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CALCULATION AND EXPERIMENTAL DETERMINATION OF CRITICAL SECTIONS OF ELECTRIC WIRES AND CABLES IN THE CIRCUITS OF DEVICES OF HIGH-VOLTAGE HIGH-CURRENT PULSE TECHNIQUE

***Purpose.** Implementation of calculation and experimental determinations of critical sections and current densities in electric wires and cables of circuits of devices of high-voltage high-current impulse technique (HHIT), characterized flowing of pulse current $i_p(t)$ with different amplitude-temporal parameters (ATPs). **Methodology.** Electrophysics bases of technique of high-voltage and large pulse currents, theoretical bases of electrical engineering, bases of electrical power energy, technique of high electric and magnetic fields, and also measuring technique. **Results.** The results of the developed electrical engineering approach are resulted in calculation choice on the condition of electric explosion (EE) in atmospheric air of current-carrying parts of cable-conductor products of critical sections of S_{CCi} of the uninsulated wires, and also the insulated wires and cables with polyvinyl chloride (PVC), rubber (R) and polyethylene (PET) insulation with copper (aluminum) cores (shells) on which in the circuits of HHIT the pulse axial-flow current $i_p(t)$ flows with arbitrary ATPs. On the basis of this approach the results of choice of critical sections S_{CCi} are shown for the indicated electric wires (cables) of power circuits of HHIT with pulse current, ATPs of which with amplitudes of I_{mp}=(0.1-1000) kA change on a aperiodic law or law of attenuation of sine wave in nano-, micro- and millisecond temporal ranges. The results of calculation estimation of critical amplitudes of current densities δ_{CCi} of -pulses of current $i_p(t)$ of the examined temporal shapes are presented in the indicated electric wires and cables of circuits of HHIT. By a calculation way it is set that critical amplitudes of current densities δ_{CCi} of pulse current $i_p(t)$ for its indicated temporal shapes in the copper (aluminum) cores of the uninsulated wires and insulated wires and cables with copper (aluminum) cores (shells), PVC, R and PET insulation for nanosecond range are numerically 1176 (878) kA/mm^2, for the microsecond range 64 (48) kA/mm^2 and for the millisecond range 1.29 (0.97) kA/mm^2. By the powerful high-voltage generator of current of artificial lightning experimental verification of applicability of the offered calculation relations is executed for the choice of critical sections S_{CCi} and amplitudes of current densities δ_{CCi} in wires (cables) at their EE. **Originality.** First by a calculation way for the specific temporal shapes of pulse currents $i_p(t)$ in the discharge circuits of HHIT, changing in nano-, micro- and millisecond temporal ranges with the wide change of the amplitudes I_{mp} on an aperiodic law or law of attenuation of sine wave, the numeral values of critical sections S_{CCi} and amplitudes of current densities δ_{CCi} are obtained for the uninsulated wires, insulated wires and cables with copper (aluminum) cores (shells), PVC, R and PET insulation. **Practical value.** Application of the obtained results is in practice of tests of objects of electrical power energy, aviation and space-rocket technique on resistibility to action of pulse currents $i_p(t)$ with different ATPs of natural (currents of the imitated lightning) and artificial (discharge currents of HHIT) origin will be instrumental in the increase of electro-thermal resistibility of the uninsulated wires, and also the insulated wires and cables with PVC, R and PET insulation of HHIT widely applied in power circuits.* References 15, tables 7, figures 6.

Key words: **high-voltage high-current pulse technique, electric wires and cables, calculation choice of critical sections of wires and cables in circuits of pulse technique, experiment.**

