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A CHOICE OF ACCEPTABLE SECTIONS OF ELECTRIC WIRES AND CABLES IN ON-BOARD CIRCUITS OF AIRCRAFT ELECTRICAL EQUIPMENT

Purpose. Implementation of choice of maximum permissible sections S_{il} of the uninsulated wires and insulated wires (cables) with copper (aluminum) cores (shells) in the on-board power circuits of electrical equipment of different aircrafts with AC current of frequency f>50 Hz. Methodology. Theoretical bases of the electrical engineering, electrophysics bases of technique of high voltage and high pulsed currents, applied thermal physics. Results. The engineering approach is developed for a calculation choice on the condition of thermal resistibility of aircraft cable-conductor products (CCP) of maximum permissible sections 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 operation of on-board aircraft network with AC frequency of f>50 Hz flows of $i_k(t)$ current at single phase short circuit (SC) with given amplitude-temporal parameters. It is determined that in the on-board power circuits of electrical equipment of aircrafts (f=400 Hz; for permanent time of slump of T_a=3 ms of aperiodic constituent of current of SC) maximum permissible amplitudes of current density of $\delta_{ilm}\approx I_{mk}/S_{il}$ of single phase SC at time of its disconnecting t_{kC}=5 ms in the on-board network of aircraft without dependence on the numerical value of amplitude I_{mk} of the given current of SC for the uninsulated wires with copper (aluminum) cores is accordingly about 2.48 (1.40) kA/mm^2, for wires (cables) with copper (aluminum) cores (shells) and PVC (R) with insulation – 1.85 (1.18) kA/mm^2, and for wires (cables) with copper (aluminum) cores (shells) and PET insulation – 1.53 (0.99) kA/mm^2. The influence on a choice in the on-board network of aircrafts of maximum permissible sections S_{il} of its CCP and accordingly maximum permissible amplitudes of current density δ_{ilm} of current copper (aluminum) parts of its wires and cables of frequency f of AC in the on-board network of aircraft is determined, but duration of flow t_{kC} (time of disconnecting) renders in the on-board network of aircrafts of emergency current of SC i_k(t. For diminishing in the on-board power circuits of electrical equipment of aircrafts of maximum permissible sections S_{il} of the electric wires (cables) applied in them and accordingly providing of decline for different aircrafts of mass and overall indicators of their on-board CCP is needed in the on-boar networks of aircrafts along with the use of enhance frequency of f=400 Hz of AC to apply the fast-acting devices of their protecting from SC in course of time wearing-outs of t_a<<100 ms. It isshown that application of enhance frequency of f=400 Hz of AC in the on-board networks of aircrafts as compared to its frequency of f=50 Hz results in the considerable increase (in four times) of fast-acting of devices of their protection from SC, operation of which is based on the air electric explosion of metallic wire. Originality. First for the on-board network of aircrafts with AC of frequency of f=400 Hz the maximum permissible sections S_{il} and amplitudes of current density δ_{ilm} of SC are determined for the uninsulated wires and insulated wires (cables) with copper (aluminum) cores (shells), PVC, R and PET insulation. Practical value. Theobtained results will be used in the increase of thermal resistibility of CCP with copper (aluminum) cores (shells), PVC, R and PET insulation applied in the on-board electric networks of different aircrafts. References 18, tables 5.

Key words: **aircraft, on-board power circuits of electrical equipment, electric wires and cables, frequency of alternating current, selection of maximum permissible cross-sections of cable products.**

Надані результати запропоноаного інженерного електротехнічного підходу до розрахункового вибору гранично допустимих поперечних 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 у бортових силових колах електрообладнання літальних апаратів (ЛА) в аварійному режимі протікає струм $i_k(t)$ однофазного короткого замикання (КЗ) із заданими амплітудно-часовими параметрами. На підставі цього підходу здійснений вибір гранично допустимих поперечних перерізів S_{il} для вказаних дротів (кабелів) бортових силових кіл електрообладнання ЛА з частотою змінного струму f=400 Гц. Виконана розрахункова оцінка гранично допустимих амплітуд щільності δ_{ilm} струму $i_k(t)$ вказаного КЗ в даних дротах і кабелях бортових силових кіл ЛА. Бібл. 18, табл. 5.

Ключові слова: **літальний апарат, бортові силові кола електрообладнання, електричні дроти і кабелі, частота змінного струму, вибір гранично допустимих перерізів кабельно-провідниковій продукції.**

Приведены результаты предложенного инженерного электротехнического подхода к расчетному выбору предельно допустимых поперечных 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 бортовых силовых цепях электрооборудования летательных аппаратов (ЛА) в аварийном режиме протекает ток $i_k(t)$ однофазного короткого замыкания (КЗ) с заданными амплитудно-временными параметрами. На основании этого подхода осуществлен выбор предельно допустимых поперечных сечений S_{il} для указанных проводов (кабелей) бортовых силовых цепей электрооборудования ЛА с частотой переменного тока f=400 Гц. Выполнена расчетная оценка предельно допустимых амплитуд плотности δ_{ilm} тока $i_k(t)$ указанного КЗ в рассматриваемых проводах и кабелях бортовых силовых цепей ЛА. Библ. 18, табл. 5.

