UDC 621.3.022: 621.315.3: 537.311.8 **doi: 10.20998/2074-272X.2018.6.08**

M.I. Baranov

A CHOICE OF SECTIONS OF ELECTRIC WIRES AND CABLES IN CIRCUITS OF DEVICES OF HIGH-VOLTAGE HIGH-CURRENT IMPULSE TECHNIQUE

Purpose. Implementation of calculation choice of sections of electric wires and cables in circuits of devices of high-voltage high-current impulse technique (HHIT), characterized flowing of pulsed current $i_p(t)$ with different amplitude-temporal parameters (ATP). Methodology. Electrophysics bases of technique of high-voltage and high pulsed currents, theoretical bases of the electrical engineering, bases of electrical power engineering, technique of high electric and magnetic fields, and also measuring technique. Results. The results of the developed generalized electrical engineering investigations are resulted in a calculation choice on the condition of thermal resistibility of cable products of boundary permissible sections S_{Cil} of the electric uninsulated wires, and also insulated wires and cables with copper (aluminum) cores (shells) with polyvinyl chloride (PVC), rubber (R) and polyethylene (PET) insulation, on which in the circuits of HHIT the axial-flow of pulsed current $i_p(t)$ flows with arbitrary ATP. On the basis of this approach the results of concrete choice of sections S_{Cil} are presented for the indicated electric wires (cables) of power circuits of HHIT with pulsed current, ATP of which with amplitudes of I_{mp} = (0.1-1000) kA change on an aperiodic law or law of damped sinusoid in nano-, micro- and millisecond temporal ranges. The results of calculation estimation present maximum permissible approximations of δ_{Cil} of pulsed current $i_p(t)$ of the examined temporal shapes in the indicated electric wires and cables of power circuits of HHIT. It is shown that the values of current approximations of δ_{Cil} for the uninsulated copper (aluminum) wires in the nanosecond temporal range of ATP of pulsed currents $i_p(t)$ are about 495 (293) kA/mm^2, in the microsecond temporal range – 26 (15) kA/mm^2 and in a millisecond temporal range – 543 (320) A/mm^2. By a calculation it is set that for the insulated wires (cables) with copper (aluminum) cores (shells) and PET with insulation the indicated current approximation of δ_{Cil} is approximately: for the nanosecond range – 361 (233) kA/mm^2; for the microsecond range – 19 (12) kA/mm^2; for the millisecond range – 396 (256) A/mm^2. Originality. Firstly by a calculation for the concrete temporal shapes of pulses of current $i_p(t)$ in the discharge circuits of HHIT, changing in the wide range of the amplitudes I_{mp} on a aperiodic law or law of damped sinusoid, the numeral values of cross-sections S_{Cil} and current approximations of δ_{Cil} are obtained for the uninsulated wires, insulated wires and cables with copper (aluminum) cores (shells) with PVC, R and PET insulation. Practical value. Application in practice of model tests of objects of electrical power engineering, aviation and space-rocket technique on resistibility to direct action of pulsed currents $i_p(t)$ with different ATP of natural (currents of lightning) and artificial (discharge currents of HHIT) origin to increase electro-thermal resistibility of the electric uninsulated wires, and also the insulated wires and cables with PVC, R and PET insulation of HHIT widely applied in power circuits. References 13, tables 11, figures 2.

Key words: **high-voltage high-current impulse technique, electric wires and cables, calculation choice of boundary permissible sections of wires and cables in the circuit of impulse technique.**

Приведены результаты разработанного обобщенного электротехнического подхода к расчетному выбору по условию термической стойкости предельно допустимых сечений S_{Cil} электрических неизолированных проводов, а также изолированных проводов и кабелей с поливинилхлоридной (ПВХ), резиновой (Р) и полиэтиленовой (ПЭТ) изоляцией с медными (алюминиевыми) жилами (оболочками), по которым в цепях высоковольтной сильноточной импульсной техники (ВСИТ) протекает аксиальный импульсный ток $i_p(t)$ с произвольными амплитудно-временными параметрами (АВП). На основании данного подхода продемонстрированы результаты конкретного выбора сечений S_{Cil} для указанных электрических проводов (кабелей) силовых цепей ВСИТ с импульсным током, АВП которого с амплитудами I_{mp}=(0,1-1000) кА изменяются по апериодическому закону или закону затухающей синусоиды в нано-, микро- и миллисекундному временных диапазонах. Представлены результаты расчетной оценки предельно допустимых плотностей δ_{Cil} импульсного тока $i_p(t)$ рассматриваемых временных форм в указанных электрических проводах и кабелях силовых цепей ВСИТ. Полученные результаты будут способствовать повышению электротермической стойкости электрических неизолированных проводов, а также изолированных проводов и кабелей с ПВХ, Р и ПЭТ изоляцией, широко применяемых в силовых цепях ВСИТ. Библ. 13, табл. 11, рис. 2.

