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MODEL ASSESS THE IMPACT OF THE CHEMICAL COMPOSITION OF THE CONDUCTIVE VEINS ON THE OPERATIONAL CHARACTERISTICS OF AN ISOLATED ELECTRICAL WIRE

The influence of the chemical composition of the conductive core of an insulated electric wire with single-layer isolation on its heating temperature depending on the operating time at different load currents is investigated. An improved mathematical model was used, which allows us to estimate the temperature increase of a single-core electric wire with the time of operation. The calculations were carried out using computer equipment in the MATHCAD software package for a copper conductor with impurities of iron, cobalt, and manganese in different proportions. For example, the temperature-time dependences for the PVC1 2.5 (H05V-U 2.5) electric wire were built for load currents less than, equal to, and greater than the maximum permissible values. The analysis of the obtained temperature-time characteristics made it possible to state that the heating temperature of electric wires during their operation is significantly determined by the impurity material of the copper conductor. The paper shows that the temperature-time characteristics of PVC1 2,5 (H05V-U 2,5) electric wires with different materials of copper conductor impurities have approximately the same nonlinear character at load currents of 20, 30 and 40 A. The simulation results show that for materials of iron, cobalt, manganese impurities to copper, the highest heating temperature for load currents of 20, 30 and 40 A is achieved by electric wires PVC1 2,5 (H05V-U 2,5) with an iron impurity, and the lowest - with a manganese impurity. It is shown that the heating temperature of an electric wire depends significantly on the number of impurities in the conductor material - as the number of impurities increases, the temperature rises. Therefore, the heating temperature of electric wires with different volumes of impurities in the conductor material will differ significantly. At the same time, a tendency was observed to increase the difference between the heating temperatures of electric wires with an increase in the volume of various impurities in the materials of conductive cores for all values of the load current. It was concluded that modeling allows to determine the time during which PVC1 2.5 (H05V-U 2.5) electric wires with various impurities in the conductor material heat up to critical temperatures.

Keywords: *current loading; electrical wire; intensity of heating; material of electrical core; material of the isolation.*

Introduction

Formulation of the problem. At present, the phenomenon of the influence of the chemical composition of conductive cores on the performance characteristics of the CP is not sufficiently studied. Impurities can both improve and deteriorate the performance characteristics of the CP, for example, change the heating temperature during operation.

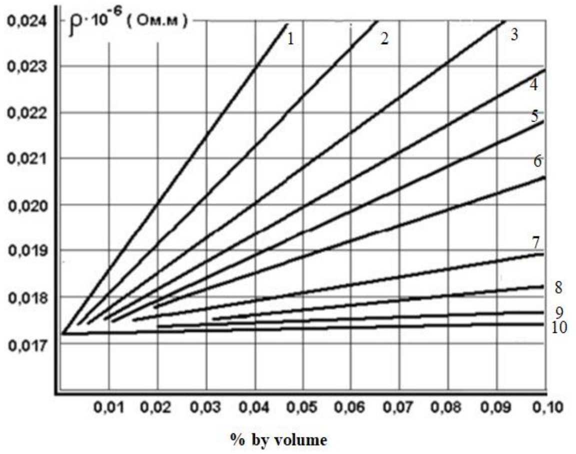
Thus, the problem of determining the influence of the chemical composition of conductive cores on the performance characteristics of the CP is relevant.

The conductors cores of the CP are usually made of aluminum or copper. Metals are not chemically pure substances and may contain various impurities. The main electrical characteristic of metals for CP is their electrical conductivity. The metals of CP`s conductive cores are also subject to requirements for their mechanical properties (in particular, strength), which is due to the peculiarities of their operation. Increasing strength is achieved by introducing impurity chemical elements, which leads to a change in the electrical conductivity of the material of the CP`s conductive core. Therefore, there is a necessity to search for the optimal amount of impurities in the materials of conductive cores of CP and, as a result, to study the effect of impurities on the electrical conductivity of conductive materials.

Analysis of recent research and publications. The thermal effect of electric current is one of the main causes of fires in/from cable products (CP) used as part of electrical networks [1–4]. The ignition of the isolation of CP is caused by internal and external ignition sources [5–6]. The most common internal ignition sources are the thermal effect of short-circuit current and the thermal effect of overload current. External ignition sources in some cases accelerate the fire development process [7]. Isolated CP potentially contribute to the development of fires in premises and buildings [8–11], which leads to environmental pollution [12–13]. To detect pollutants in the atmosphere, various methods and tools are used to determine their composition and concentration [14–17].

