REFINED SELECTION OF ALLOWABLE CROSS-SECTIONS OF ELECTRICAL CONDUCTORS AND CABLES IN THE POWER CIRCUITS OF INDUSTRIAL ELECTRICAL EQUIPMENT TAKING INTO ACCOUNT EMERGENCY OPERATING MODES

Purpose. Implementation and clarification of the existing engineering approach for determination in industrial power engineering for allowable sections of cable-conductor products (CCP) $S_{d}$ of electric wires and cables in the circuits of electrical equipment of the general industrial installations characterized flowing in malfunction of current $i(t)$ of short circuit (SC) with different amplitude-temporal parameters (ATPs). Methodology. Scientific and technical bases of electrical power engineering, electrophysics bases of technique of high voltage and high pulse currents, theoretical bases of the electrical engineering. Results. The results of the developed engineering approach are resulted in the calculation determination on the condition of thermal resistibility of CCP permissible sections of $S_{d}$ of the uninsulated wires, insulated wires and cables with copper (aluminum) cores (shells), polyvinyl chloride (PVC), rubber (R) and polyethylene (PET) insulation, on which in malfunction of their operation the current $i(t)$ of SC can flow with the set by normative documents of ATP. It is shown that divergence between the values of basic calculation coefficient of $C_{d}$ by existing and offered to the engineering calculations selection of permissible sections of $S_{d}$ of cores (shells) of the tested wires and cables for normal of their operating time at the nominal current load of CCP makes no more (3-8) %, and in the mode of de-energizing of CCP arrives at at (9-26) %. Analytical correlation is got for the specified calculation determination of integral of action of $J_{ak}$ of current $i(t)$ of SC (Joule integral) in the power circuits of the tested electrical equipment. It is set that in the circuits of the general industrial installations (for permanent time of slump of $T_{a}=20$ ms of aperiodic cosmopolitan of current of SC) maximum possible amplitudes of density of $\delta_{ilm}=\delta_{ilm}/S_{d}$ of SC current at time of his disconnecting $t_{dC}=100$ ms for the uninsulated wires with copper (aluminum) cores make according to approximately 0.64 (0.36) $kA/mm^{2}$, for cables with copper (aluminum) cores (shells), PVC and R insulation – 0.47 (0.30) $kA/mm^{2}$, and for cables with copper (aluminum) cores (shells) and PET insulation – 0.39 (0.25) $kA/mm^{2}$. At time of disconnecting $t_{dC}=160$ ms of SC current in the circuits of electrical equipment ($T_{a}=20$ ms) permissible amplitudes of current density of $\delta_{ilm}^{*}$ of SC for the uninsulated wires with copper and aluminum cores are accordingly about 0.52 (0.29) $kA/mm^{2}$, for cables with copper (aluminum) cores (shells), PVC and R insulation of 0.39 (0.25) $kA/mm^{2}$, and for cables with copper (aluminum) cores (shells) and PET insulation – 0.32 (0.21) $kA/mm^{2}$. Originality. First by a calculation the specified numeral values of sections of $S_{d}$ and amplitudes of density $\delta_{ilm}$ of SC current are determined for the uninsulated wires, insulated wires and cables with copper (aluminum)cables (shells), PVC, R and PET insulation. New analytical correlation is offered for the calculation estimation of thermal resistibility of tested CCP to the action of current of SC. Practical value. The obtained results will be useful in the increase of thermal resistibility of CCP with copper (aluminum) cores (shells), PVC, R and PET insulation, widely applied in the power circuits of electrical equipment of the general purpose industrial installations. References 6, tables 6.

Key word: electric power engineering, electric wires and cables of circuits of electrical installations of the general industrial purpose, calculation selection of allowable sections of wires and cables in the circuits of electrical equipment.

Надійні результати розробленого інженерного електротехнічного підходу до уточненого розрахункового вибору гранично допустимих перерізів $S_{d}$ електричних неізольованих дротів, ізольованих дротів і кабелей з поліленіхтидоринною (ПЛХ), гумовою (Г) і поліетиленовою (ПЕТ) ізоляцією і мідними (алюмінієвими) жилами (оболонками) по умові їх термічної стійкості, по яких в силових кабеллях електроустановок загальнопромислового призначення в аварійному режимі протікає струм $i(t)$ короткого замикання (КЗ) із заданими параметрами. На підставі цього підходу здійснений уточнений вибір перерізів $S_{d}$ для вказаних дротів (кабелей) силових кіл досліджуваного електрообладнання. Виконана розрахункова оцінка гранично допустимих амплітуд цілісності $\delta_{ilm}$ струму $i(t)$ КЗ в даних дротах і кабелях силових кіл вказанних електроустановок. Отримані результати сприяють підвищенню термічної стійкості електричних незольованих дротів, ізольованих дротів і кабелей з ПЛХ, Г і ПЕТ ізоляцією і мідними (алюмінієвими) жилами (оболонками), які широко застосовуються в силових кабеллях електроустановок загальнопромислового призначення. Бібл. 6, табл. 6.