Ключевые слова: **высоковольтная сильноточная импульсная техника, электрические провода и кабели, расчетный выбор предельно допустимых сечений проводов и кабелей в цепях импульсной техники.**

Introduction. One of the challenges in the field of high-voltage high-current impulse technology (HHIT) is a reasonable choice of cross-sections S_C of used in it electrical wires and cables. It is known that in wires and cables in the area of HHIT can flow in normal and emergency modes of operation of such equipment pulsed currents $i_p(t)$ with different amplitude-temporal parameters (ATP). In this case, the amplitudes I_{mp} of these currents can vary in the range from hundreds of amperes to thousands of kiloamperes, and their duration τ_p varies from tens of nanoseconds to hundreds of milliseconds [1, 2]. The well-known approach for choosing sections S_C of electrical wires (cables) for short-term modes of their operation, used now in traditional industrial electric power engineering, is based on the thermal resistance of cable-conductor products (CCP) under the conditions of a short circuit (SC) current acting on it with specified ATP [3]. In this case, the thermal resistibility of electrical wires and cables is limited by the maximum permissible short-term temperature θ_{lS} of heating of the parts of wires (cables) at SC. In Table 1, according to the results of [3], the numerical values of the temperature θ_{lS} of heating are given for the main conductive and insulating materials of electrical wires and cables at SC. From the data of Table 1 it can be seen that the value of θ_{lS} should not exceed for used in power electric circuits with current frequency of 50 Hz uninsulated copper and aluminum cores (wires) in SC mode the highest level of 250 °C and 200 °C, and for cables (insulated wires) with copper and aluminum cores and PVC (R), PET insulation, respectively, the level of 150 °C and 120 °C [3].

Table 1
The values of the maximum permissible short-term temperature θ_{lS} of heating for the main conductor and insulation materials of wires (cables) of industrial electric power circuits under the action of SC [3]

No.	Name of the wire (cable) part	θ_{lS}, °C
1	Tire (core), copper, uninsulated at stresses less 20 N/mm^2	250
2	Tire (core), aluminum, uninsulated at stresses less 10 N/mm^2	200
3	Cable and insulated wire with copper (aluminum) cores and polyvinyl chloride (PVC) or rubber (R) insulation	150
4	Cable and insulated wire with copper (aluminum) cores and polyethylene (PET) Insulated	120
5	Aluminum part of the steel-aluminum wires of power lines	200

We point out that in the industrial electric power industry, the long-term permissible temperature θ_{ll} of heating the conductive and insulating parts of electrical wires and cables is limited by the conditions for reliable operation of electrical contacts and contact connections or by the conditions of their insulation [3]. In Table 2, according to the data of [3], the well-known numerical values of the heating temperature θ_{ll} for the main types of electrical wires and cables used in the field of modern power engineering are given.

Table 2
The values of long-term permissible temperature θ_{ll} for the main types of electrical wires (cables) [3]

No.	Name of the wire (cable) or the core	θ_{ll}, °C
1	Wires (cores) uninsulated with any current-carrying tires (parts)	70
2	Cables (wires) with copper (aluminum) tires, PVC, R and PET insulation	65
3	Cables with impregnated cable insulation paper for voltage up to 6 kV	65
4	Cables with impregnated cable insulation paper for voltage up to 35 kV	50

From the data of Table 2 it follows that the maximum long-term permissible temperature θ_{ll} of heating for uninsulated wires and cables with PVC, PET and R insulation, which are under current load in industrial electric power circuits, should not exceed respectively the level of 70 °C and 65 °C. Taking into account the data of Table 1, 2, as well as the condition that the wire (cable) before the impulse effect of SC current on it was fully electrically loaded and had temperature θ_{ll}, and at SC it heated to temperature θ_{lS}, in [3] to select the minimum permissible cross-section S_{lmin} of electrical wire (cable) wire the following calculated ratio is recommended:

$$S_{l\min} = B_k^{1/2} / C_k \,, \qquad (1)$$

where $B_k = \int_0^{t_k} i_k^2(t)dt$ is the Joule (action) integral of the SC current $i_k(t)$ with duration t_k (a technique of calculation of B_k is presented in [3]), A^2·s; C_k is the coefficient (A·s$^{1/2}$/mm^2), whose numerical values are given in Table 3.

Table 3
The values of the coefficient C_k for the main types of electrical wires and cables of industrial electric power circuits under the action of SC [3]

No.	Name of the wire (cable) and the core	C_k, A·s$^{1/2}$/mm^2
1	Wires (cores), copper, uninsulated	170
2	Wires (cores), aluminum, uninsulated	90
3	Cables (insulated wires) with PVC and R insulation and copper cores	120
4	Cables (insulated wires) with PVC and R insulation and aluminum cores	75
5	Cables (insulated wires) with PET insulation and copper cores	103
6	Cables (insulated wires) with PET insulation and aluminum cores	65

Taking into account the fact that ATP of pulsed currents $i_p(t)$, used in the field of HHIT, usually do not correspond to ATP of SC current in industrial electric network, application of (1) and data of Table 3 for the calculation determination of sections S_C of electrical wires (cables) in the HHIT circuits is essentially impossible technical way. In this regard, an approximate calculation of sections S_C of electrical wires and cables of HHIT for various ATPs of the pulsed current $i_p(t)$ flowing through them is an actual applied scientific and technical problem.

The goal of the paper is performing a calculation selection of sections S_C of electrical wires and cables in circuits of HHIT devices, characterized by the flow of pulsed current $i_p(t)$ with various ATPs.