Currently, there are mathematical models that allow estimating the heating temperature of the CP over time (calculating the temperature-time characteristics of the CP), for example [18–19]. In [18], a mathematical model was built based on the heat balance equation to determine the dependence of the heating temperature of the isolation material of a single-core electric wire with single-layer isolation on the current strength and time of its flow. In [19], using the mathematical model proposed in [18], the influence of the thickness of the insulation material (polyethylene, polyvinyl chloride, enamel, rubber) of the wire on its heating temperature during operation was assessed.

Impurities can significantly change the electrophysical properties of a material. The degree and nature of this effect depend on the properties of the materials themselves. Figure 1 shows the results of the effect of impurities on the electrical resistance of copper [20]. Even with the addition of 0.1 % silver (a metal with a lower resistivity) to copper, the overall resistance of the metal compound increases by several percent. Chemical impurities such as phosphorus, iron, cobalt, and arsenic reduce the electrical conductivity of copper especially sharply.



1 – phosphorus; 2 – iron; 3 – cobalt; 4 – arsenic; 5 – beryllium; 6 – manganese; 7 – tin; 8 – lead; 9 – silver; 10 – cadmium

Fig.1. Effect of impurities on the electrical resistance of copper

A source: generated by the Authors.

The analysis of literature sources has shown the lack of research on the influence of the chemical composition of conductors on the performance characteristics of CP, in particular, their heating temperature at different current loads. An increase in the heating temperature of CP beyond the permissible values [21] leads to an increase in the likelihood of fire or damage to CP.

Thus, the unresolved part of the problem considered is the lack of a model for assessing the influence of the chemical composition of conductive cores on the temperature and time characteristics of CP.

The purpose of the article is to improve a mathematical model for assessing the influence of the chemical composition of conductive cores on the temperature and time characteristics of CP in the form of an isolated electric wire.

Achieving this goal requires solving the following tasks:

1. To create or modify an existing mathematical model for assessing the influence of the chemical composition of the core on the temperature and time characteristics of an isolated electric wire.

2. Construction and analysis of temperature and time characteristics for the most common macro-sizes of isolated electric wires at different chemical impurities to chemically pure materials of their conductive cores.

Main part

Let's assume that the temperature of the conductor and isolation of the electric wire is constant throughout their thickness, and the electric wire is located openly in the air (for example, laid singly on brackets).

Practical calculations will be carried out on the example of an isolated single-core electric wire with a copper conductor with three types of impurities (iron, cobalt, manganese) and single-layer polyvinyl chloride insulation – PVC1 wire (according to national labelling rules [22]), which is equivalent to H05V-U wire (according to European labelling rules [23]).

The object of study is a single-core electric wire with a copper core and polyvinyl chloride isolation.

The subject of the study is the effect of impurities in the material of the conductive core on the temperature and time characteristics of a single-core electric wire with copper conductor and polyvinyl chloride isolation.

It is assumed that impurities will have a certain effect on the temperature and time characteristics of a single-core electric wire with copper conductor and polyvinyl chloride isolation, which will lead to a change in the safe operating modes of the electric wire.

To build a mathematical model, we will modify the previously proposed model, which allows us to estimate the temperature increase of a single-core electric wire with the time of operation.

The calculations will be carried out by computer hardware in the MATHCAD software package.

In [19], a mathematical model is proposed that allows estimating the temperature increase of a single-core electric wire with the time of operation. The final expression for the calculation is as follows:

$$T(t) = T_a + \frac{T_a}{\varphi_1}\left[\varphi_2(\omega-1)t + \varphi_2^2\omega(\omega-1)\frac{t^2}{2} + \varphi_2^3\omega(\omega-1)(3\omega-2)\frac{t^3}{6}\right], \quad (1)$$

where

$$\omega = \frac{\delta_1(\delta_3+\delta_5)}{(1+\delta_4)(\delta_6-\delta_2)}+1\,, \qquad (2)$$

$$\varphi_1 = \frac{\delta_3+\delta_5}{1+\delta_4}\,, \qquad (3)$$

$$\varphi_2 = \frac{\delta_6-\delta_2}{1+\delta_4}\,, \qquad (4)$$

$$\delta_1 = \frac{I^2\rho_{c0}}{\pi^2 r_c^4 \gamma_c C_{c0} T_a}\,, \qquad (5)$$