Ключевые слова: **летательный аппарат, бортовые силовые цепи электрооборудования, электрические провода и кабели, частота переменного тока, выбор предельно допустимых сечений кабельно-проводниковой продукции.**

Introduction. In [1, 2], as applied to the tasks of industrial electric power industry, the issues of a refined choice of the maximum allowable S_{il} and critical S_{iC} cross-sections of uninsulated electric wires, as well as insulated wires and cables with polyvinyl chloride (PVC), rubber (R) and polyethylene (PET) insulation and copper (aluminum) cores (sheaths) according to conditions of their, respectively, thermal stability and electric explosion (EE) are considered. As is known, the calculation modes for choosing the maximum allowable cross-sections S_{il} of cable-conductor products (CCP) used in power circuits of electrical equipment with alternating current of frequency f=50 Hz are the modes of single or three-phase short circuit (SC) [3, 4]. The technical data given in [1-4] for the selection of CCP relate to power circuits of electrical equipment used in land-based stationary objects during their industrial power supply with AC with frequency of f=50 Hz. And what about the choice of the maximum allowable cross-sections S_{il} of CCP for objects of aviation and rocket and space technology, in the on-board electrical networks of which it is possible to use alternating current with frequency f, significantly different from the traditional power frequency of 50 Hz? It is no secret that the overall dimensions and mass indicators of the on-board CCP, and hence the cross-sectional values S_{il} of its metal conductors (shell-screens), for such objects «go» to the forefront of the developers of this high technology. In this part, it should be noted that, for example, on the modern Airbus 380 airliner, the length of CCP of its on-board network is more than 530 km [5]. Here, the total power of electric power sources on board of military and civil aircrafts can range from 20 kW for light aircrafts to 600 kW and more for heavy aircrafts [6]. In this regard, the tasks related to the study of the peculiarities of application of AC with frequency f>50 Hz in the on-board power circuits of aircraft electrical equipment and the choice of maximum permissible cross-sections S_{il} of electrical wires and cables containing internal copper (aluminum) cores (i=1) and external reverse (protective) shells (i=2), as well as PVC, R and PET belt insulation for such frequencies become relevant in the field of applied electrical engineering in relation to modern aircraft.

The goal of the paper is the choice of the maximum permissible cross-sections S_{il} of bare wires and insulated wires (cables) with copper (aluminum) cores (shells) in the on-board power circuits of electrical equipment of various aircrafts with alternating current with frequency f>50 Hz.

1. Problem definition. Let us consider uninsulated copper and aluminum wires widely used in on-board power circuits of aircraft electrical equipment, as well as insulated wires and cables with copper (aluminum) inner cores and outer shell-shields, having PVC, R and PET belt (protective) insulation [7]. We assume that in round solid (split) copper (aluminum) cores (shells) of the indicated wires (cables) of the power circuits of the aircraft electrical equipment located in the air at temperature of θ_0=20 °C in the normal mode of their operation under the rated current load, in the longitudinal direction alternating current flows with frequency f>50 Hz, and the maximum long-term permissible temperature θ_{ll} of the Joule heating for non- and insulated wires (cables) with PVC, R and PET insulation does not numerically exceed those regulated by the applicable for electric power devices of levels of 70 °C and 65 °C, respectively [8]. Suppose that, for the generality of the electrical engineering problem to be solved, in the power circuits of aircrafts with CCP, their operation modes are possible when some sections of their wires (cables) can be completely de-energized. We believe that the thermal stability of the electrical wires and cables of the aircraft on-board circuits under consideration, as well as for stationary ground electric equipment with a two-wire power supply network, is limited by the maximum permissible short-term heating temperature θ_{lS} of the current-carrying parts of wires (cables) at the single-phase type of SC in the aircraft on-board network under study. In the first approximation of the solution of the formulated problem, we assume that the values of θ_{lS} correspond to the known maximum permissible short-term heating temperatures of the CCP with alternating SC current of power frequency f=50 Hz [8]. In this regard, the numerical values of the temperature θ_{lS} for uninsulated copper wires with strains less than 20 N/mm^2 will be 250 °C, and for uninsulated aluminum wires with strains less than 10 N/mm^2 – 200 °C [8]. For insulated wires and cables with copper and aluminum cores, PVC and R insulation, the numerical values of the temperature θ_{lS} then turn out to be 150 °C, and for the considered CCP with PET insulation – 120 °C [8]. We assume that when choosing the cross-sections S_{il}, the electric current $i_k(t)$ of the single-phase SC in the on-board network of the aircrafts, made according to a single or two-wire circuit, is almost uniformly distributed over the cross-section of the core and the screen-shell of the studied wire (cable).