Ключові слова: електроенергетика, електричні дроти і кабелі кіл електроустановок загальнопромислового призначення, розрахунковий вибір гранично допустимих перерізів дротів і кабелей в кабелях електрообладнання.

Приведені результати дослідження інженерного електротехнічного підходу до уточненого розрахунку вибору гранично допустимих перерізів $S_{d}$ електричних неізольованих проводів, ізольованих проводів і кабелей з поліленіхтидоринною (ПЛХ), гумовою (Г) і поліетиленовою (ПЕТ) ізоляцією і мідними (алюмінієвими) жилами (оболонками) по умові їх термічної стійкості, по яких в силових кабеллях електроустановок загальнопромислового призначення в аварійному режимі протікає струм $i(t)$ короткого замикання (КЗ) із заданими параметрами. На основі цього підходу освоєнені уточнений вибір перерізів $S_{d}$ для вказаних проводів (кабелей) силових кіл електрообладнання. Виконана розрахункова оцінка гранично допустимих амплітуд плотностей $\delta_{ilm}$ струму $i(t)$ КЗ до розглядуваного електрообладнання. Отримані результати пропонують підвищення термічної стійкості електричних неізольованих проводів, ізольованих проводів і кабелей з ПЛХ, Г і ПЕТ ізоляцією і мідними (алюмінієвими) жилами (оболонками), широко застосованими в силових кабеллях електроустановок загальнопромислового призначення. Бібл. 6, табл. 6.

Ключові слова: електроенергетика, електричні проводи і кабелі цепей електроустановок загальнопромислового призначення, розрахунковий вибір гранично допустимих перерізів дротів і кабелей в кабелях електрообладнання.
Introduction. Issues of a reasonable selection of cross sections of electrical wires and cables used in electrical equipment (electrical installations) of industrial electric power industry have been and are being given increased attention [1]. Particularly acute these issues arise during emergency operation of its electrical equipment, due to all types of short-circuit (SC) in electrical networks (ENs). No less dangerous for the reliable operation of electrical equipment powered from industrial power supply networks are modes of operation associated with the current overloads of its wide range of cable and conductor products (CCP). Most fires of CCP of circuits of electrical equipment of industrial electric power industry (at temperatures of current-carrying wires cores and cables of about 450 °C [1]), which lead to a prolonged de-energization of consumers of electrical energy, as well as to great material damage and loss of people lives, just related to similar modes of their operation. Of the possible emergency modes of operation of the EN (SC of various types, ignition of the CCP and other types of its damage), calculated to select their electrical equipment, including its components such as electrical apparatus, and accordingly its CCP is SC mode [2, 3]. In [1], a well-known electrical engineering approach was presented on the approximate selection in the field of industrial electric power industry of the minimum allowable $S_{min}$ cross sections of various brands of electrical wires and cables for short-term modes of their operation from the condition of their thermal resistance to the action of SC current. The “bottleneck” in this engineering approach is the calculation finding of the Joule integral $B_0$ for the SC current (integral of the SC current action), which determines the accuracy of calculating the values of the specified sections $S_{min}$. The graphic materials given in [1] (for example, Fig. 36.38) for three types of materials of wires cores and cables (copper, aluminum and steel) used in determining the final temperature $\theta_t$ of Joule heating by SC current of the current transmission parts of CCP do not fully describe the features of the process of approximate calculation of the numerical values of the specified integral $B_0$ and allowable cross sections $S_{min}$ (for example, selecting the amplitude-time parameters (ATPs) for these purposes of periodic and aperiodic components of the SC current, duration $t_{SC}$ of the SC process, etc.). In addition, the absence in [1] of the analytical relation for the approximate determination of the temperature $\theta_t$ of Joule heating by SC current of the current-carrying parts of the CCP makes it difficult for the wires and cables to check whether the condition of their thermal resistance to the SC current is met.

Therefore, in the field of industrial electric power engineering, when choosing the values of the minimum allowable cross sections $S_{min}$ for the CCP of power circuits of electrical equipment, there is a need for a more detailed and refining calculation of the allowable cross sections $S_B$ of electrical wires and cables containing metal cores ($i=1$) and return shells ($i=2$), as well as one or another belt and protective insulation.

The goal of the paper is to carry out the engineering approach refining the existing ones that determines the minimum allowable cross sections $S_{min}$ of the cable and conductor products in industrial power engineering for calculation selection of the maximum allowable cross sections $S_B$ of electrical wires and cables in the power circuits of industrial electrical equipment taking into account the flow of three-phase short-circuit current $i_{sc}(t)$ in emergency mode.