$$\delta_2 = \frac{I^2\rho_{c0}\alpha}{\pi^2 r_c^4 \gamma_c C_{c0}}\,, \qquad (6)$$

$$\delta_3 = T_a \varphi_c\,, \qquad (7)$$

$$\delta_4 = \frac{\gamma_{iz}\pi\left(\Delta r_{iz}^2 + 2r_c\Delta r_{iz}\right)C_{iz0}}{\gamma_c \pi r_c^2 C_{c0}}\,, \qquad (8)$$

$$\delta_5 = \frac{\gamma_{iz}\pi\left(\Delta r_{iz}^2 + 2r_c\Delta r_{iz}\right)C_{iz0}\phi_{iz}T_a}{\gamma_c \pi r_c^2 C_{c0}}\,, \qquad (9)$$

$$\delta_6 = \frac{2\pi\left(r_c+\Delta r_{iz}\right)a}{\gamma_c \pi r_c^2 C_{c0}}\,, \qquad (10)$$

where I – current strength, A; T – heating temperature of the isolation material, ^{0}C; t – current flow time, s; T_a – air temperature, ^{0}C; r_c – wire core radius, m; Δr_{iz} – thickness of the wire isolation material, m; γ_c – density of the wire core material, kg/m^3; γ_{iz} – density of the wire isolation material, kg/m^3; C_{c0} – heat capacity of the wire core material at the initial moment of time, J/^{0}C; a – heat transfer coefficient from isolation to air, W/m$^{2\cdot 0}$C; ρ_{c0} – resistivity of the wire core material at the initial time, Ом·m; C_{iz0} – heat capacity of the wire isolation material at the initial time, J/^{0}C; α, φ_c, ϕ_{iz} – thermal coefficients.

The presented mathematical model allows us to calculate the temperature and time characteristics of the operation of single-core CP.

We modify this mathematical model to enable the calculation of temperature and time characteristics for single-core electric wires with copper conductive core with impurities, namely:

– the initial value of electrical resistance is determined according to Fig.1, depending on the volume of impurities in the conductor material;

– calculations are carried out for two volumes of impurities in copper: 0,05 % and 0,01 %.

In the mathematical model, the density of the material of the conductive core of an electric wire is approximately defined as follows:

An Example of equation

$$\gamma_c = \frac{(100-n)}{100}\cdot\gamma_{copper} + \frac{n}{100}\cdot\gamma_{impurity}\,, \qquad (11)$$

where γ_{copper} – copper density; $\gamma_{impurity}$ – density of the impurity material.

The calculations are carried out for a cable of mark-size PVC1 2,5 (H05V-U 2,5). According to [21], the maximum permissible current for this wire is 30 A. Therefore, we construct the temperature-time characteristics for three load currents I = 20; 30; 40 A.

The following input data were used in the calculations for the load time t = 300 s:

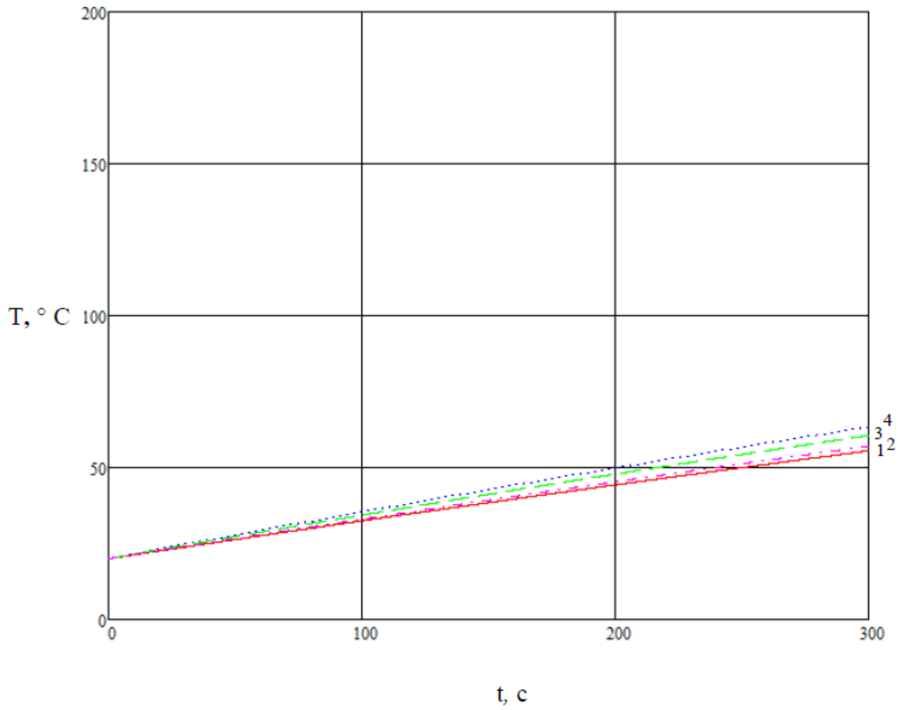
– r_c = 8,92×10^{-4} m;
– Δr_{iz} = 1×10^{-3} m;
– φ_c = 0,000257;
– ϕ_{iz} = 0,0003;
– γ_{iz} = 1350 kg/m^3;
– γ_{copper} = 8960 kg/m^3 for the copper core;
– $\gamma_{impurity}$ = 7874; 8800; 7450 kg/m^3 for iron; cobalt; manganese;
– C_c = 373 J/^{0}C;
– C_{iz} = 1200 J/^{0}C;
– a = 0,003 W/м$^{2\cdot 0}$C;
– α = 0,00433;
– T_a = 20°C;
– ρ_{c0} = 0,000000018; 0,0000000188; 0,0000000208; 0,0000000224 Ом·m (for chemically pure copper conductor; for copper conductor with manganese impurity of 0,05 %; for copper conductor with cobalt impurity of 0,05 %; for copper conductor with iron impurity of 0,05 %, respectively);
– ρ_{c0} = 0,000000018; 0,000000023; 0,0000000247; 0,0000000278 Ом·m (for chemically pure copper conductors; for copper conductors with a manganese impurity of 0,1 %; for copper conductors with a cobalt impurity of 0,1 %; for copper conductors with an iron impurity of 0,1 %, respectively).

Fig.2 shows the temperature-time characteristics for an electric wire PVC1 2,5 (H05V-U 2,5) with impurities in the conductor material of 0,05 % at a load current I = 20 A (curve 1 – copper without impurities; curve 2 – copper with manganese impurities; curve 3 – copper with cobalt impurities; curve 4 – copper with iron impurities).

Fig.3 shows similar characteristics at a load current I = 30 A, Fig.4 – at a load current I = 40 A.

Fig.5 shows the temperature-time characteristics for an electric wire PVC1 2,5 (H05V-U 2,5) with impurities in the conductor material of 0,1 % at a load current I = 20 A (curve 1 – copper without impurities; curve 2 –

copper with manganese impurities; curve 3 – copper with cobalt impurities; curve 4 – copper with iron impurities).



curve 1 – copper without impurities; curve 2 – copper with manganese impurities; curve 3 – copper with cobalt impurities; curve 4 – copper with iron impurities

Fig.2. Temperature-time characteristics for an electric wire PVC1 2,5 (H05V-U 2,5) with impurities in the conductor material of 0,05 % at a load current I = 20 A

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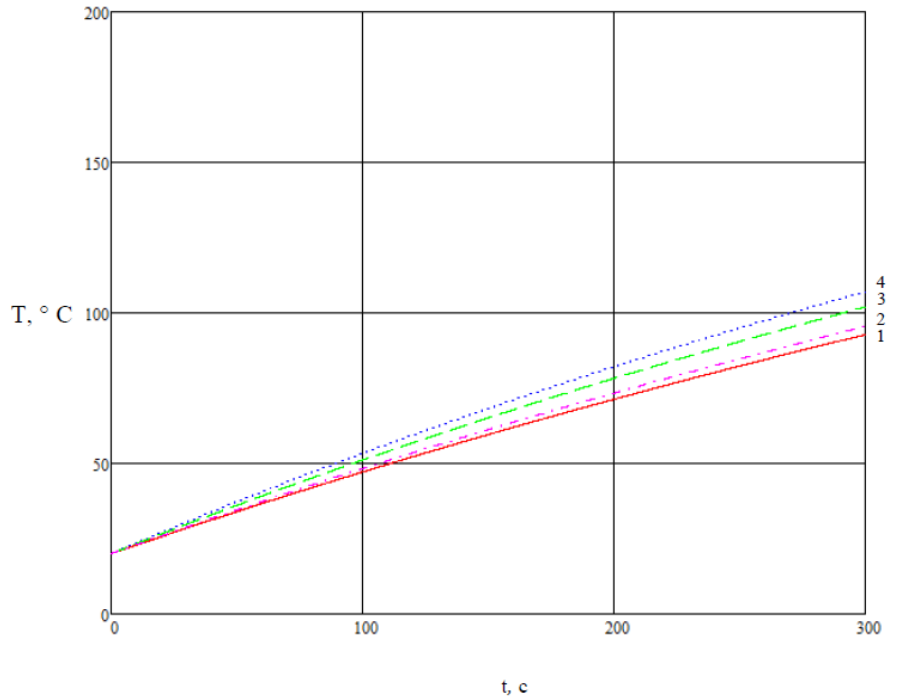