The justification for this assumption is that the minimum penetration depth Δ_i of the magnetic field (skin layer thickness) from the current $i_k(t)$ of a single-phase SC in the on-board network of the aircraft in a quasi-stationary approximation to the conductive non-ferromagnetic materials of the core (screen-shell) under consideration, determined from the calculation relation $\Delta_i \approx [1/(\pi f \mu_0 \gamma_{0i})]^{1/2}$ [9], where γ_{0i} is the specific conductivity of the core (shell) of the core (shell) of CCP at θ_0=20 °C, and $\mu_0=4\pi\cdot 10^{-7}$ H/m is the magnetic constant, for example, for emergency current frequencies f=50 Hz and f=400 Hz is numerically for copper ($\gamma_{0i}=5.81\cdot 10^7$ $(\Omega\cdot\text{m})^{-1}$) respectively about 9.3 mm and 3.3 mm, and for aluminum ($\gamma_{0i}=3.61\cdot 10^7\cdot(\Omega\cdot\text{m})^{-1}$) about 11.8 mm and 4.2 mm. It can be seen that the indicated values of the skin layer thickness Δ_i turn out to be comparable with the radii (thicknesses) of the current-carrying cores (shells) of wires and cables, usually used in electrical circuits of the aircrafts under consideration (in particular, in aircraft networks [7]). As in [1, 2], we use the condition of the adiabatic nature of the action of the current $i_k(t)$ of a single-phase SC in the on-board network of the aircraft, no more than $t_{kC}=40f^{-1}$=100 ms in the conductive materials of the cores (shells) of the thermal process in CCP under consideration, in which the influence of heat transfer from the surfaces of their current-carrying parts having current temperature $\theta_{iS} \geq \theta_0$, and the thermal conductivity of the layers of their electrically conductive materials and insulation on the Joule heating of the current-carrying parts of the cores (shells) of the studied wires (cables) can be neglected. It is required by calculation in an approximate form, taking into account the nonlinear nature of the change, due to the Joule heating of the investigated CCP of the specific conductivity γ_i of the material of its cores (shells) and the conditions of the thermal resistibility of the CCP to the action of the current $i_k(t)$ of a single-phase SC in the on-board network of the aircraft to determine in the range of change of AC frequency f = (50-400) Hz in the power circuits of its electrical equipment the maximum 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 and PET insulation, through which in emergency operation mode of the aircraft single-wire on-board network (with a common «minus» on its massive metal casing, which serves as a reverse current lead [10]) or two-wire on-board aircraft network [11] current of a single-phase SC $i_k(t)$ flows with known duration t_{kC} and with specified amplitude-temporal parameters (ATPs). In addition, taking into account the obtaining of cross-sections S_{il}, it is necessary for the investigated CCP in the aircraft to determine also the maximum permissible density amplitudes δ_{ilm} of the current $i_k(t)$ of a single-phase SC in the on-board network of the aircraft.

2. An engineering approach to the selection of the maximum allowable cross-sections S_{il} of wires and cables in aircraft electrical equipment circuits. From the heat balance equation for the current-carrying parts of the CCP of the aircraft electrical equipment circuits in the adiabatic mode and the conditions of their thermal resistibility to the current $i_k(t)$ of the indicated SC, the analytical expression for the calculation of the maximum permissible cross-sections S_{il} of the considered electric wires and cables takes the following form [1]:

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

where $J_{ak}=\int\limits_0^{t_{kC}} i_k^2(t)dt$ is the Joule (action) integral of current $i_k(t)$ of a single-phase SC, $A^2{\cdot}s$; J_{ilS}, J_{ill} are the current integrals for current-carrying parts of wires (cables), the maximum permissible short-term temperature and long-term permissible material heating temperature are θ_{lS} and θ_{ll}, respectively, $A^2{\cdot}s{\cdot}m^{-4}$; $C_{ik}=(J_{ilS}-J_{ill})^{1/2}$ is the calculation coefficient, $A{\cdot}s^{1/2}{\cdot}m^{-2}$.

It clearly follows from (1) that for the calculation determination of the values of the cross-sections S_{il}, it is necessary to know the values of the Joule integral J_{ak} and the coefficient C_{ik}.

2.1. Determination of current integrals J_{ilS}, J_{ill} and coefficient C_{ik} for CCP of on-board aircraft network. To calculate with engineering accuracy the values of the current integrals J_{ilS} and J_{ill} included in (1), used, in particular, in [9] in the form of current or inertia integrals (see formula 4.56), whose integrand, unlike the classical Joule integral, does not contain the square of the emergency current $i_k(t)$, but the square of the density of this current $\delta_{ik}(t)$ in the electrically conductive materials of the CCP of the aircraft on-board network, we use the following approximate analytical expressions [1, 12]:

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

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

where c_{0i}, β_{0i} are, respectively, quantifiable at θ_0=20 °C the specific volumetric heat capacity (J/(m^3·°C)) and the thermal coefficient of the electrical conductivity (m^3/J) of the conductive material of the core (shell) of the wire (cable) of on-board power circuit of the aircraft electrical equipment with current frequency f>50 Hz before exposure to the CCP of the emergency current $i_k(t)$ of a single-phase SC in the on-board network of the aircraft with specified ATPs.

Table 1 shows the numerical values of the used in (2), (3) electrophysical parameters γ_{0i}, c_{0i} and β_{0i} for the main conductive materials used in the current-carrying parts of the CCP of the aircraft on-board network at temperature equal to θ_0=20 °C [9, 12].

Table 1

Numerical values of the characteristics of the basic materials of current-carrying cores (shells) of non- and insulated wires (cables) of power circuits of electrical equipment of the aircraft on-board network at θ_0=20 °C [9, 12]

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

Using 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), (3), numerical values of the desired current integrals J_{ilS}, J_{ill}, and coefficient C_{ik} used in (1) for a wide range of CCP used in on-board power circuits of electrical equipment of various aircrafts can be found. Table 2 shows the numerical values of the calculated coefficient C_{ik} for the main versions of the CCP, which is widely used in the on-board power circuits of electrical equipment of various aircrafts.

