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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_{il} of electric wires and cables in the circuits of electrical equipment of the general industrial installations characterized flowing in malfunction of current $i_k(t)$ 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_{il} 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 $i_k(t)$ 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_{ik} by existing and offered to the engineering calculations selection of permissible sections of S_{il} 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 to (9-26) %.. Analytical correlation is got for the specified calculation determination of integral of action of J_{ak} of current $i_k(t)$ of SC (Joule integral) in the power circuits of the tested electrical equipment. It is set that in the circuits of of the general industrial installations (for permanent time of slump of T_a=20 ms of aperiodic constituent of current of SC) maximum possible amplitudes of density of $\delta_{ilm}\approx I_{mk}/S_{il}$ of SC current at time of his disconnecting t_{kC}=100 ms for the uninsulated wires with copper (aluminum) cores make according to approximately 0.64 (0.36) кA/mm^2, for cables with copper (aluminum) cores (shells), PVC and R insulation – 0.47 (0.30) кA/mm^2, and for cables with copper (aluminum) cores (shells) and PET insulation – 0.39 (0.25) кA/mm^2. At time of disconnecting t_{kC}=160 ms of SC current in the circuits of electrical equipment (T_a=20 ms) permissible amplitudes of current density of δ_{ilm} of SC for the unsuolated wires with copper and aluminum cores are accordingly about 0.52 (0.29) кA/mm^2, for cables with copper (aluminum) cores (shells), PVC and R insulation of 0.39 (0.25) кA/mm^2, and for cables with copper (aluminum) cores (shells) and PET insulation – 0.32 (0.21) кA/mm^2. Originality. First by a calculation the specified numeral values of sections of S_{il} and amplitudes of density δ_{ilm} of SC current are determined for the uninsulated wires, insulated wires and cables with copper (aluminum)cores 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 words: **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.**

Надані результати розробленого інженерного електротехнічного підходу до уточненого розрахункового вибору гранично допустимих перерізів S_{il} електричних неізольованих дротів, ізольованих дротів і кабелів з полівінілхлоридною (ПВХ), гумовою (Г) і поліетиленовою (ПЕТ) ізоляцією і мідними (алюмінієвими) жилами (оболонками) по умові їх термічної стійкості, по яких в силових колах електроустановок загальнопромислового призначення в аварійному режимі протікає струм $i_k(t)$ короткого замикання (КЗ) із заданими параметрами. На підставі цього підходу здійснений уточнений вибір перерізів S_{il} для вказаних дротів (кабелів) силових кіл досліджуваного електрообладнання. Виконана розрахункова оцінка гранично допустимих амплітуд щільності δ_{ilm} струму $i_k(t)$ КЗ в даних дротах і кабелях силових кіл вказаних електроустановок. Отримані результати сприятимуть підвищенню термічної стійкості електричних неізольованих дротів, ізольованих дротів і кабелів з ПВХ, Г і ПЕТ ізоляцією і мідними (алюмінієвими) жилами (оболонками), які широко застосовуються в силових колах 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 кабелів в колах електрообладнання.**

Приведены результаты разработанного инженерного электротехнического подхода к уточненному расчетному выбору предельно допустимых сечений S_{il} электрических неизолированных проводов, изолированных проводов и кабелей с поливинилхлоридной (ПВХ), резиновой (Р) и полиэтиленовой (ПЭТ) изоляцией и медными (алюминиевыми) жилами (оболочками) по условию их термической стойкости, по которым в силовых цепях электроустановок общепромышленного назначения в аварийном режиме протекает ток $i_k(t)$ короткого замыкания (КЗ) с заданными параметрами. На основании этого подхода осуществлен уточненный выбор сечений S_{il} для указанных проводов (кабелей) силовых цепей исследуемого электрооборудования. Выполнена расчетная оценка предельно допустимых амплитуд плотностей δ_{ilm} тока $i_k(t)$ КЗ в рассматриваемых проводах и кабелях силовых цепей указанных электроустановок. Полученные результаты будут способствовать повышению термической стойкости электрических неизолированных проводов, изолированных проводов и кабелей с ПВХ, Р и ПЭТ изоляцией и медными (алюминиевыми) жилами (оболочками), широко применяемых в силовых цепях электроустановок общепромышленного назначения. Библ. 6, табл. 6.