1. Problem definition. Consider uninsulated copper and aluminum wires commonly used in power circuits for electrical equipment for general industrial use, as well as insulated wires and cables with copper (aluminum) inner cores and outer shells having polyvinyl chloride (PVC), rubber (R) or polyethylene (PET) insulation [1, 4]. We assume that in the circular continuous or split copper (aluminum) cores and shells of the specified wires and cables of power circuits of electrical installations in atmospheric air with temperature of $\theta_0=20$ °C in the normal mode of their operation under the rated current load, alternate current flows in their longitudinal direction with frequency $f=50$ Hz, and the maximum long-term permissible temperature $\theta_S$ of Joule heating for non- and insulated wires and cables with PVC, R and PET insulation does not exceed numerically the regulated by current requirements levels in 70 °C in 65 °C, respectively [1]. For the generality of the problem to be solved, let us agree that in the studied power circuits with CPP, their operation modes are possible, when their current-carrying parts are completely de-energized. As in [1], we believe that the thermal resistance of the considered electrical wires and cables is limited by the permissible short-term temperature $\theta_S$ of heating the current-carrying parts of wires (cables) at three-phase SC in the EN of power supply system of the electrical installation under study. We believe that the values of $\theta_S$ correspond to the known permissible short-term temperatures of heating of the CCP by AC SC currents of power frequency [1]. In this regard, the numerical temperature values $\theta_S$ for uninsulated copper wires with tension less than 20 N/mm² will be 250 °C, and for uninsulated aluminum wires with tension less than 10 N/mm² − 200 °C [1]. For insulated wires and cables with copper and aluminum conductors, PVC and R insulation, the numerical values of the temperature $\theta_S$ are 150 °C, and for the indicated CPP with PET insulation − 120 °C [1]. When selecting $S_B$ sections, we assume that the SC current $i_{sc}(t)$ is almost uniformly distributed over the cross section of the core and the shell of the wire (cable). One of the rationales of this assumption is that the minimum penetration depth $\Delta_i$ of the magnetic field (thickness of the skin layer) from the SC current $i_{sc}(t)$ in the quasistationary approximation to the considered non-ferromagnetic conductive materials, determined from the calculated expression of the form $\Delta_i = \left[1/(\pi \sigma \mu_0 \gamma_0)\right]^{1/2}$ [5], where $\gamma_0$ is the electrical conductivity of the core (shell) material of the CPP $\theta_0=20$ °C, and $\mu_0 = 4\pi \times 10^{-7}$ H/m is the magnetic constant, numerically for copper is approximately 9.3 mm, and for aluminum is 11.8 mm. It can be seen that these values of $\Delta_i$ turn out to be comparable with the real radii (thicknesses) of the current-carrying cores (shells) of wires and cables commonly used in electrical circuits of electrical installations for general industrial purposes. Let us take...
advantage of the adiabatic nature of the taking place at acting durations of SC current $i_d(t)$ of no more than 1000 ms in the materials of cores (shells) of the CCP under consideration of the thermal processes, under which the influence of heat transfer from the surfaces of their current-carrying parts having the current temperature $\theta_S = \theta_B$ and their thermal conductivity of layers of their conductive materials and insulation on Joule heating of the current-carrying parts of the cores (shells) of wires (cables) is neglected. It is required by calculation in an approximate form taking into account the nonlinear nature of the change due to Joule heating of the indicated CCP of the specific electrical conductivity $\gamma_i$ of the material of its cores (shells) and the condition of thermal resistance of the CCP to the action of SC current in expanded form to determine the permissible cross sections $S_i$ of current-carrying parts for uninsulated copper (aluminum) wires, as well as for insulated wires and cables with copper (aluminum) cores (shells), PVC, R or PET insulation, widely used in power circuits of electrical installations of general industrial purpose and through which in emergency mode of operation of the EN the three-phase SC current $i_d(t)$ of the power frequency $f = 50$ Hz with these or other specified ATPs flows.

2. The proposed refined approach to the selection of the allowable cross-sections $S_i$ of wires and cables in circuits of electrical installations for general industrial purposes. From the heat balance equation for the current-carrying parts of the CCP of the circuits of indicated electrical installations in the adiabatic mode and the condition of their thermal resistance to current $i_d(t)$ of the adopted SC, the analytical expression for the refined calculation determination of the allowable cross sections $S_i$ of the considered electrical wires and cables takes the following form [6]:

$$S_i = [J_{\text{ak}} (J_{\text{ilS}} - J_{\text{ilI}})]^{1/2} = J_{\text{ak}}^{1/2} / C_{ik},$$

where $J_{\text{ak}} = B_k = \int_{0}^{t_c} i_d(t) dt$ is the Joule (action) integral of the SC current $i_d(t)$, $A^2 \cdot s$; $J_{\text{ilS}}, J_{\text{ilI}}$ are the current integrals for the current-carrying parts of the wires (cables), the permissible short-term temperature and the long-term permissible heating temperature of the material of which are $\theta_B$ and $\theta_B$, respectively, $A^2 \cdot s \cdot m^{-4}$; $C_{ik} = (J_{\text{ilS}} - J_{\text{ilI}})^{1/2}$ is the coefficient, the numerical values of which will be listed below and compared with the known ones, $A^2 \cdot s^{1/2} \cdot m^{-2}$.