Table 2

The numerical values of the coefficient C_{ik} for non- and insulated wires (cables) with copper (aluminum) cores (shells) used in on-board power circuits of aircraft electrical equipment [1]

Type of insulation in the wire (cable) of the aircraft electrical equipment circuit	Core (shell) material of wire (cable)	Numerical value of C_{ik}, 10^8 A·s$^{1/2}$/m^2	
		$J_{ill}\neq0$	$J_{ill}=0$
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

In Table 2, the case when $J_{ill}\neq0$ corresponds to the rated current load of the CCP in the on-board power circuits of the aircraft electrical equipment under study (the temperature of their current-carrying parts is θ_{ll}), and the case when $J_{ill}=0$ corresponds to the de-energized state of the CCP in the aircraft (temperature of their current-carrying parts before flowing through them of the current $i_k(t)$ of a single-phase SC in the on-board network of the aircraft corresponds to the temperature of the surrounding CCP the air environment, which we adopted equal to θ_0=20 °C). Next, we focus on finding the Joule integral J_{ak}, which is the main parameter for the calculation determination of the desired cross-section S_{il} by (1).

2.2. Determination of the integral of action J_{ak} of emergency current during SC in the on-board network of an aircraft. To do it, we first write down the analytical relation describing the variation in time t of current $i_k(t)$ of a single-phase SC in the on-board power circuits of electrical equipment used in various aircraft and launch vehicles and fed from an on-board AC source with frequency of f>50 Hz. According to [1, 4], the ATPs of this current $i_k(t)$ of SC in the on-board network of an aircraft containing active and reactive resistances obey the following time dependence:

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

where I_{mk} is the amplitude of the steady current $i_k(t)$ of SC in the power circuit of the electrical equipment of the aircraft, A; T_a is the decay time constant of the aperiodic component of the emergency current $i_k(t)$ of SC in the on-board circuit of the aircraft, s.

From (4) at f=400 Hz and t=1.25 ms, which corresponds to the largest amplitude of the shock current $i_k(t)$ of a single-phase SC in the on-board network of the aircraft, an analytical expression for the calculated shock coefficient k_S, which is typical for the considered on-board power supply system of the aircraft in emergency mode follows:

$$k_S = [1 + \exp(-0{,}00125/T_a)]. \tag{5}$$

At T_a=3 ms, according to (5), the value of the shock coefficient k_S turns out to be numerically equal to 1.66. Therefore, at an operating voltage of alternating current with frequency f=400 Hz in the on-board network of an aircraft produced, for example, by an on-board converter of the ПОС-1000 type and equal to 115 V [6], in the single-phase SC mode the amplitude of the shutdown current is in accordance with the data [13-15] can reach a level of (2-25) kA.

Then, taking into account (1) and (4), the expression for the desired integral of action J_{ak} of the current $i_k(t)$ of the SC in the on-board circuit of the aircraft electrical equipment in the accepted approximation takes on the following analytical form [1]:

$$\begin{aligned} J_{ak} = I_{mk}^2 \Big\{ & 0{,}5t_{kC} + 0{,}25(\pi f)^{-1}\sin(2\pi f t_{kC}) \times \\ & \times \cos(2\pi f t_{kC}) - 2T_a^2(1 + 4\pi^2 f^2 T_a^2)^{-1}\Big[e^{-t_{kC}/T_a} \times \\ & \times [2\pi f \sin(2\pi f t_{kC}) - T_a^{-1}\cos(2\pi f t_{kC}) + T_a^{-1}]\Big] + \\ & + 0{,}5T_a(1 - e^{-2t_{kC}/T_a})\Big\}. \end{aligned} \tag{6}$$

From (6) it follows that the values of the action integral J_{ak} of the SC current $i_k(t)$ in the aircraft on-board power supply system are directly proportional to the square of the amplitude I_{mk} of the steady-state SC current and duration t_{kC} (switching off time equal to the operation time t_a of the on-board protection devices [13, 14]) against the course of the SC under consideration. It can be seen that the larger the numerical values of I_{mk} and t_{kC}, the greater will be the numerical values of the desired value of the integral J_{ak}. Table 3 at T_a=3 ms (f=400 Hz) for four fixed numerical values of the amplitude I_{mk} of the steady-state SC current (3, 5, 10, and 30 kA) and two possible numerical values of the duration t_{kC} of a single-phase SC in the on-board network of the aircraft (5 ms and 100 ms) according to [13, 14] shows the numerical values of the action integral J_{ak} of the current $i_k(t)$ of the indicated SC calculated according to (6).