Ключевые слова: **электроэнергетика, электрические провода и кабели цепей электроустановок общепромышленного назначения, расчетный выбор предельно допустимых сечений проводов и кабелей в цепях электрооборудования.**

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_{lmin} 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_k for the SC current (integral of the SC current action), which determines the accuracy of calculating the values of the specified sections S_{lmin}. 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 θ_k 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_k and allowable cross sections S_{lmin} (for example, selecting the amplitude-time parameters (ATPs) for these purposes of periodic and aperiodic components of the SC current, duration t_{kC} of the SC process, etc.). In addition, the absence in [1] of the analytical relation for the approximate determination of the temperature θ_k of Joule heating by the 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_{lmin} 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_{il} 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_{lmin} of the cable and conductor producta in industrial power engineering for calculation selection of the maximum allowable cross sections S_{il} of electrical wires and cables in the power circuits of industrial electrical equipment taking into account the flow of three-phase short-circuit current $i_k(t)$ 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 θ_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 θ_{ll} 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 и 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 θ_{lS} 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 θ_{lS} 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 θ_{lS} for uninsulated copper wires with tension less than 20 N/mm^2 will be 250 °C, and for uninsulated aluminum wires with tension less than 10 N/mm^2 − 200 °C [1]. For insulated wires and cables with copper and aluminum conductors, PVC and R insulation, the numerical values of the temperature θ_{lS} are 150 °C, and for the indicated CPP with PET insulation − 120 °C [1]. When selecting S_{il} sections, we assume that the SC current $i_k(t)$ 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 Δ_i of the magnetic field (thickness of the skin layer) from the SC current $i_k(t)$ in the quasistationary approximation to the considered non-ferromagnetic conductive materials, determined from the calculated expression of the form $\Delta_i \approx [1/(\pi f \mu_0 \gamma_{0i})]^{1/2}$ [5], where γ_{0i} is the electrical conductivity of the core (shell) material of the CPP θ_0=20 ºC, and $\mu_0=4\pi\cdot10^{-7}$ 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 Δ_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 $i_k(t)$ 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 $\theta_{iS} \geq \theta_0$ 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 γ_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_{il} 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 $i_k(t)$ 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_{il} 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 $i_k(t)$ of the adopted SC, the analytical expression for the refined calculation determination of the allowable cross sections S_{il} of the considered electrical wires and cables takes the following form [6]:

$$S_{il} = \left[J_{ak} / (J_{ilS} - J_{ill})\right]^{1/2} = J_{ak}^{1/2} / C_{ik}, \qquad (1)$$

where $J_{ak} = B_k = \int_0^{t_{kC}} i_k^2(t)dt$ is the Joule (action) integral of the SC current $i_k(t)$, A^2·s; J_{ilS}, J_{ill} 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 θ_{lS} and θ_{ll}, respectively, A^2·s·m^{-4}; $C_{ik}=(J_{ilS}-J_{ill})^{1/2}$ is the coefficient, the numerical values of which will be listed below and compared with the known ones, A·s$^{1/2}$·m^{-2}.

2.1. Calculation of the current integrals J_{ilS}, J_{ill} and coefficient C_{ik}. For the calculation definition with engineering accuracy of the values of the current integrals in (1) J_{ilS} and J_{ill} 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 $i_k(t)$, but the square of the density of the specified current $\delta_i(t)$ in electrically conductive materials of the CCP we use the following approximate analytical expressions [6]:

$$J_{ilS} = \gamma_{0i} \beta_{0i}^{-1} \ln\left[c_{0i} \beta_{0i} (\theta_{lS} - \theta_0) + 1\right]; \qquad (2)$$

$$J_{ill} = \gamma_{0i} \beta_{0i}^{-1} \ln\left[c_{0i} \beta_{0i} (\theta_{ll} - \theta_0) + 1\right], \qquad (3)$$

where c_{0i}, β_{0i} 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 $i_k(t)$ of the SC with arbitrary ATPs, quantified at θ_0=20 °C.

Table 1 shows the numerical values of the used values of γ_{0i}, c_{0i} и β_{0i} for the main conductor materials of the current-carrying parts of the CCP at the temperature of the medium equal to θ_0=20 °C [5, 6].