2.1. Calculation of the current integrals $J_{\text{ilS}}, J_{\text{il}}$ and coefficient $C_{ik}$. For the calculation definition with engineering accuracy of the values of the current integrals in (1) $J_{\text{ilS}}$ and $J_{\text{il}}$ used in [5] in the form of current or inertia integrals (see formula 4.56), whose integrand function, unlike the classical Joule integral, contains not the square of current $i_d(t)$, but the square of the density of the specified current $i_d(t)$ in electrically conductive materials of the CCP we use the following approximate analytical expressions [6]:

$$J_{\text{ilS}} = \gamma_0 \beta_{\text{il}}^{-1} \left[ c_{\gamma} \beta_{\gamma} \theta_B (\theta_S - \theta_B) + 1 \right];$$

$$J_{\text{ilI}} = \gamma_0 \beta_{\text{il}}^{-1} \left[ c_{\gamma} \beta_{\gamma} \theta_B (\theta_S - \theta_B) + 1 \right],$$

where $c_{\gamma}, \beta_{\gamma} \theta_B$ are, respectively, the specific volumetric heat capacity and the thermal coefficient of the electrical conductivity of the conductive material of the core (shell) of the wire (cable) of the considered power circuit of the electrical installation before the impact on the tested CCP of the emergency current $i_d(t)$ of the SC with arbitrary ATPs, quantified at $\theta_B = 20 ^\circ C$.

Table 1 shows the numerical values of the used values of $\gamma_0, c_{\gamma} \beta_{\gamma} \theta_B$ for the major conductor materials of the current-carrying parts of the CCP at the temperature of the medium equal to $\theta_B = 20 ^\circ C [5, 6]$.

| Material of the core (shell) of the wire (cable) | Numerical value of the characteristic 
|-----------------------------------------------|---------------------------------|
| $\gamma_0$, $10^2$ (Ω·m)$^{-1}$ | $c_{\gamma} \beta_{\gamma}$, $10^3$ (J/(m$^3$·K)) | $\beta_{\gamma} \theta_B$, $10^3$ (m$^3$·J) |
| Copper | 5.81 | 3.92 | 1.31 |
| Aluminum | 3.61 | 2.70 | 2.14 |

Knowing the values of the indicated characteristics $\gamma_0, c_{\gamma} \beta_{\gamma} \theta_B$ (see Table 1), for given values of the normalized temperatures $\theta_S, \theta_B$, and $\theta_B$, using (2) and (3), the numerical values of the current integrals $J_{\text{ilS}}, J_{\text{il}}$ and the coefficient $C_{ik}$ used in (1), can be relatively easily founded for a wide range of the CPP used in the power circuits of the considered electrical installations. Table 2 shows the numerical values of the desired coefficient $C_{ik}$ for the main versions of the CPP used in the power circuits of electrical installations for industrial purposes.

Table 2

| Type of insulation in the wire (cable) of the circuit of the electrical installation | Material of the core (shell) of the wire (cable) | Numerical value of $C_{ik}$, $10^2 \cdot A^{-1/2} \cdot m^2$ |
|-----------------------------------------------|---------------------------------|---------------------------------|
| Without insulation | Copper | 1.56 | 1.86 |
| | Aluminum | 0.88 | 1.09 |
| PVC, R | Copper | 1.16 | 1.51 |
| | Aluminum | 0.74 | 0.97 |
| PET | Copper | 0.96 | 1.36 |
| | Aluminum | 0.62 | 0.88 |

Note that in Table 2 the case, when $J_{\text{il}} \neq 0$, corresponds to the rated load current of the CCP in the circuits of the electrical installations under study (the temperature of their current-carrying parts is $\theta_B$), and the case $J_{\text{il}} = 0$ – to the de-energization mode of the CCP (the temperature of their current-carrying parts before the flow of the SC current $i_d(t)$ through them equal to the ambient air temperature $\theta_B = 20 ^\circ C$). To compare the obtained refined data for the coefficient $C_{ik}$ (see Table 2), Table 3 shows its numerical values known according to [1], corresponding to the mode of operation of the CCP, when $J_{\text{il}} \neq 0$.
Known values of the coefficient \( C_k \) for the main types of electrical wires and cables with copper (aluminum) cores in industrial electric power circuits under the action of SC current on them [1]

| No. | Name of the wire (cable) and core | \( C_k \) A·s²/m² | 
|-----|----------------------------------|-----------------|
| 1   | Copper wires (cores), uninsulated | 1.70            |
| 2   | Aluminum wires (cores), uninsulated | 0.90            |
| 3   | Cables (insulated wires) with PVC and R insulation and copper cores | 1.20            |
| 4   | Cables (insulated wires) with PVC and R insulation and aluminum cores | 0.75            |
| 5   | Cables (insulated wires) with PET insulation and copper cores | 1.03            |
| 6   | Cables (insulated wires) with PET insulation and aluminum cores | 0.65            |

From the comparison of data of Tables 2, 3 it follows that at \( J_{ck} \neq 0 \), their corresponding numerical values for the coefficient \( C_k \) depend on the type of the CCP, differ by no more than (3-8)\%, and for the mode of operation of the CCP in electrical installation circuits, when \( J_{ck} = 0 \), these differences increase and reach (9-26)\%. In this regard, demonstratively executed on the basis of the mathematical relations (2) and (3), taking into account the nonlinear change in the specific electrical conductivity \( \gamma \) of the material of the cores (shells) of the CCP during its Joule heating by SC current \( i(t) \), the calculation refinement of numerical values for the coefficient \( C_k \) directly used to determine by (1) the permissible cross sections \( S_p \) is an electrotechnically justified and expedient action.