Table 3

Numerical values of the action integral J_{ak} for the SC current $i_k(t)$ according to (4), flowing in the on-board power circuits of the aircraft electrical equipment (f = 400 Hz; T_a = 3 ms)

Numerical value of the amplitude I_{mk} of the steady-state current $i_k(t)$ of a single-phase SC in the on-board power circuit of the aircraft electrical equipment, kA	Value of the action integral J_{ak} for the Sc current $i_k(t)$ by (4), $A^2 \cdot s$	
	t_{kC}=5 ms	t_{kC}=100 ms
3	$3.55 \cdot 10^4$	$4.63 \cdot 10^5$
5	$9.86 \cdot 10^4$	$12.86 \cdot 10^5$
10	$39.46 \cdot 10^4$	$51.44 \cdot 10^5$
30	$35.51 \cdot 10^5$	$46.30 \cdot 10^6$

Determining by (6) the values of the action integral J_{ak} of the SC current $i_k(t)$ (see Table 3) and knowing the numerical values of the coefficient C_{ik} (see Table 2), on the basis of (1) numerical values of the maximum permissible cross-sections S_{il} of current-carrying parts of the CCP under consideration in the on-board power circuits of the aircraft electrical equipment can be found. Using the assumptions made, for given amplitudes I_{mk} from a relationship of the form $\delta_{ilm} \approx I_{mk}/S_{il}$, the maximum permissible current density amplitudes δ_{ilm} in the materials of the cores (shells) of the CCP under study of the aircraft on-board network for emergency SC conditions can be quantified.

2.3. The results of the selection of the maximum allowable cross-sections S_{il} and current densities δ_{ilm} in the wires and cables of the on-board network of the aircraft. Table 4 shows the results of the calculation according to (1), taking into account the data summarized in Table 2, 3, of maximum permissible cross-sections S_{il} of current-carrying copper (aluminum) parts of the CCP of on-board power circuits of the aircraft electrical equipment at =400 Hz, $J_{ill} \neq 0$, t_{kC}=5 ms and amplitude I_{mk} of a single-phase SC current $i_k(t)$ in the onboard network of the aircraft (launch vehicle), which varies discretely in the range (3-30) kA.

Table 4

Values of the maximum allowable cross-sections S_{il} for wires (cables) with copper (aluminum) cores (shells) in the on-board power circuits of the aircraft electrical equipment with current amplitude I_{mk} of single-phase SC current $i_k(t)$ from 3 to 30 kA (f=400 Hz; $J_{ill} \neq 0$; t_{kC}=5 ms; T_a=3 ms)

Type of insulation in the wire (cable) of the aircraft electrical equipment circuit	Core (shell) material of wire (cable)	Cross-section value S_{il}, mm^2			
		Amplitude I_{mk} of the steady-state SC current, kA			
		3	5	10	30
Without insulation	Copper	1.21	2.01	4.03	12.08
	Aluminum	2.14	3.57	7.14	21.41
PVC, R	Copper	1.62	2.71	5.41	16.24
	Aluminum	2.55	4.24	8.49	25.46
PET	Copper	1.96	3.27	6.54	19.63
	Aluminum	3.04	5.06	10.13	30.39

It should be pointed out that the questions of choosing the maximum permissible cross-sections S_{il} of cores (shells-shields) of the studied CCP for the case when f=50 Hz (J_{ill}≠0; t_{kC}=(100-160) ms; I_{mk}=(30-100) kA; T_a=20 ms) were considered in detail by the author in [1]. Comparing the data for S_{il} from the above Table 4 and from Table 5 in [1], we can conclude that the transition in the on-board network of an aircraft to AC frequency of f=400 Hz (eight times the frequency f=50 Hz used in power circuits of ground-based power facilities) allows for the use in the on-board network of the aircraft of high-speed protection devices against SC (for example, type A3-250 for currents with amplitude of up to 6 kA) [13, 14] and, accordingly, a sharp decrease at f=400 Hz in time t_{kC} of the action of the current $i_k(t)$ of a single-phase SC in the on-board network of an aircraft (from 100 ms to 5 ms) significantly reduce the numerical values of the maximum allowable cross-sections S_{il} of its copper (aluminum) wires and cables (for emergency operation at I_{mk}=30 kA about 3.9 times). This can lead to a similar decrease (3.9 times) in the overall dimensions and mass indicators of the indicated CCP installed on board of the aircraft. Of course, in spite of the indicated advantages of using in aircraft on-board networks of AC frequency f=400 Hz and fast-acting circuit breakers protecting against SC (for example, for A3-250 circuit breakers t_a=5 ms), this is not so easily to transfer available in aviation and space techniques and circuit-technical solutions in part of thermal protection against SC of relatively low-power low-voltage aircraft on-board networks (f=400 Hz) to ground powerful high-voltage electric networks of industrial power supply (f=50 Hz).

From the data of Table 4 it follows that the maximum permissible amplitude of the density δ_{ilm}≈I_{mk}/S_{il} of the current $i_k(t)$ of a single-phase SC at the time of its flow (shutdown) t_{kC}=5 ms in the on-board power circuits of the aircraft electrical equipment (f=400 Hz; T_a=3 ms) for uninsulated wires with copper and aluminum cores are approximately 2.48 kA/mm^2 and 1.40 kA/mm^2, respectively, for cables with copper (aluminum) cores (shells), PVC and R insulation – 1.85 (1.18) kA/mm^2, and for cables with copper (aluminum) cores (shells) and PET insulation – 1.53 (0.99) kA/mm^2. Here, the indicated numerical values of the maximum permissible amplitudes of the SC current density δ_{ilm} in the considered conductive materials of the current-carrying parts of the wires (cables) of the aircraft on-board network do not depend on the amplitude level I_{mk} of the steady-state emergency current with frequency of f=400 Hz in them.