Надані результати розробленого електротехнічного підходу до розрахункового вибору за умовою електричного вибуху (ЕВ) струмопровідних частин кабельно-провідникової продукції критичних перерізів S_{CCi} неізольованих дротів, а також ізольованих дротів і кабелів з полівінілхлоридною (ПВХ), гумовою (Г) і поліетиленовою (ПЕТ) ізоляцією з мідними (алюмінієвими) жилами (оболонками), по яких в колах високовольтної сильнострумної імпульсної техніки (ВСІТ) протікає імпульсний аксіальний струм $i_p(t)$ з довільними амплітудно-часовими параметрами (АЧП). На підставі цього підходу продемонстровані результати вибору критичних перерізів S_{CCi} для вказаних електричних дротів (кабелів) силових кіл ВСІТ з імпульсним струмом, АЧП якого з амплітудами I_{mp}=(0,1-1000) кА змінюються по аперіодичному закону або закону затухаючої синусоїди в нано-, мікро- і мілісекундному часових діапазонах. Представлені результати розрахункової оцінки критичних амплітуд щільностей δ_{CCi} імпульсів струму $i_p(t)$ цих часових форм у вказаних електричних дротах і кабелях кіл ВСІТ. Виконана експериментальна перевірка працездатності запропонованих розрахункових співвідношень для вибору перерізів S_{CCi} і щільностей δ_{CCi} струму в дротах (кабелях) при їх ЕВ. Отримані результати сприятимуть забезпеченню електротермічної стійкості електричних неізольованих дротів, а також ізольованих дротів і кабелів зі ПВХ, Г і ПЕТ ізоляцією, які широко застосовуються у силових колах ВСІТ. Бібл. 15, табл. 7, рис. 6.

Ключові слова: **високовольтна сильнострумна імпульсна техніка, електричні дроти і кабелі, розрахунковий вибір критичних перерізів дротів і кабелів в колах імпульсної техніки, експеримент.**

Приведены результаты разработанного электротехнического подхода к расчетному выбору по условию электрического взрыва (ЭВ) токонесущих частей кабельно-проводниковой продукции критических сечений S_{CCi} 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 импульсный аксиальный ток $i_p(t)$ с произвольными амплитудно-временными параметрами (АВП). На основании этого подхода продемонстрированы результаты выбора критических сечений S_{CCi} 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 критических амплитуд плотностей δ_{CCi} импульсов тока $i_p(t)$ рассматриваемых временных форм в указанных электрических проводах и кабелях цепей ВСИТ. Выполнена экспериментальная проверка работоспособности предлагаемых расчетных соотношений для выбора сечений S_{CCi} и плотностей δ_{CCi} тока в

проводах (кабелях) при их ЭВ. Полученные данные будут способствовать обеспечению электротермической стойкости электрических неизолированных проводов, а также проводов и кабелей с ПВХ, Р и ПЭТ изоляцией, широко применяемых в силовых цепях ВСИТ. Библ. 15, табл. 7, рис. 6.

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

Introduction. In practice, when designing, building and operating high-power electrical installations in the field of high-voltage high-current impulse technology (HHIT), specialists need to be able to determine the critical cross sections S_{CCi} of electrical wires and cables used in their circuits and containing metal wires (i=1) and shells (i=2). The critical sections S_{CCi} of wires (cables) are their cross sections that are not able to withstand the current loads acting on them with one or another amplitude-temporal parameters (ATPs), leading to the appearance of the electric explosion (EE) phenomenon of metal cores (shells) of specified wires and cables and, accordingly, to their failure [1, 2]. Note that the EE phenomenon of current-carrying parts can also be observed in the field of industrial electric power engineering, when wires and cables not reasonably used in power grids are not designed for the flow of high short-circuit (SC) currents through them, reaching at durations of (60-100) ms amplitude values up to (10-100) kA [3]. One of the peculiarities of electrical installations of HHIT, in contrast to electrical installations of industrial electric power engineering, is that pulse currents of various ATPs related to the nano-, micro- and millisecond time ranges can flow through the current-carrying parts of their electrical circuits. In this case, the amplitude values I_{mp} of such pulse currents can reach values that usually vary in the range (0.1–1000) kA [1, 2].

In [4], the author presented a generalized electrical engineering approach that allows for the condition of thermal durability of cable-conductor products (CCP) to carry out an approximate computational choice of the maximum allowable cross sections S_{Cli} of uninsulated wires, insulated wires and cables with copper (aluminum) conductors (shells) with polyvinyl chloride (PVC), rubber (R) and polyethylene (PET) insulation, the current-carrying parts of which are influenced in the adiabatic mode by the direct effect of the axial pulse current $i_p(t)$, the ATPs of which with amplitudes of 0.1 kA$\leq I_{mp}\leq$1000 kA can vary in nano-, micro- and millisecond time ranges. In this regard, the issues of determining the numerical values of the critical cross sections S_{CCi} of electrical wires and cables in relation to the power circuits of HHIT remain relevant in the world and are subject to their decision.