2.2. Calculation at the SC of the action integral \( J_{ak} \) of the emergency current. To do this, we first write an analytical relation describing the change in time \( t \) of the SC current \( i(t) \) in the power circuits of electrical installations used in industrial electric power industry. According to [1, 3], ATPs of a given SC current \( i(t) \) obey the following temporal dependence:

\[
i(t) = I_{mk} \exp(-t/T_a) - \cos(2\pi t/T_p), \tag{4}
\]

where \( I_{mk} \) is the amplitude of the steady-state SC current in the power circuit of the electrical installation \( i(t) \); \( T_a, T_p \) are, respectively, the time constant of decay of the aperiodic component and the oscillation period of the periodic component of the SC emergency current \( i(t) \) in the circuit under study.

It is interesting to note that from (4) at \( T_p = 20 \text{ ms} \) and \( t = 10 \text{ ms} \), corresponding to the largest amplitude of the shock SC current in circuits of the EN, the well-known calculation formula for the shock coefficient \( k_5 \) relating to the characteristic elements and parts of the electric power system (EPS) (for example, for synchronous generators, electric motors, etc.) follows [1]:

\[
k_5 = \left[ 1 + \exp(-0.01/T_a) \right]. \tag{5}
\]

Note that for turbogenerators with power of (100-1000) MW, the numerical value of \( T_p \) is approximately 500 ms (see Table 35.5 in [1]). In this regard, for such electric power elements, the value of the shock coefficient \( k_5 \) at SC will be numerically about 1.98. For distribution cable networks with voltage (6-10) kV, according to the above-mentioned Table 35.5 of [1], the time constant of the decay of the aperiodic component of the SC current takes the numerical value \( T_{a}=10 \text{ ms} \). In the latter case, according to (5), the shock coefficient is \( k_5 \approx 1.37 \). As for the known maximum levels of SC currents in EPS networks, at nominal network voltage of \( U_{n}=110 \text{ kV} \), the numerical value of the switching off current amplitude (in fact \( I_{ak} \)) is about 50 kA (see Table 36.7 in [1]). At \( U_{n}=10 \text{ kV} \) in the SC mode, the amplitude of the switching off current in accordance with the data in Table 36.7 of [1] can reach a level of 125 kA.

Taking into account (1) and (4), the calculation expression for the desired integral of action \( J_{ak} \) of the SC current \( i(t) \) in the circuit of the electric installation under consideration in the adopted approximation takes the following analytical form:

\[
J_{ak} = I_{mk}^2 \left[ 0.5T_{ck} + 0.25\pi^{-1}T_p \sin(2\pi T_{ck}/T_p) \times \right.
\]

\[
\left. \times \cos(2\pi T_{ck}/T_p) - 2T_a^2T_p^2 - 4T_p^2R_a^2 \right] \frac{1}{\left. e^{-T_p/T_a} \times \right.}
\]

\[
\left. + 0.5T_p \left[ 1 - e^{-2T_a/T_p} \right] \right] \tag{6}
\]

From (6) it clearly follows that the value of the integral of action \( J_{ak} \) of the SC current \( i(t) \) is directly proportional to the square of the amplitude \( I_{ak} \) of the steady-state SC current and duration (switch off time) \( T_{ck} \) of the SC. The greater the numerical values \( I_{ak} \) and \( T_{ck} \), the greater will be the numerical values of the desired quantity \( J_{ak} \). In Table 4 at \( T_p=20 \text{ ms} \) (\( T_{ck}=20 \text{ ms} \)) for four fixed numerical amplitude values \( I_{ak} \) of the steady-state SC current (30, 50, 70 and 100 kA) and two numerical values of the duration \( T_{ck} \) of the SC specified by [1] (100 and 160 ms) the numerical values of the integral of action \( J_{ak} \) of the SC current \( i(t) \), calculated by (6) are shown.

### Table 4

| Amplitude value \( I_{ak} \) of the steady-state SC current \( i(t) \) in the power circuit of industrial electrical installation, kA | Values of the integral of action \( J_{ak} \) for the SC current \( i(t) \) by (4), \text{A·s}² | 
|---|---|
| 30 | 5.4·10⁷ | 10 ms |
| 50 | 15.0·10⁷ | 22.5·10⁷ |
| 70 | 29.4·10⁷ | 44.1·10⁷ |
| 100 | 60.0·10⁷ | 90.0·10⁷ |

Having determined from (6) the numerical values of the integral of action \( J_{ak} \) of the SC current \( i(t) \) (see Table 4) and knowing the numerical values of the coefficient \( C_k \) (see Table 2), taking into account (1), the refined numerical values of the allowable cross-sections \( S_p \) of the current-carrying parts of the considered CCP in the power circuits of general-purpose electrical installations can be found. Using accepted assumptions, the allowable amplitudes of current density \( \delta_{lim} \) in the materials of the cores (shells) of the wires (cables) under study for the fault SC mode can be quantified from the ratio \( \delta_{lim} = I_{ak}/S_p \).