curve 1 – copper without impurities; curve 2 – copper with manganese impurities; curve 3 – copper with cobalt impurities; curve 4 – copper with iron impurities

Fig.3. Temperature-time characteristics for an electric wire PVC1 2,5 (H05V-U 2,5) with impurities in the conductor material of 0,05 % at a load current I = 30 A

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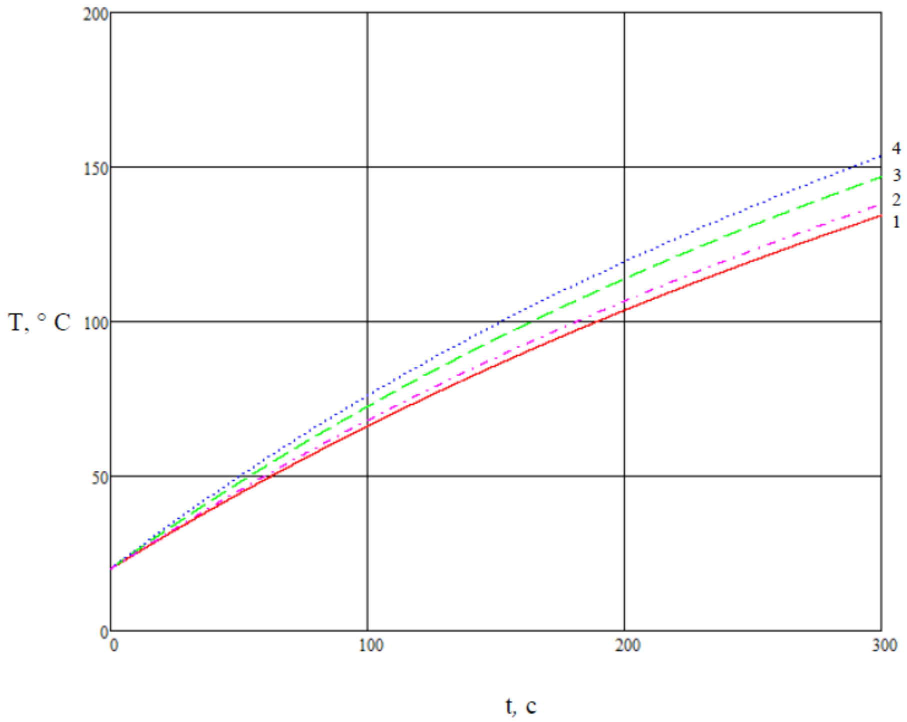

curve 1 – copper without impurities; curve 2 – copper with manganese impurities; curve 3 – copper with cobalt impurities; curve 4 – copper with iron impurities

Fig.4. Temperature-time characteristics for an electric wire PVC1 2,5 (H05V-U 2,5) with impurities in the conductor material of 0,05 % at a load current $I = 40$ A