The above numerical data for δ_{ilm} in the CCP of the on-board aircraft network (f=400 Hz) compared with similar numerical values from [1] of the maximum permissible current density amplitudes δ_{ilm} of the current $i_k(t)$ of SC characteristic for this case (J_{ill}≠0; t_{kC}=100 ms; I_{mk}=30 kA; T_a=20 ms) and the considered CCP of power circuits of electrical equipment of general industrial use (f=50 Hz), turn out to be approximately 3.9 times larger. To assess the effect of the duration t_{kC} of SC in the on-board power circuit of an aircraft on the choice of values of the maximum allowable cross-sections S_{il} of the studied wires and cables, Table 5 shows the data corresponding to the case t_{kC}=100 ms.

Table 5

Values of the maximum allowable cross-sections S_{il} for wires (cables) with copper (aluminum) cores (shells) in the on-board power circuits of the aircraft electrical equipment with current amplitude I_{mk} of single-phase SC current $i_k(t)$ from 3 to 30 kA (f=400 Hz; J_{ill}≠0; t_{kC}=100 ms; T_a=3 ms)

Type of insulation in the wire (cable) of the aircraft electrical equipment circuit	Core (shell) material of wire (cable)	Cross-section value S_{il}, mm^2			
		Amplitude I_{mk} of the steady-state SC current, kA			
		3	5	10	30
Without insulation	Copper	4.36	7.27	14.54	43.62
	Aluminum	7.73	12.89	25.77	77.32
PVC, R	Copper	5.86	9.78	19.55	58.66
	Aluminum	9.19	15.32	30.65	91.95
PET	Copper	7.09	11.81	23.62	70.88
	Aluminum	10.97	18.29	36.58	109.75

Note that the quantitative results for the sections S_{il} of the current-carrying parts of the CCP of the aircraft on-board network (f=400 Hz) presented in Table 5 were obtained according to (1), taking into account the data in Table 2, 3 for the mode when the equality T_a=3 ms is fulfilled in the on-board electrical circuits of an aircraft with active-inductive load, and А3Д3-200 circuit breakers (t_a=100 ms) are used as on-board protection devices on an aircraft against SC [13, 14]. From the data of Table 5, it follows that at t_{kC}=100 ms, regardless of the numerical value of the current amplitude I_{mk}, the maximum permissible density amplitudes δ_{ilm}≈I_{mk}/S_{il} of the emergency current $i_k(t)$ at the SC for bare wires with copper and aluminum cores in the on-board electrical circuits of the aircraft electrical equipment (T_a=3 ms) are about 0.69 kA/ mm^2 and 0.39 kA/mm^2, respectively, for cables with copper (aluminum) cores (shells), PVC and R insulation – 0.51 (0.33) kA/mm^2, and for cables with copper (aluminum) cores (shells) and PET insulation – 0.42 (0.27) kA/mm^2. The results obtained for both S_{il} and δ_{ilm} (f=400 Hz; t_{kC}=100 ms) from the corresponding quantitative data for S_{il} and δ_{ilm} (f=50 Hz; t_{kC}=100 ms) from [1] differ (due to different values of parameter T_a, which in the first case was numerically 3 ms, and in the second case – 20 ms) by almost no more than 8%. Hence, it can be concluded that the choice in the on-board aircraft network of the maximum permissible cross-sections S_{il} of its CCP and, accordingly, the maximum permissible amplitudes of the current density δ_{ilm} in the current-carrying copper (aluminum) parts of its wires and cables is determined not by the frequency f of alternating current in the aircraft on-board network, but duration t_{kC} of emergency SC current $i_k(t)$ in the considered electric network emergency current.

Considering the above, in order to reduce the maximum allowable cross-sections S_{il} of the electrical wires (cables) used in the aircraft electrical equipment on-board electrical circuits and, accordingly, to ensure a decrease for aircrafts in the weight and size characteristics of their on-board CCP, it is necessary in the aircraft on-board networks along with the use of increased frequency of alternating current (for example, f=400 Hz) to use high-speed short-circuit protection devices having operation times t_a<<100 ms.

2.4. Calculation estimation of thermal resistibility of wires and cables in the on-board network of aircrafts. The proposed approach to the calculation of the maximum permissible cross-sections S_{il} of the wires (cables) in the on-board power circuits of the aircraft electrical equipment (f=400 Hz) allows the calculation of their thermal stability to be carried out. Here, as in [1, 8], it is proposed to determine the thermal resistibility of the investigated CCP in the aircraft on-board network by the following thermophysical condition:

$$\theta_{iS} \le \theta_{lS}\,, \tag{7}$$

where θ_{iS}, θ_{lS} are, respectively, the current (final) and maximum permissible short-term heating temperatures of the current-carrying parts of the electrical wires and cables in the aircraft on-board circuits.