1. Problem definition. We consider the widely used in electric circuits of HHIT uninsulated copper and aluminum wires, as well as insulated wires and cables with copper (aluminum) inner cores and outer shells, having PVC, R and PET insulation [1, 2]. It is assumed that in the round solid or split copper (aluminum) cores and shells of these wires and cables of HHIT electric circuits in their longitudinal direction pulsed currents $i_p(t)$ flow, ATPs of which correspond to nano-, micro- or millisecond time ranges with amplitudes I_{mp}, varying in a wide range from 0.1 kA to 1 MA. We believe that the wires and cables under investigation are placed in the surrounding air environment, the temperature of which is θ_0=20 °C. We use the assumption that in the first approximation the pulsed current $i_p(t)$ is almost uniformly distributed over the cross-section S_{Ci} of the core (i=1) and the shell (i=2) of the wire (cable). One of the rationales of this assumption is that, for example, for a current pulse of a short lightning discharge of the temporal shape τ_f/τ_p=10 μs/350 μs (τ_f, τ_p are, respectively, the front duration at the level (0.1-0.9) I_{mp} and the current pulse duration at the level of 0.5 I_{mp}) the penetration depth Δ_i of the azimuthal magnetic field of the specified artificial lightning current into the studied non-ferromagnetic materials of the wire (cable) is approximately 0.65 mm for copper and 0.82 mm for aluminum [4]. These numerical values of Δ_i

in practice can be commensurate with the real radii of the core and the wall thickness of the wire (cable) shell. For current pulses $i_p(t)$, related to the millisecond time range (as for SC currents in circuits of power facilities), the use of such an assumption in the calculation of the cross-sections S_{Ci} of wires (cables) becomes even more legitimate. Let us take advantage of the adiabatic nature of pulsed current $i_p(t)$ with a duration of no more than 1000 ms in the materials of the cores (shells) of the considered CCP of electrothermal processes, under which the influence of heat transfer from the surfaces of their current-carrying parts having the current temperature $\theta_{Ci} \geq \theta_0$ and thermal conductivity of their materials and insulation on Joule heating of the current-carrying parts of the cores (shells) of wires (cables) is neglected. We believe that the thermal resistivity of wires (cables) of electric circuits of HHIT when exposed to a pulsed current $i_p(t)$ is limited by their maximum permissible short-term heating temperature θ_{CiS}, depending on the degree of reduction of the mechanical strength of the core (shell) material and the thermal conditions of operation conditions of the CCP insulation in the mode of its short-term heating by a current pulse of nano-, micro- or millisecond duration, flowing through their current-carrying parts. As in [4], we assume that the value of temperature θ_{CiS} corresponds to the maximum permissible short-term temperature θ_{iS} of heating wires and cables by SC currents of industrial frequency (see Table 1) known from [3]. Then, in accordance with the data of Table 1, for uninsulated copper (aluminum) wires of circuits of HHIT, the value of θ_{CiS} will be approximately 250 °C (200 °C), for their insulated wires (cables) with copper and aluminum cores (shells) and PVC (R) insulation $\theta_{CiS} \approx 150$ °C, and for their CCP with the indicated conductors (shells) and PET insulation $\theta_{CiS} \approx 120$ °C. It is required by calculation in an approximate form to determine the boundary permissible cross-sections S_{Cil} of current-carrying parts for uninsulated copper (aluminum) wires, as well as for insulated wires and cables with copper (aluminum) cores (shells) and PVC (R), PET insulation, used in HHIT circuits and experiencing a direct axial pulsed current $i_p(t)$ of various amplitudes I_{mp} in the nano-, micro- and millisecond time ranges.

2. A generalized approach to the choice of sections S_{Cil} of electrical wires (cables) in the field of HHIT. For the boundary permissible cross-sections S_{Cil} of the current-carrying cores (shells) of the considered electric wires and cables with axial pulsed current $i_p(t)$ of arbitrary ATPs, the following approximate calculated dependence [5] follows from the equation of their heat balance in the adiabatic mode:

$$S_{Cil} = (J_{CiA})^{1/2} / C_l \, , \quad (2)$$

where $J_{CiA} = \int_0^{\tau_p} i_p^2(t)dt$ is the action integral of the pulsed current $i_p(t)$ with duration τ_p and given ATPs, $A^2 \cdot s$; $C_l = (J_{ClS} - J_{Cll})^{1/2}$, $A \cdot s^{1/2}/m^2$; J_{ClS}, J_{Cll} are, respectively, the current integrals for the current-carrying cores (shells) of the studied electric wires and cables of the HHIT power circuits, the maximum permissible short-term and long-term heating temperatures of the material of which correspond to θ_{lS} (see Table 1) and θ_{ll} (see Table 2) values, $A^2 \cdot s/m^4$.

To find the numerical values of the J_{ClS} and J_{Cll} current integrals included in (2), the following analytical expressions can be used [2, 5]:

$$J_{ClS} = \gamma_{0i} \beta_{0i}^{-1} \ln[c_{0i} \beta_{0i} (\theta_{lS} - \theta_0) + 1] \, ; \quad (3)$$

$$J_{Cll} = \gamma_{0i} \beta_{0i}^{-1} \ln[c_{0i} \beta_{0i} (\theta_{ll} - \theta_0) + 1] \, , \quad (4)$$

where γ_{0i}, c_{0i}, β_{0i} are, respectively, the specific electrical conductivity, the specific volume heat capacity and the thermal coefficient of specific electrical conductivity of the core (shell) material of the wire (cable) of the HHIT electrical circuit under study before they are subjected to a pulsed current $i_p(t)$ with arbitrary ATPs.

Table 4 presents numerical values of γ_{0i}, c_{0i} and β_{0i} at temperature θ_0=20 °C [2, 6].