Table 1

The values of the characteristics of the main materials of the current-carrying cores (shells) of non- and insulated wires and cables of power circuits of electrical installations for general industrial use at θ_0=20 °C [5, 6]

Material of the core (shell) of the wire (cable)	Numerical value of the characteristic		
	γ_{0i}, 10^7·(Ω·m)$^{-1}$	c_{0i}, 10^6·J/(m^3·°C)	β_{0i}, 10^{-9}·m^3/J
Copper	5.81	3.92	1.31
Aluminum	3.61	2.70	2.14

Knowing the values of the indicated characteristics γ_{0i}, c_{0i} and β_{0i} (see Table 1), for given values of the normalized temperatures θ_0, θ_{lS} and θ_{ll}, using (2) and (3), the numerical values of the current integrals J_{ilS}, J_{ill} and the coefficient $C_{ik.}$ used in (1), can be relatively easy 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

Refined values of the coefficient C_{ik}. for non- and insulated wires (cables) with copper (aluminum) cores (shells) in the power circuits of electrical installations for general industrial purposes

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}., 10^8 A·s$^{1/2}$/m^2	
		J_{ill}≠0	J_{ill}=0
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_{ill}≠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 θ_{ll}), and the case J_{ill}=0 – to the de-energization mode of the CCP (the temperature of their current-carrying parts before the flow of the SC current $i_k(t)$ through them equal to the ambient air temperature θ_0=20 °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_{ill}≠0.

Table 3

Known values of the coefficient C_{ik} 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, 10^8 $A \cdot s^{1/2}/m^2$
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 $J_{Cil} \neq 0$, their corresponding numerical values for the coefficient C_{ik}. depending 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 $J_{Cil}=0$, 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 γ_i of the material of the cores (shells) of the CCP during its Joule heating by SC current $i_k(t)$, the calculation refinement of numerical values for the coefficient C_{ik}, directly used to determine by (1) the permissible cross sections S_{il}, 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 $i_k(t)$ in the power circuits of electrical installations used in industrial electric power industry. According to [1, 3], ATPs of a given SC current $i_k(t)$ obey the following temporal dependence:

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

where I_{mk} is the amplitude of the steady-state SC current in the power circuit of the electrical installation $i_k(t)$; 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 $i_k(t)$ in the circuit under study.

It is interesting to note that from (4) at T_p=20 ms and t = 10 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_S relating to the characteristic elements and parts of the electric power system (EPS) (for example, for synchronous generators, electric motors, etc.) follows [1]:

$$k_S = [1 + \exp(-0.01/T_a)]. \quad (5)$$

Note that for turbogenerators with power of (100-1000) MW, the numerical value of T_a 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_S 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 $T_a \approx 10$ ms. In the latter case, according to (5), the shock coefficient is $k_S \approx 1.37$. As for the known maximum levels of SC currents in EPS networks, at nominal network voltage of U_n=110 kV, the numerical value of the switching off current amplitude (in fact I_{mk}) is about 50 kA (see table 36.7 in [1]). At U_n=10 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 $i_k(t)$ in the circuit of the electric installation under consideration in the adopted approximation takes the following analytical form:

$$\begin{aligned} J_{ak} = I_{mk}^2 \{ & 0.5 t_{kC} + 0.25\pi^{-1} T_p \sin(2\pi t_{kC}/T_p) \times \\ & \times \cos(2\pi t_{kC}/T_p) - 2T_a^2 T_p^2 (T_p^2 + 4\pi^2 T_a^2)^{-1} [e^{-t_{kC}/T_a} \times \\ & \times [2\pi T_p^{-1} \sin(2\pi t_{kC}/T_p) - T_a^{-1} \cos(2\pi t_{kC}/T_p) + T_a^{-1}]] + \\ & + 0.5 T_a (1 - e^{-2t_{kC}/T_a}) \} \end{aligned} \quad (6)$$

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

Table 4

Values of the integral action J_{ak} for the SC current $i_k(t)$ according to (4) flowing in the power circuits of electrical installations for general industrial purposes (at T_a=20 ms)