2.3. Results of the refined calculation selection of the permissible cross-sections \( S_p \) and current densities...
\( \delta \) in wires and cables of circuits of electrical installations for general industrial purposes. Table 5 shows the results of the refined calculation by (1), taking into account the data of Table 2, 4 of the permissible cross sections \( S_d \) of current-carrying copper (aluminum) parts of wires and cables of power circuits for general industrial electrical installations at \( J_{\text{eff}} \neq 0 \), \( t_{\text{SC}} = 100 \) ms and the amplitude \( I_{\text{m}} \) of the SC current changing discretely in the range (30-100) kA.

Table 5

| Type of insulation in the wire (cable) of the circuit of the electrical installation | Material of the core (shell) of the wire (cable) | Section value \( S_{\text{m}} \), mm² | Amplitude \( I_{\text{m}} \) of the steady-state SC current, kA |
|---|---|---|---|
| Without insulation | Copper | 30 | 50 | 70 | 100 |
| | Aluminum | 47.11 | 78.51 | 109.91 | 157.02 |
| PVC, R | Copper | 63.35 | 105.58 | 147.81 | 211.16 |
| | Aluminum | 99.30 | 165.51 | 231.71 | 331.01 |
| PET | Copper | 76.55 | 127.58 | 178.61 | 255.15 |
| | Aluminum | 118.52 | 197.54 | 276.55 | 395.08 |

From the data of Table 5 it follows that the permissible density amplitudes \( \delta_{\text{m}} = \frac{I_{\text{m}}}{S_{\text{m}}} \) of the SC current at its flow (switching off) time \( t_{\text{SC}} = 100 \) ms for uninsulated wires with copper and aluminum cores in the circuits of general industrial installations (\( T_a = 20 \) ms) are approximately \( 0.64 \) kA/mm² and \( 0.36 \) kA/mm², respectively, for cables with copper (aluminum) cores (shells), PVC and R insulation \( 0.47 \) (0.30) kA/mm², and for cables with copper (aluminum) cores (shells) and PET insulation \( 0.39 \) (0.25) kA/mm². Note that the indicated numerical values of the permissible amplitudes of the density \( \delta_{\text{m}} \) of the SC current in the materials of the current-carrying parts of the wires (cables) do not depend on the amplitude level \( I_{\text{m}} \) of the steady-state emergency current of power frequency 50 Hz in them.

Table 6 presents the results of the refined determination by (1) taking into account the data of Table 2, 4 for the case \( J_{\text{eff}} \neq 0 \) of permissible cross sections \( S_d \) of current-carrying copper (aluminum) parts of wires and cables of power circuits for general industrial purposes at \( t_{\text{SC}} = 160 \) ms and the amplitude \( I_{\text{m}} \) of steady-state SC current changing discretely in the range (30-100) kA (\( T_a = 20 \) ms).

From the data of Table 6 we find that at the time of the SC current flow (switching off) \( t_{\text{SC}} = 160 \) ms, regardless of the numerical value of the current amplitude \( I_{\text{m}} \), the permissible density amplitudes \( \delta_{\text{m}} = \frac{I_{\text{m}}}{S_{\text{m}}} \) of the emergency current for uninsulated wires with copper and aluminum cores in electrical installation circuits of general purpose (\( T_a = 20 \) ms) is about \( 0.52 \) kA/mm² and \( 0.29 \) kA/mm², respectively, for cables with copper (aluminum) cores (shells), PVC and R insulation \( 0.39 \) (0.25) kA/mm², and for cables with copper (aluminum) cores (shells) and PET insulation \( 0.32 \) (0.21) kA/mm².

From the analysis of data of Table 5, 6 for the refined values of the permissible cross sections \( S_d \) of the current-carrying parts of the CCP in power circuits for general-purpose electrical equipment \( (J_{\text{eff}} \neq 0); T_a = 20 \) ms), we can conclude that for the indicated amplitudes \( I_{\text{m}} \) of the steady-state SC current satisfying the range (30-100) kA, an increase in the switching off time \( t_{\text{SC}} \) of the SC current by 1.6 times (from 100 ms to 160 ms) leads to a decrease in the permissible density amplitudes \( \delta_{\text{m}} \) of the SC current in the materials of the wires and cables under consideration by about 1.2 times. At the same time, the values of the permissible cross sections \( S_d \) copper (aluminum) cores and shells (return conductors) of the CCP under study increase by the same amount (~1.2 times). From here, practical recommendations supported by the above-mentioned refined engineering calculations of the values of \( S_d \) and \( \delta_{\text{m}} \) follows for the operating conditions of electrical installations for general industrial purposes: in their power circuits to ensure the thermal stability of the CCP, the switching off time \( t_{\text{SC}} \) of the SC current (types of phase-applied relay protection and switches in EN) and practically selected values of the permissible cross-sections \( S_d \) of their current-carrying parts must be obligatorily mutually agreed.

