance of the current-carrying core material;
- duration of the emergency mode of operation.

Devices for the protection of electrical networks may be triggered with a delay. Therefore, it is quite important to estimate the temperature (and therefore the fire hazard) to which the cable product will heat up before the electrical network is disconnected by the protection device.

Currently, mathematical models are proposed, the use of which allows you to estimate the heating temperature of cable products in emergency and normal operating modes. In [17], a thermodynamic model of the operation of a loaded cable line was built. The obtained mathematical ratio allows determining the maximum permissible current load of the cable line in the form of a single-core cable product with single-layer insulation, depending on the material and the thickness of the insulation layer. In work [18], a mathematical model was built based on the heat balance equation, which allows obtaining the dependence of the heating temperature of the insulation material of a single-core electric wire with single-layer insulation on the strength of the current flowing and the time of its flow. In work [19], using the mathematical model proposed in [18], the influence of the thickness of the insulation material (polyethylene, polyvinyl chloride, enamel, and rubber) of the wire on its heating temperature during operation was estimated.

In [20], studies of temperature changes during a fire in a cable tunnel were carried out. During the research, a sequence of procedures was created with a detailed selection of equipment and test samples in order to provide reliable experimental data in the investigation of the temperature regime of the fire in the cable tunnel. It was established that the temperature increases faster in the burning zone compared to the standard fire temperature regime.

In the paper [21], the authors presented the results of studies of the electrothermal effect of aperiodic pulses of a temporary form of 10/350 μs current of a short stroke of artificial lightning on experimental samples of electric wires and cables with copper and aluminum cores and sheaths made of polyvinyl chloride and polyethylene. It is shown that the thermal stability of such wires and cables is determined by the integral of the action of the specified current pulse; the authors found the maximum permissible and critical densities of this pulse in copper and aluminum current-carrying parts of wires and cables.

2 Unresolved Issues

The analysis of literary sources [17–21] and others showed the inadequacy of the study of the intensity of heating of insulating materials of electric wires of typical standard sizes depending on the time of operation at different current loads for different materials from which the electric wire is made. Since CP objects have a long length and a large number of connections, the probability of their ignition and damage from internal and external sources of ignition is very high. In this regard, there is a high risk of failure of the security systems to perform their functions due to failure of the cable power lines of these systems. However, the fire hazard of CP can be reduced to a minimum if the above aspects of fire hazard are taken into account in the complex during the design of CP, their manufacture and application at objects [22, 23].

3 Main Part

We assume that the temperature of the core and insulation of an electric wire is the same throughout its thickness, while the wire is located in the air.

In work [18], the dependence of the temperature T of the heating material of the insulation of a single-core electric wire with single-layer insulation (fig. 1) on the strength of the flowing current I and the time t of its flow (formula (1)) was mathematically obtained.

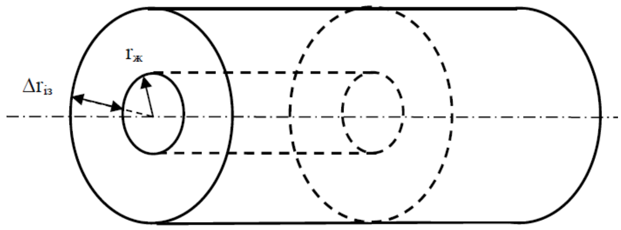

Fig. 1. A wire with the single-layer isolation ($r_ж$ – radius of the conducting lived, $\Delta r_{iз}$ – thickness of isolation of the wire)

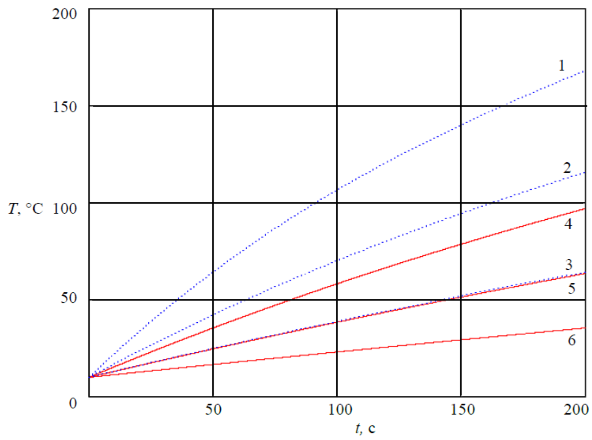

Fig. 2. Dependence of the temperature T of the H05V-A 2,5 and H05V-U 2,5 wires on the operating time t at load currents *I* (curve 1 – H05V-A 2,5 at *I* = 40 A; curve 2 – H05V-A 2,5 at *I* = 30 A; curve 3 – H05V-A 2,5 at *I* = 20 A; curve 4 – H05V-U 2,5 at *I* = 40 A; curve 5 – H05V-U 2,5 at *I* = 30 A; curve 6 – H05V-U 2,5 at *I* = 20 A)