Table 4
The main thermophysical characteristics of the material of the current-carrying cores (shells) of electric uninsulated wires and insulated wires as well as cables of power circuits of HHIT at θ_0=20 °C [2, 6]

Material of the core (shell) of the wire (cable)	Values γ_{0i}, $10^7 \cdot (\Omega \cdot m)^{-1}$	Values c_{0i}, $10^6 \cdot J/(m^3 \cdot {}^\circ C)$	Values β_{0i}, $10^{-9} \cdot m^3/J$
Copper	5.81	3.92	1.31
Aluminum	3.61	2.70	2.14

As for the calculation definition in (2) of the integral of action J_{CiA} of the pulsed current $i_p(t)$ with arbitrary ATPs, for the case of its change over time t according to the aperiodic law of the form

$$i_p(t) = k_{p1} I_{mp} [\exp(-\alpha_1 t) - \exp(-\alpha_2 t)] \, , \quad (5)$$

where $\alpha_1 \approx 0.76/\tau_p$, $\alpha_2 \approx 2.37/\tau_f$ are, respectively, the shape coefficients of the aperiodic current pulse with given ATPs flowing in the electric circuit of the HHIT; $k_{p1}=[(\alpha_1/\alpha_2)^m - (\alpha_1/\alpha_2)^n]^{-1}$ is the normalization factor; $m=\alpha_1/(\alpha_2-\alpha_1)$; $n=\alpha_2/(\alpha_2-\alpha_1)$; the calculated expression for the integral of action J_{CiA} of the current pulse $i_p(t)$ flowing in the HHIT circuit takes the following convenient analytical form [7]:

$$J_{CiA} \approx k_{p1}^2 I_{mp}^2 [0.658 \tau_p - 0.633 \tau_f] \, , \quad (6)$$

where τ_f, τ_p are respectively, the durations of the front and the half-fall of the current pulse $i_p(t)$.

In the case of a change in time t of the acting on the materials of the wire (cable) of the HHIT pulsed current $i_p(t)$ according to the law of a damped sinusoid of the form

$$i_p(t) = k_{p2} I_{mp1} \exp(-\delta t) \sin(\omega t) \, , \quad (7)$$

where $\delta=\Delta_p/T_p$ is the current attenuation coefficient; $\omega=2\pi/T_p$ is the circular frequency of the current oscillations; T_p is the period of the current oscillations; $\Delta_p=\ln(I_{mp1}/I_{mp3})$ is the logarithmic decrement of pulsed current oscillations with the first I_{mp1} and the third I_{mp3} amplitudes in the HHIT circuit; $k_{p2} = [\exp(-\Delta_p/2\pi \cdot \mathrm{arcctg}\Delta_p/2\pi) \cdot \sin(\mathrm{arcctg}\Delta_p/2\pi)]^{-1}$ is the normalization factor for damped sinusoidal current; the calculated expression for the integral of action J_{CiA} of the current pulse $i_p(t)$ flowing in the HHIT circuit takes the following simple analytical form [5]:

$$J_{CiA} \approx k_{p2}^2 I_{mp1}^2 [T_p (4\Delta_p)^{-1} - \Delta_p T_p (4\Delta_p^2 + 16\pi^2)^{-1}] \, . \quad (8)$$

From (4) it can be seen that at $\theta_{ll}=\theta_0=20$ °C (wires and cables are de-energized) the value of the current integral $J_{Cll}=0$, which will lead by (2) to a decrease in the cross-section S_{Cil}.

Knowing from normative documents or experimental data the numerical values of I_{mp}, τ_f, τ_p, Δ_p, T_p, taking into account the estimates of the values of the normalizing coefficients k_{p1} and k_{p2} by (2)-(8) for the specified temporal shapes of the pulsed current $i_p(t)$, we can be calculate in the approximate form (with an error of up to 5 %), the boundary permissible cross-sections S_{Cil} of the conductive wires (shells) of wires and cables used in the electric circuits of HHIT. Finding the values of the S_{Cil} sections, taking into account the accepted assumptions, the maximum permissible pulsed current densities of the pulsed current $i_p(t)$ of one or another shape in electrical wires (cables) of the HHIT circuits can be determined in the first approximation from the dependence like $\delta_{Cil}\approx I_{mp}/S_{Cil}$.

3. The choice of cross-sections S_{Cil} of electrical wires (cables) for nanosecond current pulses in the field of HHIT. First, we will focus on the selection of the S_{Cil} sections of the wires (cables) under consideration, along copper (aluminum) cores (shells) under the conditions $J_{Cll}=0$ or $J_{Cll}\neq 0$, the axial aperiodic current pulse of the time shape τ_f/τ_p=5 ns/200 ns flows [8]. Note that at one time this nanosecond current pulse $i_p(t)$ of both polarities was used when imitating in HHIT discharge circuits with the necessary air field-formation systems and, accordingly, in their working air volumes with powerful electromagnetic pulse (EMP) dimensions of the high-altitude nuclear explosion (HNE) [9, 10]. From (5) we find that for this calculation case, the form coefficients α_1 and α_2 of the current pulse $i_p(t)$ take the following numerical values: $\alpha_1\approx 3.8\cdot 10^6$ cs^{-1}; $\alpha_2\approx 4.7\cdot 10^8$ s^{-1}. Here, for this current pulse, the normalizing coefficient k_{p1} is approximately equal to $k_{p1}\approx 1.049$. Table 5 presents by (6) the numerical values of the action integral J_{CiA} for a series of values of the amplitude I_{mp} of the considered powerful nanosecond current pulse of the time shape 5 ns/200 ns used in testing military and civilian objects for resistibility to EMP of HNE [9, 10].