The goal of the paper is to perform the calculation and experimental determination of critical cross sections S_{CCi} and current densities δ_{CCi} in wires and cables of HHIT circuits characterized by the flow of pulse axial currents $i_p(t)$ along the current-carrying parts of their CCP with different ATPs.

1. Problem definition. Consider the widely used uninsulated copper and aluminum wires in HHIT power circuits, as well as insulated wires and cables with copper (aluminum) inner conductors and outer shells (reverse conductors) with specific electrical conductivity γ_{0i} of their nonmagnetic material, which usually have PVC, R and PET insulation [1-3]. It is assumed that in the round solid or split copper (aluminum) conductors (shells) of the above wires and cables of the HHIT electrical circuits pulse currents $i_p(t)$ flow in their longitudinal direction, the ATPs of which correspond to nano-, micro- or millisecond time ranges with amplitudes I_{mp} varying in the range from 100 A to 1000 kA. We assume that the wires and cables under consideration are placed in the surrounding air environment, the temperature of which corresponds to room temperature and equal to θ_0 = 20 °C [2]. We suppose that the preliminary current load of the current-carrying parts of the CCP of power circuits of HHIT is absent. Therefore, the initial temperature θ_{Ci} (before the affect of the pulse current $i_p(t)$ on the CCP) of the core (shell) material of the wire (cable) will be equal to the ambient air temperature θ_0. We use the assumption that the pulse axial current $i_p(t)$ is almost uniformly distributed over the cross section S_{Ci} of the core and shell (screen) of the wire (cable). At the same time, we remember that the penetration depth $\Delta_i\approx[6t_m/(\pi\mu_0\gamma_{0i})]^{1/2}$ in the quasi-stationary mode, where $\mu_0=4\pi\cdot10^{-7}$ H/m is the magnetic constant [2], of the azimuthal magnetic field pulse with time t_m corresponding to its amplitude, for example, for an aperiodic microsecond current pulse of artificial lightning of the temporal shape τ_f/τ_p=10 μs/350 μs ($t_m\approx1.6\tau_f\approx$16 μs) [5], where τ_f, τ_p are the front duration and the duration of the current pulse at the level of its half-decay, in the studied non-ferromagnetic materials of the core (shell) of the wire (cable) is for copper approximately 0.65 mm, but for aluminum is 0.82 mm [4]. These numerical values Δ_i are often commensurate with the actual radii of the cores and the thicknesses of the shells of the wires (cables) under consideration, in which the EE phenomenon of the current-carrying parts of the CCP may be observed. For millisecond axial current pulses $i_p(t)$, the accepted assumption about the uniform nature of its radial distribution in the studied conductors (shells) of wires and cables becomes even more legitimate. Thus, for example, for an aperiodic millisecond pulse of a long-term C- component of artificial lightning current of the temporal shape τ_f/τ_p= = 7 ms/160 ms ($t_m\approx$11 ms), the considered penetration depth Δ_i for copper is about 17 mm, and for aluminum is 22 mm. We use the condition of adiabatic nature of the electrothermal processes taking place at durations of pulsed current $i_p(t)$ of no more than 1000 ms in the materials of the cores (shells) of the CCP under study, at which the influence of heat transfer from the surfaces of their current-carrying parts having the current temperature $\theta_{Ci}\geq\theta_0$ as well as the thermal conductivity of layers of their conductive materials of the core (shell) and insulation on Joule heating of the current-carrying parts of the CCP are neglected.

It is required by calculation in an approximate form to determine the critical sections S_{CCi} 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, used in HHIT circuits and influenced by direct effect of axial pulse current $i_p(t)$ of various amplitudes I_{mp}, varying in nano-, micro- and millisecond time ranges. In addition, it is necessary to experimentally verify the operability of the obtained relations for the approximate calculation of the critical sections S_{CCi} of wires (cables) and critical densities δ_{CCi} of the pulse current $i_p(t)$ in them on the operating electrical installations of HHIT.