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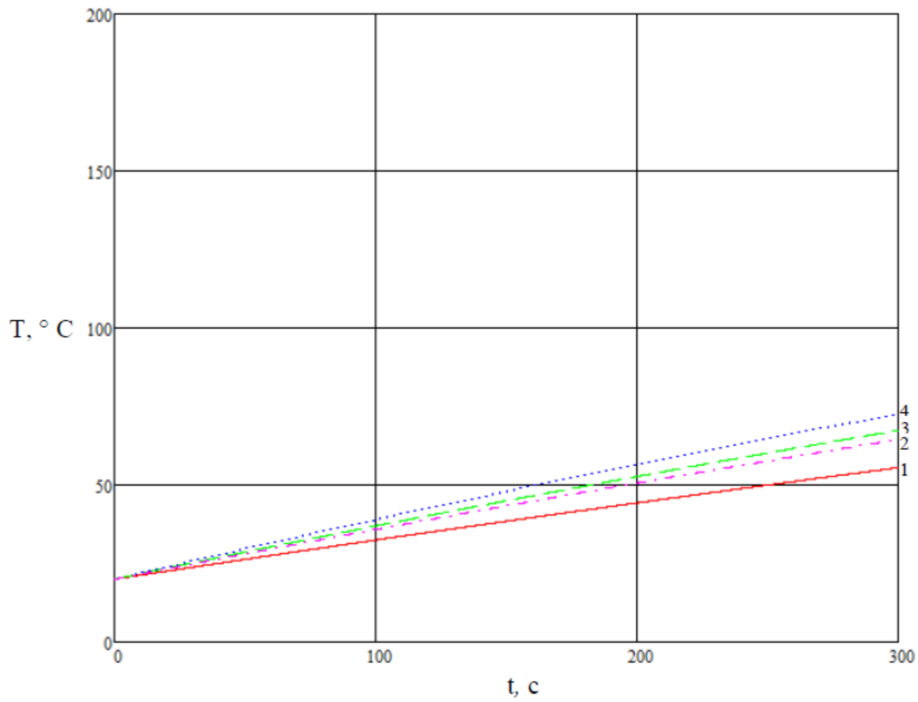

curve 1 – copper without impurities; curve 2 – copper with manganese impurities; curve 3 – copper with cobalt impurities; curve 4 – copper with iron impurities

Fig.5. Temperature-time characteristics for an electric wire PVC1 2,5 (H05V-U 2,5) with impurities in the conductor material of 0,05 % at a load current $I = 20$ A

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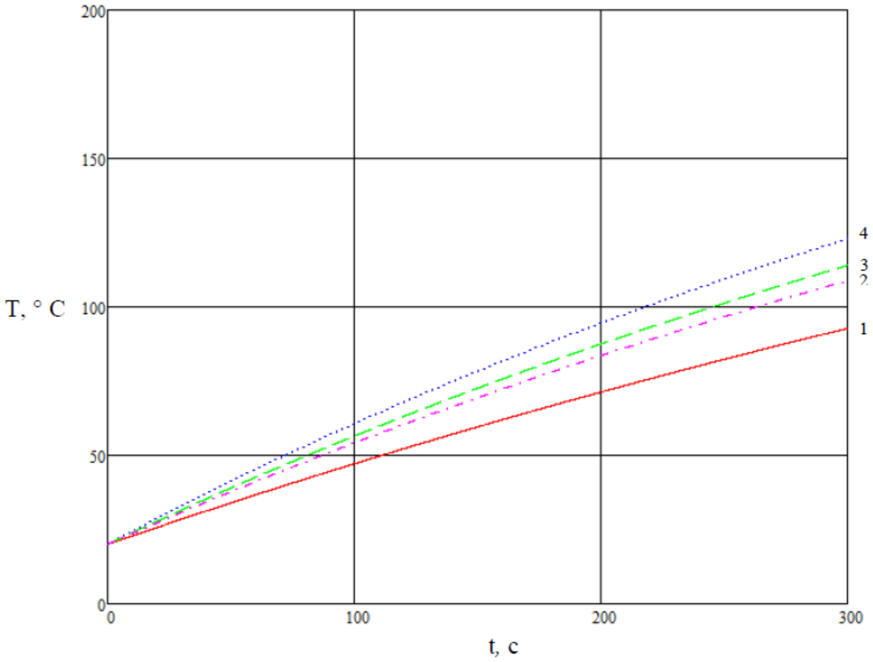

curve 1 – copper without impurities; curve 2 – copper with manganese impurities; curve 3 – copper with cobalt impurities; curve 4 – copper with iron impurities