Table 5

The values of the integral of action J_{CiA} for nanosecond aperiodic current pulse of the shape 5 ns/200 ns

The value of the amplitude I_{mp} of the current pulse of the shape 5 ns/200 ns, kA	The value of the integral of action J_{CiA} of the current pulse 5 ns/200 ns, $A^2\cdot s$
1	0.141
10	14.13
30	$1.27\cdot 10^2$
50	$3.53\cdot 10^2$
70	$6.92\cdot 10^2$
100	$1.41\cdot 10^3$
200	$5.65\cdot 10^3$
500	$3.53\cdot 10^4$
1000	$1.41\cdot 10^5$

Table 6 shows the calculated by (2) the numerical values of the coefficient C_l for uninsulated wires with copper (aluminum) cores and insulated wires (cables) with copper (aluminum) cores (shells) with PVC, R and PET insulation for the cases of their preliminary current load ($J_{Cll}\neq 0$) or full de-energizing ($J_{Cll}=0$).

Comparison of data of Table 3, 6 indicates that the numerical values of the coefficients C_k и C_l for the considered wires and cables in the case when $J_{Cll}\neq 0$ and the value of this integral of the current is determined from (4) differ from 3 to 8 %. In the case when $J_{Cll}=0$ (the case traditional for HHIT), these differences increase and range from 9 to 26 %. In Table 7 based on (2) and calculated data of Table 5, 6 at $J_{Cll}=0$ (wires and cables in the HHIT power circuit are without prior current load) the results of the selection of the boundary permissible cross-sections S_{Cil} for the wires (cables) in the HHIT circuits under study, along which a powerful nanosecond current pulse of the time shape of 5 ns/200 ns with amplitude I_{mp} equal to 10, 50, 100, and 500 kA are presented.

Table 6

The values of the coefficient C_l values for uninsulated wires, insulated wires (cables) with copper (aluminum) cores (shells) in HHIT circuits with nano-, micro- and millisecond current pulses

Insulation type in the wire (cable) of the HHIT power circuit	Material of the core (shell) of the wire (cable)	Values of C_l, 10^8 $A\cdot s^{1/2}/m^2$	
		$J_{Cll}=0$	$J_{Cll}\neq 0$
Without insulation	Copper	1.860	1.563
	Aluminum	1.096	0.880
PVC, R	Copper	1.506	1.160
	Aluminum	0.972	0.745
PET	Copper	1.355	0.957
	Aluminum	0.877	0.616

Table 7

The values of the boundary permissible cross-sections S_{Cil} for wires (cables) with copper (aluminum) cores (shells) in HHIC circuits with a nanosecond current pulse of the shape 5 ns/200 ns, the amplitude of which varies in a wide range from 10 kA to 500 kA

Insulation type in the wire (cable) of the HHIT power circuit	Material of the core (shell) of the wire (cable)	Values of the cross-section S_{Cil}, mm^2			
		Amplitude I_{mp} of the current pulse 5 ns/200 ns, kA			
		10	50	100	500
Without insulation	Copper	0.020	0.101	0.202	1.010
	Aluminum	0.034	0.171	0.342	1.714
PVC, R	Copper	0.025	0.125	0.250	1.250
	Aluminum	0.039	0.193	0.386	1.933
PET	Copper	0.028	0.138	0.278	1.386
	Aluminum	0.043	0.214	0.428	2.142

From the data of Table 7 it follows that the estimated maximum allowable density $\delta_{Cil}\approx I_{mp}/S_{Cil}$ of a nanosecond current pulse of the shape 5 ns/200 ns for uninsulated wires with copper and aluminum cores is approximately 495 kA/mm^2 and 293 kA/mm^2, and for cables with copper (aluminum) cores (shells) and PET insulation 361 (233) кA/mm^2.

4. The choice of cross-sections S_{Cil} of electrical wires (cables) for microsecond current pulses in the field of HHIT. Fig. 1 shows a typical oscillogram of a pulsed A- component of an artificial lightning current reproduced in the discharge circuit of a powerful lightning current generator (LCG) for testing aeronautical and rocket-space technology objects for lightning resistibility in accordance with the requirements of US SAE ARP 5412: 2013 [11] and SAE ARP 5416: 2013 [12]. It can be seen that the indicated component of the pulsed current $i_p(t)$ of the lightning simulated under laboratory conditions in time t varies according to the damped sinusoid law. We make the choice of cross-sections S_{Cil} of wires and cables for the discharge circuit of the LCG applicable to a given current pulse $i_p(t)$.

From the experimental data presented in Fig. 1, we find that for the bipolar oscillatory current pulse used in the calculations of the cross-sections S_{Cil}, $\Delta_p=\ln(I_{mp1}/I_{mp3})=2.505$. Then by (7) for this current the coefficient $k_{p2}=1.731$. Table 8 shows the numerical values of the integral of action J_{CiA} calculated by (8) for a given microsecond current pulse [13], changing according to the law of a damped sinusoid.