$$T(t) = T_п + \frac{T_п}{\psi_1} \cdot \left[\psi_2 \cdot (\omega - 1) \cdot t + \psi_2^2 \cdot \omega \cdot (\omega - 1) \cdot \frac{t^2}{2} + \psi_2^3 \cdot \omega \cdot (\omega - 1) \cdot (3\omega - 2) \cdot \frac{t^3}{6} \right], \tag{1}$$

where the coefficients are determined by formulas

$$\omega = \frac{\delta_1 \cdot (\delta_3 + \delta_5)}{(1 + \delta_4) \cdot (\delta_6 - \delta_2)} + 1, \; \psi_1 = \frac{\delta_3 + \delta_5}{1 + \delta_4}, \; \psi_2 = \frac{\delta_6 - \delta_2}{1 + \delta_4}, \; \delta_1 = \frac{I^2 \cdot \rho_{ж0}}{\pi^2 \cdot r_ж^4 \cdot \gamma_ж \cdot C_{ж0} \cdot T_п},$$

$$\delta_2 = \frac{I^2 \cdot \rho_{ж0} \cdot \alpha}{\pi^2 \cdot r_ж^4 \cdot \gamma_ж \cdot C_{ж0}}, \; \delta_3 = T_п \cdot \varphi_ж, \; \delta_4 = \frac{\gamma_{iз} \cdot \pi \cdot (\Delta r_{iз}^2 + 2 r_ж \cdot \Delta r_{iз}) \cdot C_{iз0}}{\gamma_ж \cdot \pi \cdot r_ж^2 \cdot C_{ж0}},$$

$$\delta_5 = \frac{\gamma_{iз} \cdot \pi \cdot (\Delta r_{iз}^2 + 2 r_ж \cdot \Delta r_{iз}) \cdot C_{iз0} \cdot \varphi_{iз} \cdot T_п}{\gamma_ж \cdot \pi \cdot r_ж^2 \cdot C_{ж0}}, \quad \delta_6 = \frac{2 \cdot \pi \cdot (r_ж + \Delta r_{iз}) \cdot a}{\gamma_ж \cdot \pi \cdot r_ж^2 \cdot C_{ж0}}$$

and the following designations apply:
T – is the heating temperature of the insulation material, ^{0}C;
I – current strength, A;
t – current flow time, s;
$T_п$ – air temperature, ^{0}C;
$r_ж$ – radius of the wire core, m;
$\Delta r_{iз}$ – thickness of wire insulation material, m;
$\gamma_ж$ – density of the wire core material, kg/m^3;
$\gamma_{iз}$ – density of wire insulation material, kg/m^3;
$C_{ж0}$ – heat capacity of the material of the wire core at the initial moment of time, J/^{0}C;
a – heat transfer coefficient from insulation to air, W/m^2 ^{0}C;
$\rho_{ж0}$ – specific electrical resistance of the material of the wire core at the initial moment of time, Ohm·m;
$C_{iз0}$ – heat capacity of the insulation material of the wire at the initial moment of time, J/^{0}C;
α, $\varphi_ж$, $\varphi_{iз}$ – thermal coefficients.

Formula (1) takes into account the relationship between the parameters of the radius of the cable product and the cross-sectional area of the insulation, the relationship between the radius of the cable product and the radius of the core taking into account the thickness of the insulation, the relationship between the cross-sectional area of the insulation and the cross-sectional area of the core.

Formula (1) makes it possible to analyze the influence of the composition of the core and the insulation of the electric wire on the temperature of its heating during their operation at specified values of the currents and, thus, to determine dangerous modes of operation.

Let's determine the intensity of heating of polyvinyl chloride and rubber insulation of a loaded electric wire with copper and aluminum single-wire cores. According to the national classification electrical wires of standard sizes ПВ1 2,5, АПВ 2,5 (according to GOST 6323 [24]), ПР1 2,5 and АПР 2,5 will be investigated (according to the European classification [25] – electric wires of standard sizes H05V-U 2,5, H05V-A 2,5, H05R-U 2,5 and H05R-A 2,5).