Table 6

| Type of insulation in the wire (cable) of the circuit of the electrical installation | Material of the core (shell) of the wire (cable) | Section value \( S_{\text{m}} \), mm² | Amplitude \( I_{\text{m}} \) of the steady-state SC current, kA |
|---|---|---|---|
| Without insulation | Copper | 30 | 50 | 70 | 100 |
| | Aluminum | 57.69 | 96.15 | 134.61 | 192.31 |
| PVC, R | Copper | 102.27 | 170.45 | 238.64 | 340.91 |
| | Aluminum | 77.58 | 129.31 | 181.03 | 258.62 |
| PET | Copper | 93.75 | 156.25 | 218.75 | 312.50 |
| | Aluminum | 145.16 | 241.93 | 338.71 | 483.87 |

2.4. Calculation estimation of the thermal stability of electrical wires and cables in circuits of electrical installations for general industrial purpose. Within the framework of the proposed approach to the selection of the allowable cross sections \( S_d \) of wires (cables) in the power circuits of electrical installations for general industrial purposes, the calculation estimation of their thermal stability can be demonstratively carried out. For this purpose, as in [1, 6], we determine the thermal stability of the wires and cables under consideration in the circuits of the electrical installations under investigation according to the following thermophysical condition:

\[
\theta_{IS} \leq \theta_{IS}^*,
\]

where \( \theta_{IS} \), \( \theta_{IS}^* \) are, respectively, the current (final) and permissible short-term temperature of heating of the current-carrying parts of the considered electrical wires and cables in the power circuits of the EN.
To find in (7) the values of the current or final temperature \( \theta_{S} \) of heating the material of the current-carrying parts of the CCP, determined by Joule heat from the action of the SC current \( i(t) \) on it, we first use the well-known nonlinear dependence of the specific electrical conductivity \( \gamma_i \) of the material of the core (shell) of the wire or cable on the value of temperature \( \theta_{S} \) [5]:

\[
\gamma_i = \gamma_0 [1 + c_0 \beta_0 (\theta_{S} - \theta_0)]^{-1}.
\]

(8)

It should be noted that the expression (8) in the temperature range from 20 °C to the melting temperature of materials of the cores (shells) of the CCP, according to experimental data from [5], approximates the temperature dependence of \( \gamma_i \) for copper and aluminum with an error of no more than 5 %. In addition, we note that, both earlier and in (8), the value \( \gamma_0 \) means the electrical conductivity \( \gamma_i \) of the material of the current-carrying parts of the CCP at temperature \( \theta_0 = 20 \) °C. Taking into account (8), the solution of a non-uniform differential equation of the first order for the final temperature \( \theta_{S} \) of Joule heating by SC current \( i(t) \) of the material of the core (shell) of the CCP in the circuit of the electrical installation of general industrial purpose under the initial condition of the form \( [\theta_{S}(t = 0) - \theta_0] = 0 \) can be written in the following approximate analytical form [6]:

\[
\theta_{S} = \theta_0 + (c_0 \beta_0)^{-1} \exp\left(J_{ak} T_{0i} \beta_0 / S_i^2\right) - 1
\]

(9)

where \( \theta_0 \) is the initial material temperature of the material of current-carrying parts of the CCP, equal depending on the operating mode of the power circuits of electrical equipment to \( \theta_0 (J_{ak} = 0) \) or \( \theta_0 = 20 \) °C (\( J_{ak} = 0\)).

From (9) it can be seen that under the accepted assumptions, the known numerical values of the thermophysical characteristics \( \gamma_0, \ c_0 \) and \( \beta_0 \) for the materials used in the current-carrying parts of the CCP (see data from Table 1 and [5]), and also for founded by (1) and (6) the numerical values of the permissible cross sections \( S_i \) of copper (aluminum) cores (shells) of wires (cables) and the integral of action \( J_{ak} \) of the SC current \( i(t) \), determination of the desired final temperature \( \theta_{S} \) does not cause any electrical engineering difficulties.

As one of the examples (the first example) of the practical implementation of the results obtained, we carry out at \( \theta_0 = \theta_{C} = 70 \) °C (\( J_{ak} = 0\)), according to (7) and (9), the calculation estimation of the thermal stability of uninsulated (bare) copper wire of the power circuit of general-purpose electrical equipment for the emergency case when \( t_{dc} = 160 \) ms, \( T_0 = 20 \) ms and \( I_{ms} = 100 \) kA. According to the calculated data (see Table 6), the permissible cross-section \( S_i \) of the accepted copper wire is numerically approximately 192.31 mm². In this case, the value of the integral of action \( J_{ak} \) of the SC current \( i(t) \) by (6) will be numerically about 9·10⁸ A²·s (see Table 4). Then by (9) taking into account the data of Table 1, the final temperature \( \theta_{S} \) of the Joule heating by the emergency SC current \( i(t) \) of the copper wire under consideration will be approximately numerically equal to 212.4 °C. It can be seen that this temperature value is less than the normalized permissible short-term temperature \( \theta_0 \) of heating of checked for thermal resistance the copper wire of the power circuit of electrical equipment, which according to [1] is 250 °C at tension in it (wire) less than 20 N/mm². Therefore, we can conclude that condition (7) for the specified calculation case is satisfied.