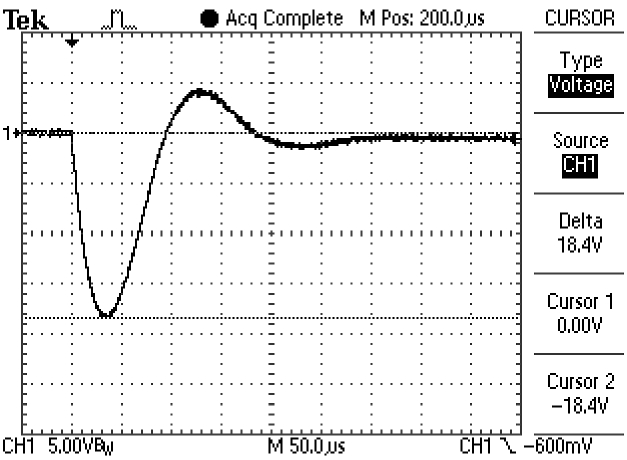

Fig. 1. A typical oscillogram of a microsecond pulsed A- component of an artificial lightning current flowing in a discharge circuit of a high-voltage LCG ($I_{mp1}\approx -207$ kA; $I_{mp3}\approx -16.9$ kA; $T_p\approx 185$ μs; vertical scale 56.3 kA/division; horizontal scale 50 μs/division) [13]

Table 8

The values of the integral of action J_{CiA} for current pulse $i_p(t)$, changing in the microsecond time range according to the law of damped sinusoid of the form (7)

The value of the first amplitude I_{mp1} of the damped sinusoidal current pulse, kA	The value of the integral of action J_{CiA} of the current pulse of the form (7), $A^2\cdot s$
10	$4.77\cdot10^3$
30	$4.29\cdot10^4$
50	$1.19\cdot10^5$
70	$2.34\cdot10^5$
100	$4.77\cdot10^5$
207	$2.05\cdot10^6$
300	$4.29\cdot10^6$
500	$11.92\cdot10^6$
700	$23.4\cdot10^6$
1000	$47.7\cdot10^6$

Using the calculated data for the coefficient C_l, given in Table 6, (2) and summarized in Table 8 the results of determining the integral of action J_{CiA}, we find the boundary permissible cross-sections S_{Cil} for the wires (cables) under study in HHIT circuits, in which a microsecond current pulse of the form (7) flows with ATPs corresponding to the data typical of Fig. 1. In Table 9 at $J_{Cil}=0$, the results of such a determination of the boundary permissible cross-sections of S_{Cil} for the wires and cables under consideration used in the discharge circuits of HHIT are presented.

From the presented in Table 9 the calculated data, it follows that the estimated maximum allowable density $\delta_{Cil}\approx I_{mp1}/S_{Cil}$ of the microsecond pulsed current $i_p(t)$ with the ATP corresponding to the data in Fig. 1, for uninsulated wires with copper and aluminum cores is approximately 26 kA/mm^2 and 15 kA/mm^2, and for cables with copper (aluminum) cores (shells) and PET insulation 19 (12) кA/mm^2.

Table 9

The values of the boundary permissible S_{Cil} cross-sections for wires (cables) with copper (aluminum) cores (shells) in HHIT circuits with a microsecond current pulse of the form (7), the first amplitude I_{mp1} of which varies in a wide range from 30 kA to 207 kA

Insulation type in the wire (cable) of the HHIT power circuit	Material of the core (shell) of the wire (cable)	The values of the cross-section S_{Cil}, mm^2 — The first amplitude I_{mp1} of the current pulse of the form (7), kA			
		30	50	100	207
Without insulation	Copper	1.113	1.854	3.713	7.698
	Aluminum	1.889	3.147	6.301	13.06
PVC, R	Copper	1.375	2.290	4.586	9.507
	Aluminum	2.131	3.549	7.105	14.73
PET	Copper	1.528	2.546	5.097	10.57
	Aluminum	2.362	3.933	7.875	16.32

5. The choice of cross-sections S_{Cil} of electrical wires (cables) for millisecond current pulses in the field of HHIT. Fig. 2 shows a typical oscillogram of a long-term C-component of the artificial lightning current generated according to the requirements of [11, 12] in the discharge circuit of the LCG for the purpose of the experimental determination of lightning resistibility of aerospace equipment objects in flight conditions in air. It can be seen that the aperiodic current pulse $i_p(t)$ of the negative polarity of this component in the composition of the total artificial lightning discharge current varies in a millisecond time range. Its amplitude I_{mp} which corresponds to the time $t_{mp}\approx 11$ ms, is about 835 A. At the same time, the duration of the front of the test current pulse is approximately $\tau_f\approx 7$ ms, and its duration at the level of 0.5 I_{mp} is $\tau_p\approx 160$ ms. According to the requirements of [11, 12], the total duration of the flow of the specified component of the current pulse of artificial lightning in the conductors of the discharge circuit of a powerful high-voltage LCG reaches about 1000 ms. On the basis of the proposed electrical engineering approach, we perform the choice of cross-sections S_{Cil} of wires (cables) for a discharge circuit of the LCG involved in generating the specified current pulse $i_p(t)$.