In fig. 2 shows the dependence of the temperature T of H05V-A 2,5 and H05V-U 2,5 wires, calculated by formula (1), on the operating time t in the range t=0÷200 s at load currents *I*=20, 30, 40 A.

In fig. 3 shows the dependence of the temperature T of H05R-A 2,5 and H05R-U 2,5 wires, calculated by formula (1), on the operating time t in the range t=0÷200 s at load currents *I*=20, 30, 40 A.

In fig. 4 shows the dependence of the temperature T of wires of standard sizes H05R-A 2,5, H05V-A 2,5, H05R-U 2,5 and H05V-U 2,5 on the operating time t in the range t= 0÷200 s with load current *I*=20 A. In fig. 5 shows a similar dependence at the load current *I*=30 A. Fig. 6 shows a similar dependence at the load current *I*=40 A.

The following input data were used in the calculations:

radius of the core of the wire $r_{ж} = 8.92\times10^{-4}$ m;

wire insulation thickness $\Delta r_{із} = 10^{-3}$ m;

thermal coefficient for aluminum and copper core $\varphi_{ж} = 0.00026$;

thermal coefficient for polyvinyl chloride plastic and rubber wire insulation $\varphi_{із} = 0.0003$;

density of polyvinyl chloride plastic wire insulation material $\gamma_{із} = 1350$ kg/m^3;

density of the material of the rubber insulation of the wire $\gamma_{із} = 900$ kg/m^3;

density of the material for the copper core of the wire $\gamma_{ж}=8960$ kg/m^3;

density of the material for the aluminum core of the wire $\gamma_{ж}=2700$ kg/m^3;

the heat capacity of the copper core of the wire at the initial moment of time $C_{ж0} = 373$ J/^{0}C;

the heat capacity of the aluminum core of the wire at the initial moment of time $C_{ж0} = 673$ J/^{0}C;

heat capacity of polyvinyl chloride plastic wire insulation at the initial moment of time $C_{із} = 1200$ J/^{0}C;

heat capacity of the rubber insulation of the wire at the initial moment of time $C_{із} = 1400$ J/^{0}C;

thermal coefficient for polyvinyl chloride plastic and rubber insulation of the wire a = 0.003 W/m$^2\cdot{}^0$C;

thermal coefficient for aluminum and copper wire core $\alpha = 0.00433$;

air temperature $T_{п} =10$ °C;

air temperature $\rho_{ж0}=1.89\cdot10^{-8}$ $\Omega\cdot$m;

specific electrical resistance of the aluminum core of the wire at the initial moment of time $\rho_{ж0}=3.2\cdot10^{-8}$ $\Omega\cdot$m.

Load current values *I* chosen for the reasons of the maximum permissible currents, normalized according to [26] for the wires of the marked sizes that were studied. The continuous maximum permissible current load during open laying is for wires: ПВ1 2,5 (H05V-U 2,5) and ПР1 2,5 (H05R-U 2,5) – 30 A; АПВ 2,5 (H05V-A 2,5) and АПР 2,5 (H05R-A 2,5) – 24 A.

Dependencies were calculated using the MahtCad mathematical software package.

According to national standards [26], for cable products with polyvinyl chloride plastic or rubber insulation, the maximum allowable core heating temperature for long-term insulation is 70 °C, for short-term overload – 90 °C, for short-circuit current – 160 °C.

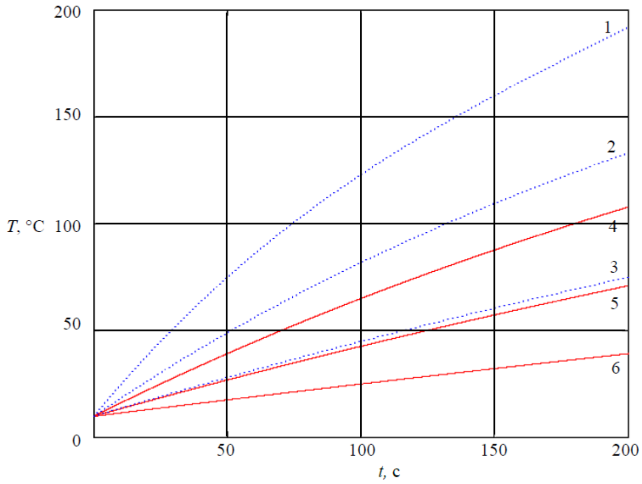

Fig. 3. Dependence of the temperature T of the H05R-A 2,5 and H05R-U 2,5 wires on the operating time t at load currents *I* (curve 1 – H05R-A 2,5 at *I* = 40 A; curve 2 – H05R-A 2,5 at *I* = 30 A; curve 3 – H05R-A 2,5 at *I* = 20 A; curve 4 – H05R-U 2,5 at *I* = 40 A; curve 5 – H05R-U 2,5 at *I* = 30 A; curve 6 – H05R-U 2,5 at *I* = 20 A)