2. Electrical engineering approach to the calculation selection of the critical sections S_{CCi} and current densities δ_{CCi} in electrical wires and cables of HHIT circuits. For critical cross sections S_{CCi} of conductive cores (shells) of the considered non- and insulated with PVC, R and PET insulation electrical wires and cables in HHIT circuits with pulse axial current $i_p(t)$ of arbitrary ATPs from the equation of their heat balance at the adiabatic Joule heating of current-carrying parts of the CCP the following calculated relation follows [1]:

$$S_{CCi} = (J_{CiA})^{1/2} / D_{Cik}, \qquad (1)$$

where $J_{CiA} = \int_0^{\tau_p} i_p^2(t)dt$ – the integral of the action of the pulse current $i_p(t)$ with the duration of its flow τ_p in the CCP and given ATPs, $A^2 \cdot s$; $D_{Cik} = (J_{Cik})^{1/2}$, $A \cdot s^{1/2}/m^2$; J_{Cik} is the critical value of the current integral for the material of the current-carrying cores (shells) of the studied electric wires and cables of the HHIT circuits, $A^2 \cdot s/m^4$.

In Table 1 at θ_0=20 °C known numerical values are given for such basic characteristics of copper and aluminum cores (shells) of the studied wires (cables) of the HHIT power circuits as γ_{0i} and J_{Cik}.

Table 1
Thermophysical characteristics of the material of the considered cores (shells) of electrical wires and cables of power circuits of HHIT before exposure to them of pulse axial current $i_p(t)$ (at θ_0=20 °C) [2]

Material of the core (shell) of the wire (cable)	Numerical value of the characteristic	
	γ_{0i}, 10^7 $(\Omega \cdot m)^{-1}$	J_{Cik}, 10^{17} $A^2 \cdot s \cdot m^{-4}$
Copper	5.81	1.95
Aluminum	3.61	1.09

As for the calculation determination in (1) of the integral of action J_{CiA} of the pulse axial current $i_p(t)$ with arbitrary ATPs, for the case of its change over time t according to the aperiodic law of the form [1]

$$i_p(t) = k_{p1} I_{mp} \left[\exp(-\alpha_1 t) - \exp(-\alpha_2 t)\right], \qquad (2)$$

where $\alpha_1 \approx 0.76/\tau_p$, $\alpha_2 \approx 2.37/\tau_f$ are the shape coefficients of the aperiodic current pulse with given ATPs, flowing in 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 calculation expression for the integral of action J_{CiA} of the current pulse $i_p(t)$ flowing in the HHIT power circuit takes the following approximate analytical form [4, 6]:

$$J_{CiA} \approx k_{p1}^2 I_{mp}^2 \left[0.658\tau_p - 0.633\tau_f\right]. \qquad (3)$$

In case of a change in time t of the current pulse $i_p(t)$, acting on the materials of the wire (cable) of the HHIT, according to the law of a damped sinusoid of the form [1]

$$i_p(t) = k_{p2} I_{mp1} \exp(-\delta t) \sin(\omega t), \qquad (4)$$

where $\delta=\Delta_p/T_p$ is the current attenuation coefficient; $\omega=2\pi/T_p$ is the current frequency; T_p is the current oscillation period; $\Delta_p=\ln(I_{mp1}/I_{mp3})$ is the logarithmic decrement of pulse current oscillations with the first I_{mp1} and the third I_{mp3} amplitudes in the HHIT circuit; $k_{p2}=[\exp(-\Delta_p/2\pi \cdot \mathrm{arcctg}\Delta_p/2\pi)\sin(\mathrm{arcctg}\Delta_p/2\pi)]^{-1}$ is the normalizing coefficient for the damped sinusoidal current, then the approximate calculation expression for the integral of action J_{CiA} of the pulse axial current $i_p(t)$ flowing in the HHIT power circuit takes the following simplified analytical form [4]:

$$J_{CiA} \approx k_{p2}^2 I_{mp1}^2 [T_p (4\Delta_p)^{-1} - \Delta_p T_p (4\Delta_p^2 + 16\pi^2)^{-1}]. \qquad (5)$$

Knowing from normative documents or experimental data the numerical values of the quantities I_{mp}, τ_f, τ_p, Δ_p, T_p and taking into account the estimates of the values of the normalizing coefficients k_{p1} and k_{p2} by (2)-(4) for the two temporal shapes, the changes in the pulse current $i_p(t)$, we can in an approximate form (with an error of no more than 10%) calculate the critical cross sections S_{CCi} of current-carrying cores (shells) of wires and cables used in electrical power circuits of HHIT. Having found the numerical values of the cross sections S_{CCi}, taking into account the accepted assumptions, the critical amplitudes of the densities δ_{CCi} of the pulse current $i_p(t)$ of a given temporal shape in electrical wires and cables of HHIT circuits can be determined as a first approximation from the relation $\delta_{CCi} \approx I_{mp1}/S_{CCi}$.