Amplitude value I_{mk} of the steady-state SC current $i_k(t)$ in the power circuit of industrial electrical installation, kA	Values of the integral of action J_{ak} for the SC current $i_k(t)$ by (4), $A^2 \cdot s$	
	t_{kC}=100 ms	t_{kC}=160 ms
30	$5.4 \cdot 10^7$	$8.1 \cdot 10^7$
50	$15.0 \cdot 10^7$	$22.5 \cdot 10^7$
70	$29.4 \cdot 10^7$	$44.1 \cdot 10^7$
100	$60.0 \cdot 10^7$	$90.0 \cdot 10^7$

Having determined from (6) the numerical values of the integral of action J_{ak} of the SC current $i_k(t)$ (see Table 4) and knowing the numerical values of the coefficient C_{ik}. (see Table 2), taking into account (1), the refined numerical values of the allowable cross-sections S_{il} 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 δ_{ilm} in the materials of the cores (shells) of the wires (cables) under study for the fault SC mode can be quantified from the ratio $\delta_{ilm} \approx I_{mk}/S_{il}$.

2.3. Results of the refined calculation selection of the permissible cross sections S_{il} and current densities

δ_{il} **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_{il} of current-carrying copper (aluminum) parts of wires and cables of power circuits for general industrial electrical installations at $J_{ill}\neq 0$, t_{kC}=100 ms and the amplitude I_{mk} of the SC current changing discretely in the range (30-100) kA.

Table 5
Values of the permissible cross sections S_{il} for wires (cables) with copper (aluminum) cores (shells) in the power circuits of electrical installations of general industrial purpose with amplitude I_{mk} of the SC current $i_k(t)$ of 30-100 кA (for t_{kC}=100 ms and T_a=20 ms)

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_{il}, mm^2			
		Amplitude I_{mk} of the steady-state SC current, kA			
		30	50	70	100
Without insulation	Copper	47.11	78.51	109.91	157.02
	Aluminum	83.51	139.17	194.84	278.35
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 $\delta_{ilm}\approx I_{mk}/S_{il}$ of the SC current at its flow (switching off) time t_{kC}=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/mm^2 and 0.36 kA/mm^2, respectively, 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. Note that the indicated numerical values of the permissible amplitudes of the density δ_{ilm} of the SC current in the materials of the current-carrying parts of the wires (cables) do not depend on the amplitude level I_{mk} 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 $J_{ill}\neq 0$ of permissible cross sections S_{il} of current-carrying copper (aluminum) parts of wires and cables of power circuits for general industrial purposes at t_{kC}=160 ms and the amplitude I_{mk} 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_{kC}=160 ms, regardless of the numerical value of the current amplitude I_{mk}, the permissible density amplitudes $\delta_{ilm}\approx I_{mk}/S_{il}$ 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/mm^2 and 0.29 kA/mm^2, respectively, for cables with copper (aluminum) cores (shells), PVC and R insulation 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. From the analysis of data of Table 5, 6 for the refined values of the permissible cross sections S_{il} of the current-carrying parts of the CCP in power circuits for general-purpose electrical equipment ($J_{ill}\neq 0$; T_a=20 ms), we can conclude that for the indicated amplitudes I_{mk} of the steady-state SC current satisfying the range (30-100) kA, an increase in the switching off time t_{kC} of the SC current by 1.6 times (from 100 ms to 160 ms) leads to a decrease in the permissible density amplitudes δ_{ilm} 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_{il} 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_{il} and δ_{ilm} 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_{kC} of the SC current (types of phase-applied relay protection and switches in EN) and practically selected values of the permissible cross-sections S_{il} of their current-carrying parts must be obligatory mutually agreed.

Table 6
Values of the permissible cross sections S_{il} for wires (cables) with copper (aluminum) cores (shells) in the power circuits of electrical installations of general industrial purpose with amplitude I_{mk} of the SC current $i_k(t)$ of 30-100 кA (for t_{kC}=160 ms and T_a=20 ms)