Calculation estimation by (9) with the same initial data \( \theta_0 = \theta_{C} = 70 \) °C, \( t_{dc} = 160 \) ms, \( T_0 = 20 \) ms, \( I_{ms} = 100 \) kA; \( J_{ak} = 9·10^8 \) A²·s of the final temperature \( \theta_{S} \) of the Joule heating of a copper round core of the cable with PVC or R insulation (the second example) with the permissible cross section \( S_i = 258.62 \) mm² (see Table 6) shows that in this case it reaches a level of approximately 139.1 °C. This temperature is less than the normalized level of the permissible short-term temperature \( \theta_0 \) of heating of tested for thermal resistance the cable with PVC (R) insulation, which is 150 °C [1]. As we see, the condition (7) is also satisfied for this calculation case. In this regard, it is reasonable to say that the carried out calculation estimates of the thermal resistance of both uninsulated copper wire and cable with copper core, PVC and R insulation of power circuits of electrical installations under study indicate the operability of the proposed electrical engineering approach to the refined calculation selection of the permissible cross sections \( S_i \) of current-carrying parts of the CCP used in the power circuits of electrical equipment of industrial electric power industry.

**Conclusions.**

1. The proposed electrical engineering approach allows by the condition of thermal stability of CCP of power circuits of electrical equipment for general industrial purposes to provide a refined calculation selection of permissible cross sections \( S_i \) of uninsulated wires, insulated wires and cables with copper (aluminum) cores (shells-screens) with PVC, R and PET insulation, the current-carrying parts of which in emergency mode of their operation can be affected by the current \( i(t) \) of a three-phase SC in EPS with ATPs specified by standardizing documents.

2. It is shown that the discrepancy between the numerical values of the coefficient \( C_i \) included in formula (1) and determining the values of the permissible cross sections \( S_i \) of the current-carrying parts of the CCP in the circuits of electrical installations of general purpose, according to the existing and proposed electrical engineering approaches to the calculation selection of the permissible cross sections \( S_i \) of the cores (shells) of the considered electrical wires and cables for their normal operation at \( J_{ak} \neq 0 \) (at rated current load of the CCP) is not more than (3-8)% and, at \( J_{ak} = 0 \) (in the mode of de-energizing of the CCP) it reaches up to (9-26)%.

3. An analytical relation (6) is obtained for a refined calculation determination of the value of the integral of action \( J_{ak} \) of the SC current \( i(t) \) (Joule integral \( B_i \)) in the power circuits of the electrical equipment under study, which allows for given amplitudes \( I_{ms} \) of the steady-state SC current, duration (switching off time) of the SC process \( t_{dc} \), time constant of the decay \( T_0 \) of aperiodic component of the SC current \( i(t) \) and oscillation period \( T_p = 20 \) ms of the periodic component of emergency SC current to relatively easy find required for the calculation selection of the permissible cross sections \( S_i \) of the current-carrying parts of the considered CCP the value of the integral \( J_{ak} \).
4. It is established that in the first approximation in the power circuits of electrical equipment for general industrial purpose \(T_a=20\) ms the allowable density amplitudes \(\delta_{ilm}=I_{mk}/S_d\) of the SC current \(i_d(t)\) at its switching off time \(t_{sc}=100\) ms in EPS for uninsulated wires with copper (aluminum) cores are about 0.64 (0.36) kA/mm² respectively, for cables with copper (aluminum) cores (shells) and PVC (R) insulation 0.47 (0.30) kA/mm², and for cables with copper (aluminum) cores (shells) and PET insulation 0.39 (0.25) kA/mm². If in the EPS the switching off time \(t_{sc}\) of the SC current \(i_d(t)\) in these circuits increases \(T_a=20\) ms, the permissible density amplitudes \(\delta_{ilm}\) of the fault SC current are reduced and at \(t_{sc}=160\) ms for uninsulated wires with copper (aluminum) cores equal, respectively, approximately 0.52 (0.29) kA/mm², for cables with copper (aluminum) cores (shells) and PVC (R) insulation 0.39 (0.25) kA/mm², and for cables with copper (aluminum) cores (shells) and PET insulation 0.32 (0.21) kA/mm².

5. A convenient in practical use analytical relation (9) has been proposed for carrying out, by condition (7), the calculation estimation of the thermal stability to the SC current \(i_d(t)\) of indicated electrical wires and cables, widely used in power circuits for general-purpose electrical equipment.

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