3. Calculation determination of critical cross-sections S_{CCi} and current densities δ_{CCi} in electrical wires (cables) for nanosecond current pulses in HHIT circuits. Let us consider the case when an aperiodic current pulse of temporal shape τ_f/τ_p=5 ns/200 ns flows through copper (aluminum) cores (shells) of the HHIT, which was used at the time to simulate an electromagnetic pulse (EMP) of a high-altitude nuclear explosion and test of various objects of military and civilian use for resistibility to the damaging effects of the indicated EMP [4, 7, 8]. From (2), we find that for this calculation case, the shape coefficients α_1 and α_2 of the used current pulse $i_p(t)$ take the following numerical values: $\alpha_1 \approx 3.8 \cdot 10^6$ s^{-1}; $\alpha_2 \approx 4.7 \cdot 10^8$ s^{-1}. In this case, the normalizing coefficient k_{p1} is approximately equal to $k_{p1} \approx 1.049$. In Table 2, taking into account (3) for a specific set of values of the current amplitude I_{mp}, the numerical values of the integral of action J_{CiA} are given for the aperiodic nanosecond current pulse of the temporal shape τ_f/τ_p=5 ns/200 ns flowing through the current-carrying copper and aluminum parts of the studied wires and cables [4, 9].

Knowing the numerical values of the integral of action of the current J_{CiA} (see Table 2) and the integral of current J_{Cik} (see Table 1), the critical sections S_{CCi} of the considered electrical wires (cables) can be determined relatively easily from (1). Table 3 shows the calculated by (1) numerical values of the critical sections S_{CCi} for uninsulated wires with copper (aluminum) cores and insulated wires (cables) with copper (aluminum) cores (shells), PVC, R and PET insulation, experiencing the effect of aperiodic nanosecond current pulse of the temporal shape τ_f/τ_p=5 ns/200 ns.

Table 2
Numerical values of the integral of action J_{CiA} for a nanosecond aperiodic current pulse of the temporal shape 5 ns/200 ns, flowing in the current-carrying parts of the considered CCP [4]

Amplitude value I_{mp}= I_{mp1} of the current pulse of the temporal shape 5 ns/200 ns, kA	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 3
Numerical values of the critical sections S_{CCi} for wires (cables) with copper (aluminum) cores (shells) in the HHIT power circuits with a nanosecond current pulse of 5 ns/200 ns, whose amplitude varies from 10 kA to 500 kA

Type of insulation in the wire (cable) of the HHIT power circuit	Material of the core (shell) of the wire (cable)	Value of the section S_{CCi}, mm^2			
		Amplitude I_{mp} of the pulse current 5 ns/200 ns, kA			
		10	50	100	500
Without insulation, PVC, R and PET insulation	Copper	0.008	0.042	0.085	0.425
	Aluminum	0.011	0.057	0.114	0.569

From the data of Table 3 it follows that the estimated critical amplitudes of the densities $\delta_{CCi} \approx I_{mp}/S_{CCi}$ of a nanosecond current pulse of temporal shape 5 ns/200 ns for both uninsulated wires and wires and cables with copper (aluminum) cores (shells) and PVC, R and PET insulation are, respectively, approximately 1176 kA/mm^2 and 878 kA/mm^2.

4. Calculation determination of critical cross-sections S_{CCi} and current densities δ_{CCi} in electrical wires (cables) for microsecond current pulses in HHIT circuits. Figure 1 shows a typical oscillogram of a pulsed *A*- component of an artificial lightning current formed in a high-current discharge circuit of a high-voltage lightning current generator (LCG) for testing objects of aeronautical and rocket technology on lightning resistibility in accordance with US regulations [10, 11]. It can be seen that this component of current pulses $i_p(t)$ of a lightning simulated under laboratory conditions in time t varies according to the law of damped sinusoid. Let us make the choice of critical sections S_{CCi} and densities δ_{CCi} of current in current-carrying cores (shells) of wires and cables for the discharge circuit of the LCG in relation to current pulse $i_p(t)$ of lightning shown in Fig. 1.