Fig.6. Temperature-time characteristics for an electric wire PVC1 2,5 (H05V-U 2,5) with impurities in the conductor material of 0,05 % at a load current I = 30 A
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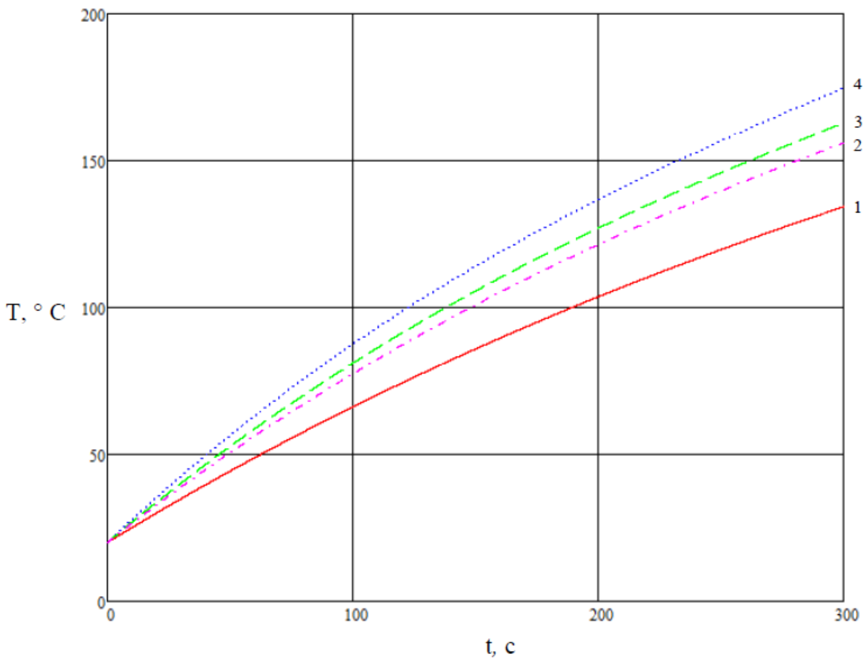

curve 1 – copper without impurities; curve 2 – copper with manganese impurities; curve 3 – copper with cobalt impurities; curve 4 – copper with iron impurities

Fig.7. Temperature-time characteristics for an electric wire PVC1 2,5 (H05V-U 2,5) with impurities in the conductor material of 0,05 % at a load current I = 40 A
A source: generated by the Authors.

Fig.6 shows similar characteristics at a load current I = 30 A, Fig.7 – at a load current I = 40 A.

Thus, the influence of the chemical composition of the conductor core of an insulated electrical wire with single-layer insulation on its heating temperature depending on the operating time at different load currents was evaluated. The calculations were performed using MATHCAD software for a copper conductor with impurities of iron, cobalt, and manganese in various proportions.

Conclusions

Thus, a mathematical model has been improved that allows estimating the temperature rise of a single-core copper conductor over time under various impurities.

The model has been improved by introducing variables for the density of the conductive core material and the initial value of its electrical resistance as functions of the volume of impurities in the material.

The analysis of the constructed temperature-time characteristics allows us to conclude the following.

1. The heating temperature of electric wires during their operation is determined by the impurity material in the copper conductor and depends on the load current.

2. The temperature-time characteristics of PVC1 2,5 (H05V-U 2,5) electric wires with different materials of copper conductor impurities have approximately the same nonlinear character at load currents of 20, 30 and 40 A.

3. For materials of iron, cobalt, manganese impurities to copper, the highest heating temperature for load currents of 20, 30 and 40 A is achieved by electric wires PVC1 2,5 (H05V-U 2,5) with an iron impurity, and the lowest - with a manganese impurity.

4. For a load current of 30 A, the heating temperature of the PVC1 2,5 (H05V-U 2,5) electric wire is less than 70°C, which is lower than the standard long-term permissible temperature for this electric wire.

5. The heating temperature of an electric wire depends significantly on the number of impurities in the conductor material – as the number of impurities increases, the temperature rises. Therefore, the heating temperature of electric wires with different volumes of impurities in the conductor material will differ significantly. At the same time, there is a tendency to increase the difference between the heating temperatures of electric wires with an increase in the volume of various impurities in the materials of conductive cores for all values of the load current. Thus, when heating an electric wire PVC1 2,5 (H05V-U 2,5) with a copper conductor with an iron impurity of 0,05 % within 100 s, the temperature reaches 35°C; 53°C; 76°C for load currents I = 20; 30; 40 A; within 200 s – 50°C; 82°C; 119°C respectively. Meanwhile, when heating a similar wire with a copper conductor with an impurity of iron to the core material of 0,1 % within 100 s, the temperature reaches the values of 39°C; 61°C; 87°C for load currents I = 20; 30; 40 A; within 200 s – 56°C; 95°C; 137°C respectively. This trend is maintained when heating electric wires with copper conductors with cobalt and manganese impurities in the amount of 0,05 % and 0,1 % of the core material.