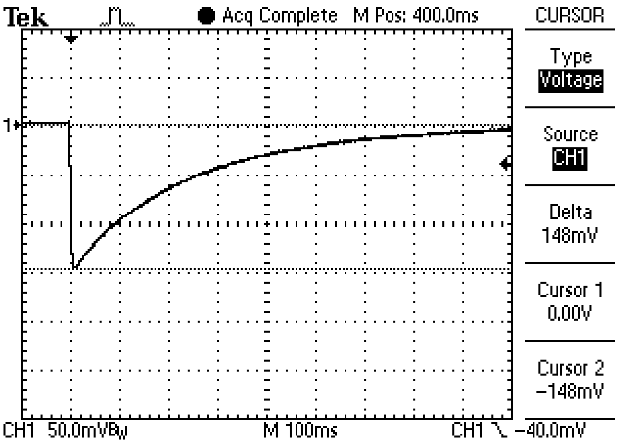

Fig. 2. A typical oscillogram of a millisecond long-term *C*- component of an artificial lightning current flowing in a discharge circuit of a powerful high-voltage LCG (I_{mp}≈ −835 A; τ_f≈7 ms; τ_p≈160 ms; vertical scale 282 A/division; horizontal scale 100 ms/division) [13]

From (5) at τ_f ≈7 ms and τ_p ≈160 ms, we find that α_1≈4.75 s^{-1} and α_2≈338·10^2 s^{-1}. Then the normalizing coefficient k_{p1} takes a numerical value of approximately k_{p1}≈1.077. Using (5) and varying the value of the current amplitude I_{mp}, it is possible to calculate the numerical indices of the integral of action J_{CiA} for the considered millisecond current pulse $i_p(t)$. Table 10 shows the numerical values of J_{CiA} for a number of amplitudes of I_{mp} of a given pulse current $i_p(t)$.

Table 10

Values of the integral of action J_{CiA} for unipolar current pulse $i_p(t)$, varying in millisecond time range by aperiodic low

The values of the amplitude I_{mp} of the unipolar millisecond aperiodic current pulse 7 ms/160 ms, A	The values of the integral of action J_{CiA} of the millisecond current pulse 7 ms/160 ms, A^2·s
100	1.17·10^3
200	4.68·10^3
300	1.05·10^4
500	2.92·10^4
700	5.73·10^4
835	8.15·10^4
1000	1.17·10^5

Further, assuming that J_{CIl}=0 (the wires and cables in the discharge circuit of HHIT are previously de-energized), we use the results of an approximate calculation of the coefficient C_l, summarized in Table 6. Taking into account these numerical values of C_l and the data of Table 10, according to (2), in the accepted approximation, it is possible to find the boundary permissible cross-sections S_{Cil} for uninsulated and insulated wires and cables with copper (aluminum) cores (shells) with PVC, R and PET insulation, which are subjected to an axial millisecond aperiodic current pulse $i_p(t)$, which ATPs correspond to the data of Fig. 2. Table 11 shows the numerical values of the boundary permissible cross-sections S_{Cil} for the indicated wires (cables) with a millisecond aperiodic current pulse $i_p(t)$, found in the manner described above. Based on the ratio of the form δ_{Cil}≈I_{mp}/S_{Cil}, the data of Table 11 allow us to estimate the numerical values of the maximum permissible densities δ_{Cil} in wires (cables), through which a millisecond aperiodic current pulse $i_p(t)$ with amplitude I_{mp}, varying in the range (100-1000) A, flows in the longitudinal direction.

Table 11

The values of boundary allowable cross-sections S_{Cil} for uninsulated wires and insulated wires (cables) with copper (aluminum) cores (shells) in HHIT circuits with a millisecond aperiodic current pulse of 7 ms/160 ms, amplitude I_{mp} of which varies in the range from 100 A to 1000 A

Insulation type in the wire (cable) of the HHIT power circuit	Material of the core (shell) of the wire (cable)	The value of the cross-section S_{Cil},mm^2			
		Amplitude I_{mp} of the current pulse 7 ms/160 ms, A			
		100	500	835	1000
Without insulation	Copper	0.184	0.919	1.535	1.839
	Aluminum	0.312	1.559	2.605	3.121
PVC, R	Copper	0.227	1.135	1.896	2.271
	Aluminum	0.352	1.758	2.937	3.519
PET	Copper	0.252	1.261	2.107	2.524
	Aluminum	0.390	1.948	3.255	3.900

From the data of Table 11 it follows that the estimated maximum permissible density δ_{Cil} of the millisecond aperiodic current pulse $i_p(t)$ with the ATPs corresponding to the data in Fig. 2, for uninsulated wires with copper and aluminum conductors is approximately 543 A/mm^2 and 320 A/mm^2, and for cables with copper (aluminum) cores (shells) and PET insulation 396 (256) A/mm^2.

The results of experimental studies in discharge circuits of HHIT with pulsed currents $i_p(t)$ of micro- and millisecond duration of electrothermal resistibility of prototypes of uninsulated wires, insulated wires and cables with copper cores (shells) with PVC and PET insulation, presented by the author in [5, 13] , confirm the validity of the basic calculation data on the choice of the cross-sections S_{Cil} presented in Table 9, 11.

Conclusions.