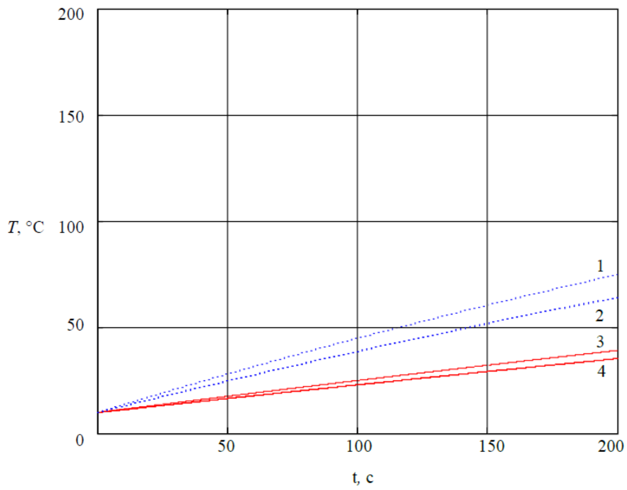

Fig. 4. Dependence on temperature T of wires of mark sizes H05R-A 2,5 (curve 1), H05V-A 2,5 (curve 2), H05R-U 2,5 (curve 3) and H05V-U 2,5 (curve 4) from the operating time t in the range t=0÷200 s at the load current *I*=20 A

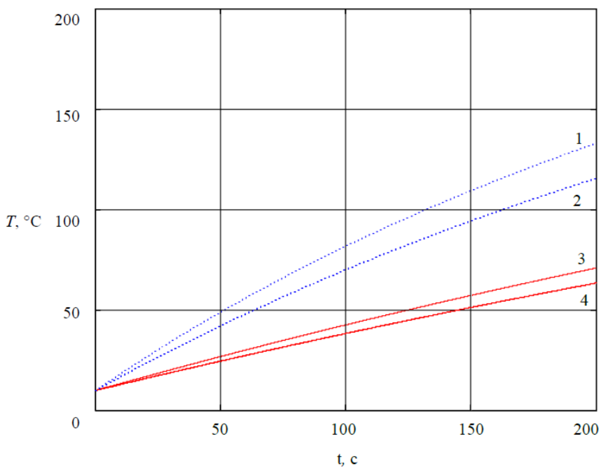

Fig. 5. Dependence on temperature T of wires of mark sizes H05R-A 2,5 (curve 1), H05V-A 2,5 (curve 2), H05R-U 2,5 (curve 3) and H05V-U 2,5 (curve 4) from the time of operation t in the range t=0÷200 s at the load current *I*=30 A

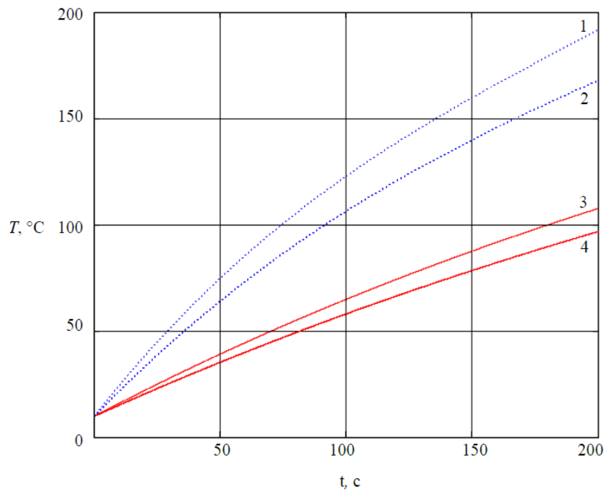

Fig. 6. Dependence on temperature T of wires of mark sizes H05R-A 2,5 (curve 1), H05V-A 2,5 (curve 2), H05R-U 2,5 (curve 3) and H05V-U 2,5 (curve 4) from the time of operation t in the range t=0÷200 s at the load current *I*=40 A

4 Conclusion

Analysis of the temperature dependences T constructed in section 3 of wires of standard sizes ПВ1 2,5 (H05V-U 2,5), ПР1 2,5 (H05R-U 2,5), АПВ 2,5 (H05V-A 2,5) and АПР 2,5 (H05R-A 2,5) from the operating time t at the specified load currents I allows the following conclusions to be drawn.