From the experimental data presented in Fig. 1, we obtain that for the used in approximate calculations of critical cross sections S_{CCi} a large exponentially decaying sinusoidal pulse current, the decrement of its oscillations is equal to Δ_p=ln(I_{mp1}/I_{mp3})=2.505. From (4) for this type of current pulse, we find that the coefficient k_{p2}=1.731. Table 4 shows the numerical values of the integral of action J_{CiA} calculated by (5) for a microsecond current pulse varying in time t according to the law of a damped sinusoid of the form (4) [12].

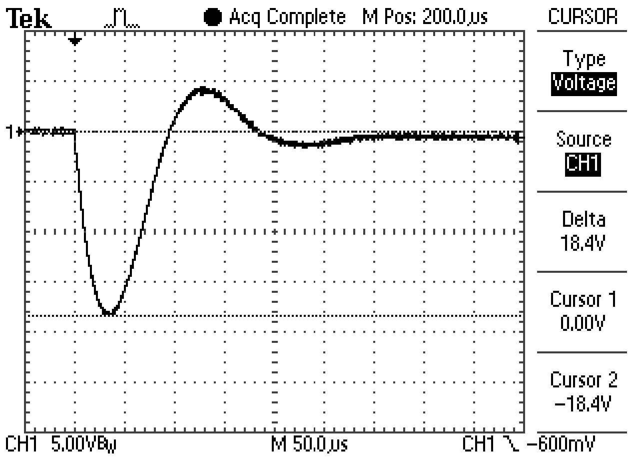

Fig. 1. Typical oscillogram of a microsecond pulsed *A*- component of an artificial lightning current flowing in a high-voltage discharge circuit of a high-voltage LCG ($I_{mp1} \approx -207$ kA; $I_{mp3} \approx -16.9$ kA; $T_p \approx 185$ µs; vertical scale - 56.3 kA/division; horizontal scale - 50 µs/division) [12]

Using (1) and summarized in Table 4 the results of the calculation of the integral of action J_{CiA} of the pulse current $i_p(t)$ of the form (4), we find the critical sections S_{CCi} for the wires (cables) under study in the HHIT power circuits, in which the microsecond current pulse of the form (4) with the ATPs corresponding to the experimental data characteristic of Fig. 1 flows. Table 5 presents the results of such a computational determination of the critical sections S_{CCi} for the wires and cables under consideration, which are widely used in HHIT discharge power circuits [1, 2, 12].

Table 4
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 (4)

Value of the first amplitude I_{mp1} of a damped sinusoidal current pulse, kA	Value of the integral of action J_{CiA} of the current pulse of the form (4), $A^2 \cdot s$
10	$4.77 \cdot 10^3$
30	$4.29 \cdot 10^4$
50	$1.19 \cdot 10^5$
70	$2.34 \cdot 10^5$
100	$4.77 \cdot 10^5$
207	$2.05 \cdot 10^6$
300	$4.29 \cdot 10^6$
500	$11.92 \cdot 10^6$
700	$23.4 \cdot 10^6$
1000	$47{,}7 \cdot 10^6$

From the presented in Table 5 calculated data, it follows that the estimated critical amplitudes of the densities $\delta_{CCi} \approx I_{mp1}/S_{CCl}$ of the microsecond current pulse $i_p(t)$ with ATPs corresponding to the experimental data of Fig. 1, both for uninsulated wires and wires (cables) with copper and aluminum cores (shells), PVC, R and PET insulation are numerically, respectively, about 64 kA/mm^2 and 48 kA/mm^2.

Table 5

Numerical values of critical sections S_{CCi} for wires (cables) with copper (aluminum) cores (shells) in HHIT circuits with a microsecond current pulse of the form (4), the first amplitude of which I_{mp1} varies from 30 kA to 207 kA

Type of insulation in the wire (cable) of the HHIT power circuit	Material of the core (shell) of the wire (cable)	Value of the section S_{CCi}, mm^2			
		The first amplitude I_{mp1} of the current pulse of the form (4), kA			
		30	50	100	207
Without insulation, PVC, R and PET insulation	Copper	0.469	0.781	1.564	3.243
	Aluminum	0.627	1.045	2.092	4.337