1. The presented generalized electrical engineering approach allows, according to the condition of thermal resistibility of CCP, to carry out an approximate calculation choice of boundary permissible cross-sections S_{Cil} of uninsulated wires, insulated wires and cables with copper (aluminum) cores (shells) with PVC, R and PET insulation, the current-carrying parts of which are affected axial current pulse $i_p(t)$, ATPs of which with different amplitudes I_{mp} can vary in nano-, micro- and millisecond time ranges.
2. Using the examples of the change in time *t* of the pulsed current $i_p(t)$ flowing through the specified wires (cables) according to aperiodic law or the damped sinusoid law, the possibilities of the proposed electrical engineering approach to the specific choice of the boundary permissible cross-sections S_{Cil} for the considered types of uninsulated wires, insulated wires and cables widely used in the discharge circuits of HHIT are demonstrated.
3. It is shown that, in the first approximation, the maximum permissible densities δ_{Cil}≈I_{mp}/S_{Cil} of the

considered temporal shapes of pulsed current $_p(t)$ in copper (aluminum) cores of non-insulated wires for the nanosecond range are numerically about 495 (293) kA/mm^2, for the microsecond range 26 (15) kA/mm^2 and for the millisecond range 543 (320) A/mm^2. For insulated wires (cables) with copper (aluminum) cores (shells) and PET insulation, the numerical values of the maximum permissible densities δ_{Cil} of the considered pulsed currents $i_p(t)$ for the nanosecond range are about 361 (233) A/mm^2, for the microsecond range 19 (12) kA/mm^2 and for the millisecond range 396 (256) A/mm^2.

REFERENCES

1. Mesiats G.A. *Impul'snaia energetika i elektronika* [Pulsed power and electronics]. Moscow, Nauka Publ., 2004. 704 p. (Rus).

2. Baranov M.I. *Izbrannye voprosy elektrofiziki. Tom 3: Teorija i praktika elektrofizicheskih zadach* [Selected topics of Electrophysics. Vol. 3: Theory and practice of electrophysics tasks]. Kharkiv, Tochka Publ., 2014. 400 p. (Rus).

3. Orlov I.N. *Elektrotehnicheskij spravochnik. Proizvodstvo i raspredelenie elektricheskoj energii. Tom 3, Kn. 1* [Electrical engineering handbook. Production and distribution of electric energy. Vol. 3, Book 1. Ed. I.N. Orlov]. Moscow, Energoatomizdat Publ., 1988. 880 p. (Rus).

4. Baranov M.I., Rudakov S.V. Electrothermal action of the pulse of the current of a short artificial-lightning stroke on test specimens of wires and cables of electric power objects. *Journal of Engineering Physics and Thermophysics*, 2018, vol.91, no.2, pp. 544-555. **doi: 10.1007/s10891-018-1775-2.**

5. Baranov M.I., Kravchenko V.I. Electrothermal resistance wire and cable to the aircraft to the striking action pulsed current lightning. *Elektrichestvo*, 2013, no.10, pp. 7-15. (Rus).

6. Knopfel' G. *Sverkhsil'nye impul'snye magnitnye polia* [Ultra strong pulsed magnetic fields]. Moscow, Mir Publ., 1972. 391 p. (Rus).

7. Baranov M.I., Kniaziev V.V., Rudakov S.V. Calculation and experimental estimation of results of electro-thermal action of rationed by the international standard IEC 62305-1-2010 impulse current of short blow of artificial lightning on the thin-walled coverage from stainless steel. *Electrical engineering & electromechanics*, 2017, no.1, pp. 31-38. (Rus). **doi: 10.20998/2074-272X.2017.1.06.**

8. Baranov M.I. *Izbrannye voprosy elektrofiziki: Monografija v 2-h tomah. Tom 2, Kn. 1: Teorija elektrofizicheskih effektov i zadach* [Selected topics of Electrophysics: Monograph in 2 vols. Vol. 2, book. 1: Theory of electrophysics effects and tasks]. Kharkov, NTU «KhPI» Publ., 2009. 384 p. (Rus).

9. Ricketts L.U., Bridges J.E., Mayletta J. *Elektromahnitnij impul's i metody zashchity* [Electromagnetic pulse and methods of protection]. Moscow, Atomizdat Publ., 1979. 328 p. (Rus).

10. Myrova L.O., Chepizhenko A.Z. *Obespechenie stojkosti apparatury svyazi k ionyzyruyushchim i elektromahnytnim izlucheniyam* [Ensuring stability of communications equipment to the ionizing and electromagnetic of radiations]. Moscow, Radio and Communications Publ., 1988. 296 p. (Rus).

11. SAE ARP 5412: 2013. Aircraft Lightning Environment and Ralated Test Waveforms. SAE Aerospace. USA, 2013. − pp. 1-56.

12. SAE ARP 5416: 2013. Aircraft Lightning Test Methods. SAE Aerospace. USA, 2013. − pp. 1-145.

13. Baranov M.I., Kravchenko V.I., Nosenko M.A. Experimental research into electrothermal stability of aircraft metallic elements against direct action of artificial lightning current. Part 2: stability of copper wires and cables. *Electrical Engineering & Electromechanics*, 2011, no.2, pp. 46-55. (Rus). **doi: 10.20998/2074-272X.2011.2.11.**

Received 07.08.2018

M.I. Baranov, Doctor of Technical Science, Professor,
Scientific-&-Research Planning-&-Design Institute «Molniya»,
National Technical University «Kharkiv Polytechnic Institute»,
47, Shevchenko Str., Kharkiv, 61013, Ukraine,
phone +380 57 7076841, e-mail: baranovmi@kpi.kharkov.ua

How to cite this article:
Baranov M.I. A choice of sections of electric wires and cables in circuits of devices of high-voltage high-current impulse technique. *Electrical engineering & electromechanics*, 2018, no.6, pp. 56-62. **doi: 10.20998/2074-272X.2018.6.08.**