For wire АПВ 2,5 (H05V-A 2,5) a temperature of 70 °C with a load current of *I* = 20 A is not reached within 200 s, with a load current of *I* = 30 A equal to 99 s, with a load current of *I* = 40 A equal to 56 s. A temperature of 90 °C at a load current of *I* = 20 A is not reached within 200 s, at a load current of *I* = 30 A it is equal to 140 s, at a load current of *I* = 40 A it is equal to 79 s. The temperature of 160 °C at load currents *I* = 20 A and *I* = 30 A is not reached within 200 s, at load current *I* = 40 A it is equal to 185 s. According to [26] the maximum allowable current load for wire АПВ 2,5 (H05V-A 2,5) with open laying is 24 A, which confirms the correctness of the obtained results.

For wire ПВ1 2,5 (H05V-U 2,5) temperature of 70 °C at load currents *I* = 20 A and *I* = 30 A is not reached within 200 s, at load current *I* = 40 A is equal to 128 s. The temperature of 90 °C at load currents *I* = 20 A and *I* = 30 A is not reached within 200 s, at load current *I* = 40 A it is equal to 180 s. The temperature of 160 °C at load currents *I* = 20 A, *I* = 30 A and *I* = 40 A is not reached within 200 s. According to [26] the maximum allowable current load for wire ПВ1 2,5 (H05V-U 2,5) with open laying is 30 A, which confirms the correctness of the obtained results.

For wire АПР 2,5 (H05R-A 2,5) a temperature of 70 °C with a load current of *I* = 20 A is equal to 182 s, with a load current of *I* = 30 A is equal to 80 s, with a load current of *I* = 40 A is equal to 45 s. The temperature of 90 °C at a load current of *I* = 20 A is not reached within 200 s, at a load current of *I* = 30 A it is equal to 114 s, at a load current of *I* = 40 A it is equal to 64 s. The temperature of 160 °C at load currents *I* = 20 A and *I* = 30 A is not reached within 200 s, at load current *I* = 40 A it is equal to 150 s. According to [26] the maximum allowable current load for wire АПР 2,5 (H05R-A 2,5) with open laying is 24 A, which confirms the correctness of the obtained results.

For wire ПР1 2,5 (H05R-U 2,5) a temperature of 70 °C with a load current of *I* = 20 A is not reached within 200 s, with a load current of *I* = 30 A is equal to 197 s, with a load current of *I* = 40 A is equal to 110 s. The temperature of 90 °C at load currents *I* = 20 A and *I* = 30 A is not reached within 200 s, at load current *I* = 40 A it is equal to 155 s. The temperature of 160 °C at load currents *I* = 20 A, *I* = 30 A and *I* = 40 A is not reached within 200 s. According to [26] the maximum allowable current load for wire ПР1 2,5 (H05R-U 2,5) with open laying is 30 A, which confirms the correctness of the results obtained.

It can be concluded that the time spent ПВ1 2,5 (H05V-U 2,5), ПР1 2,5 (H05R-U 2,5), АПВ 2,5 (H05V-A 2,5) and АПР 2,5 (H05R-A 2,5) heated to critical temperatures of 70 °C, 90 °C and 160 °C, is individual for each brand-size. For wires with a copper core (ПВ1 2,5 (H05V-U 2,5), ПР1 2,5 (H05R-U 2,5)) heating occurs more slowly compared to wires with an aluminum core (АПВ 2,5 (H05V-A 2,5) and АПР 2,5 (H05R-A 2,5)).

Wires with polyvinyl chloride core insulation (ПВ1 2,5 (H05V-U 2,5), АПВ 2,5 (H05V-A 2,5)) heat up more slowly compared to wires with rubber core insulation (ПР1 2,5 (H05R-U 2,5), АПР 2,5 (H05R-A 2,5)). In all cases, addiction temperature T of the wires from the time of operation t at different load currents *I* has a logarithmic form.

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