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_{il}, mm^2			
		Amplitude I_{mk} of the steady-state SC current, kA			
		30	50	70	100
Without insulation	Copper	57.69	96.15	134.61	192.31
	Aluminum	102.27	170.45	238.64	340.91
PVC, R	Copper	77.58	129.31	181.03	258.62
	Aluminum	121.62	202.70	283.78	405.40
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_{il} 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:

$$\theta_{iS} \leq \theta_{lS}\,, \qquad (7)$$

where θ_{iS}, θ_{lS} 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 θ_{iS} of heating the material of the current-carrying parts of the CCP, determined by Joule heat from the action of the SC current $i_k(t)$ on it, we first use the well-known nonlinear dependence of the specific electrical conductivity γ_i of the material of the core (shell) of the wire or cable on the value of temperature θ_{iS} [5]:

$$\gamma_i = \gamma_{0i}\left[1 + c_{0i}\beta_{0i}(\theta_{iS} - \theta_0)\right]^{-1}. \quad (8)$$

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 γ_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 γ_{0i} means the electrical conductivity γ_i of the material of the current-carrying parts of the CCP at temperature θ_0=20 °C. Taking into account (8), the solution of a non-uniform differential equation of the first order for the final temperature θ_{iS} of Joule heating by SC current $i_k(t)$ 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 $[\theta_{iS}(t = 0) - \theta_{0i}] = 0$ can be written in the following approximate analytical form [6]:

$$\theta_{iS} = \theta_{0i} + (c_{0i}\beta_{0i})^{-1}\left[\exp(J_{ak}\gamma_{0i}^{-1}\beta_{0i} / S_{il}^2) - 1\right], \quad (9)$$

where θ_{0i} 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 θ_{ll} (J_{ill}≠0) or θ_0 = 20 °C (J_{ill} = 0).

From (9) it can be seen that under the accepted assumptions, the known numerical values of the thermophysical characteristics γ_{0i}, c_{0i} and β_{0i} 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_{il} of copper (aluminum) cores (shells) of wires (cables) and the integral of action J_{ak} of the SC current $i_k(t)$, determination of the desired final temperature θ_{iS} 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 θ_{0i}=θ_{ll}=70 °C (J_{ill}≠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_{kC}=160 ms, T_a=20 ms and I_{mk}=100 kA. According to the calculated data (see Table 6), the permissible cross-section S_{il} of the accepted wire is numerically approximately 192.31 mm^2. In this case, the value of the integral of action J_{ak} of the SC current $i_k(t)$ by (6) will be numerically about 9·10^8 A^2·s (see Table 4). Then by (9) taking into account the data of Table 1, the final temperature θ_{iS} of the Joule heating by the emergency SC current $i_k(t)$ 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 θ_{lS} 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/mm^2. Therefore, we can conclude that condition (7) for the specified calculation case is satisfied.

Calculation estimation by (9) with the same initial data (θ_{0i}=θ_{ll}=70 °C; t_{kC}=160 ms; T_a=20 ms; I_{mk}=100 kA; J_{ak}=9·10^8 A^2·s) of the final temperature θ_{iS} 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_{il}=258.62 mm^2 (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 θ_{lS} 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_{il} 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_{il} 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 $i_k(t)$ 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_{ik} included in formula (1) and determining the values of the permissible cross sections S_{il} 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_{il} of the cores (shells) of the considered electrical wires and cables for their normal operation at J_{ill}≠0 (at rated current load of the CCP) is not more than (3-8)%, and at J_{ill}=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 $i_k(t)$ (Joule integral B_k) in the power circuits of the electrical equipment under study, which allows for given amplitudes I_{mk} of the steady-state SC current, duration (switching off time) of the SC process t_{kC}, time constant of the decay T_a of aperiodic component of the SC current $i_k(t)$ 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_{il} 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=20ms) the allowable density amplitudes $\delta_{ilm} \approx I_{mk}/S_{il}$ of the SC current $i_k(t)$ at its switching off time t_{kC}=100 ms in EPS for uninsulated wires with copper (aluminum) cores are about 0.64 (0.36) kA/mm^2 respectively, for cables with copper (aluminum) cores (shells) and PVC (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. If in the EPS the switching off time t_{kC} of the SC current $i_k(t)$ in these circuits increases (T_a=20 ms), the permissible density amplitudes δ_{ilm} of the fault SC current are reduced and at t_{kC}=160 ms for uninsulated wires with copper (aluminum) cores equal, respectively, approximately 0.52 (0.29) kA/mm^2, for cables with copper (aluminum) cores (shells) and PVC (R) insulation 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.

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 $i_k(t)$ of indicated electrical wires and cables, widely used in power circuits for general-purpose electrical equipment.

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