To find in (7) the values of the current or final heating temperature θ_{iS} of the material of the current-carrying parts of the CCP, determined by the Joule heat on the action of the SC current $i_k(t)$, we initially use the well-known nonlinear dependence of the specific conductivity γ_i of the core (shell) material of the wire and cable on the value of the temperature θ_{iS} [1, 9]:

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

It is important to note that relation (8) in the temperature range from 20 °C to the melting temperature of the core (shell) materials of the CCP, according to experimental data from [9], approximates the temperature dependence of γ_i for copper and aluminum with an error of no more than 5%. Note that in (8), the quantity γ_{0i} is understood as the specific electrical conductivity γ_i of the conductive material of the current-carrying parts of the CCP at temperature θ_0=20 °C. Then, taking into account (8), the solution of the first-order inhomogeneous differential equation for the final temperature θ_{iS} of the Joule heating by current $i_k(t)$ of the single-phase SC of the material of the core (shell) of the CCP in the on-board power circuit of the aircraft electrical equipment under the initial condition of the form $[\theta_{iS}|_{(t=0)} - \theta_{0i}]=0$ can be written in the following approximate analytical form [1, 12]:

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

where θ_{0i} is the initial temperature of the material of the current-carrying parts of the CCP, which, depending on the operating mode of the on-board electrical circuits of the electrical equipment, is θ_{ll} (J_{ill}≠0) or θ_0=20 °C (J_{ill}=0).

It can be seen from (9) that, under the assumptions made, the known numerical values of the thermophysical characteristics γ_{0i}, c_{0i} and β_{0i} for the conductive materials under consideration of the current-carrying parts of the CCP in the aircraft on-board network (see the data in Table 1), as well as for found by (1), (6) the numerical values of the maximum permissible cross-sections S_{il} of copper (aluminum) cores (shells) of wires (cables) and the action integral J_{ak} of the current $i_k(t)$ of a single-phase SC, the determination of the desired value of the final temperature θ_{iS} and its comparison by condition (7) with the known [8] permissible short-term temperature θ_{lS} does not cause any electrical engineering trouble.

As an example of the calculation estimation according to condition (7) of the thermal resistibility of the CCP of the aircraft on-board network (f=400 Hz; J_{ill}≠0; θ_{0i}=θ_{ll}=65 °C), we consider the case when for its aviation shielded wire of the БПВЛЭ brand with PVC insulation and the split copper core [7, 15] in the emergency mode of a single-phase SC, the following initial data are satisfied: I_{mk}=5 kA; t_{kC}=5 ms; T_a=3 ms. According to Table 4, for the indicated initial parameters, the maximum permissible cross-section S_{il} of the wire considered is numerically approximately 2.71 mm^2. In this case, the value of the action integral J_{ak} of the current $i_k(t)$ of a single-phase SC in the on-board network of an aircraft according to (6) will be numerically about 9.86·10^4 A^2·s (see Table 3). Then, according to (9), taking into account the data in Table 1, the final temperature θ_{iS} of the Joule heating by an emergency current $i_k(t)$ of the SC of the form (4) of the copper wire under consideration installed in the on-board network of the aircraft will be numerically equal to about 133.8 °C. It is seen that the calculated value of the final temperature θ_{iS}=133.8 °C is less than the maximum permissible short-term heating temperature θ_{lS} of the БПВЛЭ grade aviation copper wire with PVC insulation of 150 °C [8] checked for thermal resistibility. Therefore, we can conclude that condition (7) for this calculation case as applied to the on-board aircraft network is fulfilled.

In this regard, it can be said that the calculated assessment of the thermal resistibility of the БПВЛЭ brand aircraft wire with copper core and PVC insulation of the power circuits of the aircraft electrical equipment with alternating current frequency of f=400 Hz indicates the operability of the proposed electrical engineering approach to the calculation choice of permissible cross-sections S_{il} of current-carrying parts of the CCP used in on-board networks of various aircraft.

3. The influence of the frequency of the alternating current in the on-board network of the aircraft on the operation time of its protection device against short-circuit. We consider this question that has been little studied today in the field of applied electrical engineering by the example of the possible use of a short-circuit protection device (fuse) in the on-board network of an aircraft using not a metal flat plate that does not melt due to Joule heating by SC current (as in a conventional electric fuse [11, 16]), but an electrically exploding metal round wire [9, 12]. It is known that the operation time t_a of conventional fuses (for example, one of the world's best Ultra Quick series for current amplitudes of power frequency f=50 Hz up to 1.4 kA [17]) is at least 10 ms. It is possible to reduce these values of the operation time t_a of the protection device to units of milliseconds or fractions of a unit of a millisecond due to the use of high-speed fuses (HSFs) in the aircraft on-board network using the phenomenon of EE of the metal wire under the influence of emergency SC current of frequency f=400 Hz with amplitude I_{mk} of unity (tens) kiloamperes [9, 18].

We use the well-known analytical relationship that determines the time of the EE t_e in atmospheric air (operation time t_a of the HSF) of a round metal wire with cross-section S_i when emergency current $i_k(t)$ of SC flows through it in the on-board network of the aircraft [18]:

$$t_e = 1{,}333\cdot\left[J_c S_i^2 / (2\pi^2 f^2 k_s^2 I_{mk}^2)\right]^{1/3}, \tag{10}$$

where J_c is the critical value of the current integral for a conductive material of an electrically exploding metal wire (for copper – J_c=1.95·10^{17} A^2·s·m^{-4} [9]; for aluminum – J_c=1.09·10^{17} A^2·s·m^{-4} [9]).