6. The impact of the load current on the heating temperature of electric wires with all conductor material compositions increases with the increase in operating time. For example, when the electric wire PVC1 2,5 (H05V-U 2,5) with a copper conductor without impurities is heated for 100 s, the temperature reaches 32°C; 47°C; 66°C for load currents I = 20; 30; 40 A; within 200 s – 44°C; 71°C; 103°C. Meanwhile, when heating a similar electric wire with a copper conductor with an impurity of iron to the conductor material of 0,05 % for 100 s, the temperature reaches 35°C; 53°C; 76°C or load currents I = 20; 30; 40 A; within 200 s – 50°C; 82°C; 119°C respectively. This trend is maintained when heating wires with copper conductors with cobalt and manganese impurities in the amount of 0,05 % and 0,1 % of the conductor material.

7. As the operating time increases, the difference between the heating temperatures of electric wires with different conductor material compositions increases for all load current values. In particular, for the electric wire the PVC1 2,5 (H05V-U 2,5) with a copper conductor without impurities and a similar electric wire with a copper conductor with an iron impurity in the core material with a volume of 0,05 % at load current I = 20 A the difference is 3°C after 100 s; after 200 s – 6°C; at load current I = 30 A the difference is 4°C after 100 s; after 200 s – 9°C; at load current I = 40 A the difference is 10°C after 100 s; after 200 s – 16°C. This trend is maintained when heating similar wires with copper conductors with cobalt and manganese impurities in the amount of 0,05 % and 0,1 % of the conductor material.

8. According to national regulations, for cable products with polyvinyl chloride isolation, the maximum permissible core heating temperature during long-term operation is 70°C, during short-term overload – 90°C, at short-circuit current – 160°C. Therefore, from Figs.2–7, it is possible to determine the time during which electric wires PVC1 2,5 (H05V-U 2,5) with various impurities to the conductor material are heated to these critical temperatures. Further research prospects include calculations for aluminum conductors with magnesium, iron, cobalt, and manganese impurities in various ratios.

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МОДЕЛЬ ОЦІНКИ ВПЛИВУ ХІМІЧНОГО СКЛАДУ СТРУМОВІДНИХ ЖИЛ НА ЕКСПЛУАТАЦІЙНІ ХАРАКТЕРИСТИКИ ІЗОЛЬОВАНОГО ЕЛЕКТРИЧНОГО ПРОВОДУ

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Досліджено вплив хімічного складу струмопровідної жили ізольованого електричного проводу з одношаровою ізоляцією на температуру його нагріву в залежності від часу роботи при різних струмах навантаження. Використано вдосконалену математичну модель, яка дозволяє оцінити підвищення температури одножильного електричного проводу з часом експлуатації. Розрахунки проведено із використанням комп’ютерного пакету програм MATHCAD для мідного провідника з домішками заліза, кобальту та марганцю в різних співвідношеннях. Для прикладу побудовані температурно-часові характеристики електричного проводу ПВХ1 2,5 (H05V-U 2.5) для струмів навантаження, менших, рівних і більших гранично допустимих значень. Аналіз отриманих температурно-часових характеристик дозволив стверджувати, що температура нагрівання електричних проводів під час їх експлуатації суттєво визначається домішковим матеріалом в мідному провіднику. У статті показано, що температурно-часові характеристики електричного проводу ПВХ1 2,5 (H05V-U 2.5) з різними матеріалами домішок в мідному провіднику мають приблизно однаковий нелінійний характер при навантаженні 20, 30 і 40 А. Результати моделювання свідчать, що для мідного провідника з домішками заліза, кобальту, марганцю найвищу температуру нагріву при струмах навантаження 20, 30 і 40 А досягають електричні проводи ПВХ1 2,5 (H05V-U 2.5) з домішкою заліза, а найнижчу – з домішкою марганцю. Показано, що температура нагріву електричного проводу суттєво залежить від об’єму домішок до матеріалу струмопровідної жили – зі збільшенням об’єму домішок температура підвищується. Тому, температура нагріву електричних проводів з різними об’ємами домішок до матеріалу струмопровідних жил буде суттєво відрізнятися. При цьому, відмічається тенденція до збільшення різниці між температурами нагріву електричних проводів при підвищенні об’ємів різних домішок до матеріалів струмопровідних жил для усіх значень струму навантаження. Зроблено висновок, що моделювання дозволяє визначати час, протягом якого електричні проводи PVC1 2.5 (H05V-U 2.5) з різними домішками в матеріалі провідника нагріваються до критичних температур.

Ключові слова: *електричний провід; інтенсивність нагрівання; матеріал електричної жили; матеріал ізоляції; струмове навантаження.*