From (10) at f=400 Hz, k_S=1.66 (T_a=3 ms) and I_{mk}=30 kA for a round copper wire (J_c=1.95·10^{17} A^2·s·m^{-4}) with radius r_i=1 mm (S_i=3.141 mm^2) the value of the operation time t_a of the HSF under consideration (the time of the air EE t_e this wire) from exposure to it (this type of fuse) of AC SC current $i_k(t)$ in the on-board network of the aircraft is approximately 0.84 ms. As you can see, the EE of the indicated wire, which forms the basis of the HSF under consideration, occurs at the front of the first half-wave of the emergency current $i_k(t)$ (the maximum of this half-wave at f=400 Hz corresponds to the time t_m=1.25 ms), which occurs during a single-phase SC in the studied on-board network of the aircraft. We note that for I_{mk}=20 kA with the previous initial data indicated above, the operation time t_a of the HSF (the time of the EE t_e of the assumed round copper wire with cross-section S_i=3.141 mm^2) is equal to about 1.09 ms. From (10) it follows that the time of EE t_e of the metal wire in the on-board network of an aircraft with AC of frequency f is inversely proportional to the value of $(f)^{2/3}$. The higher the frequency f of the alternating current in the on-board network of the aircraft, the shorter the operation time t_a of the indicated HSF will be. The transition in the on-board network of an aircraft from frequency f=50 Hz of alternating current to its frequency f=400 Hz leads to a decrease in the operation time t_a of the HSF using the EE of a metal wire by four times.

Considering the revealed feature of the influence of the frequency f on the operation time t_a of the HSF under consideration, the use of increased alternating current frequency (for example, f=400 Hz) in the aircraft on-board network from the standpoint of the possibility of increasing the speed of its short-circuit protection device, the operation of which is based on the phenomenon of the EE of a metal wire is a technically justifiable offer.

Conclusions.

1. The proposed electrical engineering approach allows, under the condition of thermal resistibility of the CCP of the on-board power circuits of aircraft electrical equipment with alternating current of increased frequency f=400 Hz, to carry out the calculation choice of the maximum permissible cross-sections S_{il} of uninsulated wires, insulated wires and cables with copper (aluminum) cores (shells) with PVC, R and PET insulation, the current-carrying parts of which in the emergency mode of their operation can be affected by the current $i_k(t)$ of a single-phase short circuit in the on-board network of the aircraft with predicted and confirmed by many years of experience in operating various aircrafts amplitude-temporal parameters.

2. It is found that in the on-board power circuits of the aircraft electrical equipment (f=400 Hz; T_a=3 ms), the maximum permissible density amplitudes $\delta_{ilm} \approx I_{mk}/S_{il}$ of the current $i_k(t)$ of a single-phase short-circuit with its switch-off time t_{kC}=5 ms in the on-board electrical network of the aircraft regardless of the numerical value of the amplitude I_{mk} of the steady-state short-circuit current for uninsulated wires with copper (aluminum) cores, respectively, are about 2.48 (1.40) kA/mm^2, for wires and cables with copper (aluminum) cores (shells) and PVC (R) insulation – 1.85 (1.18) kA/mm^2, and for wires and cables with copper (aluminum) cores (shells) and PET insulation – 1.53 (0.99) kA/mm^2. With an increase in the on-board electrical network of the aircraft of the switch-off time t_{kC} of the current $i_k(t)$ of a single-phase short circuit in the indicated power circuits of the aircraft (T_a=3 ms), the maximum permissible density amplitudes δ_{ilm} of the emergency short circuit current also decrease and at t_{kC}=100 ms for uninsulated wires with copper (aluminum) cores are respectively approximately 0.69 (0.39) kA/mm^2, for wires and cables with copper (aluminum) cores (shells) and PVC (R) insulation – 0.51 (0.33) kA/mm^2, and for wires and cables with copper (aluminum) cores (shells) and PET insulation – 0.42 (0.27) kA/mm^2.

3. The decisive influence on the choice in the aircraft on-board network of the maximum permissible cross-sections S_{il} of its CCP and, accordingly, the maximum allowable current density amplitudes δ_{ilm} in the current-carrying copper (aluminum) parts of its wires and cables is exerted not by the frequency f of alternating current in the aircraft on-board network, but by the duration t_{kC} of the flowing (switch-off time) in the on-board electrical network of emergency short circuit current $i_k(t)$.

4. To reduce in the on-board power circuits of the aircraft electrical equipment the maximum allowable cross-sections S_{il} of used in them non- and insulated electric wires (cables) and, accordingly, to ensure the reduction in mass and size indicators of their on-board CCP for various aircraft, it is necessary along with the use of increased frequency f=400 Hz of alternating current to use high-speed short-circuit protection devices (circuit breakers) with their operation time t_a<<100 ms.

5. It is shown that the use of increased frequency f=400 Hz of alternating current in the on-board networks of aircrafts as compared with its frequency f=50 Hz leads to a significant increase (four times) in the speed of devices (fuses) for their protection against short-circuit, the operation of which is based on air EE of a round metal (in particular, copper) wire.

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