5. Calculation determination of critical cross-sections S_{CCi} and current densities δ_{CCi} in electrical wires (cables) for millisecond current pulses in HHIT circuits. Figure 2 shows a typical oscillogram of a long-term *C*- component of the artificial lightning current generated under laboratory conditions according to the requirements of [10] in the LCG discharge circuit for the purpose of experimentally determining the lightning resistibility of aerospace objects under direct lightning conditions. From the data in Fig. 2 it can be seen that the aperiodic current pulse $i_p(t)$ of the artificial lightning of negative polarity of this component of the total current of a thunderstorm discharge varies in the millisecond time range. Its amplitude I_{mp} at t_m≈11 ms is approximately 835 A. At the same time, the duration of the front of the test current pulse is about τ_f≈7 ms, and its duration at the level of $0.5I_{mp}$ is τ_p≈160 ms. In addition, from the data in Fig. 2 it follows that the total duration of the flow of the used component of the current pulse $i_p(t)$ of artificial lightning in the discharge circuit of a high-voltage LCG reaches a value of about 1000 ms. On the basis of the proposed electrical engineering approach, we perform the determination of the critical sections S_{CCi} of wires (cables) for the LCG discharge circuit involved in the formation of the specified current pulse $i_p(t)$.

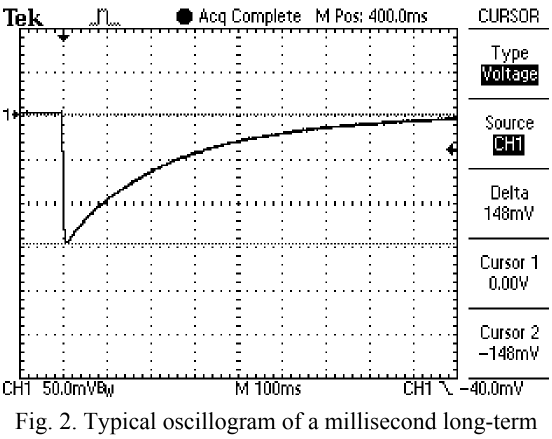

Fig. 2. Typical oscillogram of a millisecond long-term *C*- component of the current of artificial lightning flowing in the discharge circuit of a high-power high-voltage LCG (I_{mp}≈−835 A; τ_f≈7 ms; τ_p≈160 ms; vertical scale − 282 A/division; horizontal scale − 100 ms/division) [12]

From (2) at τ_f≈7 ms and τ_p≈160 ms, we find that α_1≈4.75 s^{-1} and α_2≈3.38·10^2 s^{-1}. Then the normalization coefficient k_{p1} takes a numerical value equal to about k_{p1}≈1.077. Using (3) and varying the amplitude value I_{mp}, one can calculate the numerical values of the integral of action J_{CiA} for the millisecond current pulse $i_p(t)$ used. Table 6 shows the numerical values of J_{CiA} for a series of amplitudes I_{mp} of the current pulse $i_p(t)$ of temporal shape 7 ms/160 ms.

Table 6

Numerical values of the integral of action J_{CiA} for a current pulse $i_p(t)$ varying in a HHIT circuit in the millisecond time range according to the law of the form (2)

Amplitude value I_{mp}=I_{mp1} of an unipolar millisecond aperiodic current pulse 7 ms/160 ms, A	Value of the integral of action J_{CiA} of a 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
400	1.87·10^4
500	2.92·10^4
700	5.73·10^4
835	8.15·10^4
900	0.95·10^5
1000	1.17·10^5

Then, taking into account the data of Table 6, according to (1) in the accepted approximation, one can find the critical sections S_{CCi} for uninsulated and insulated wires and cables with copper (aluminum) cores (shells), PVC, R and PET insulation, which are affected by an axial millisecond aperiodic current pulse $i_p(t)$, ATPs which correspond to the data in Fig. 2. Table 7 shows the calculated numerical values of the critical sections S_{CCi} for the indicated wires (cables) with a millisecond aperiodic current pulse $i_p(t)$ of the temporal shape 7 ms/160 ms, found as described above. Based on the relation of the form δ_{CCi}≈I_{mp}/S_{CCi}, the data of Table 7 allows us to estimate the numerical values of critical densities δ_{CCi} in wires (cables), along which a millisecond aperiodic current pulse $i_p(t)$ of a temporary shape of 7 ms/160 ms with an amplitude of I_{mp}, varying in a wide range from 100 A to 1000 A, flows in the longitudinal direction.

Table 7

Numerical values of the critical sections S_{CCi} for uninsulated wires and insulated wires (cables) with copper (aluminum) cores (shells), PVC, R and PET insulation in HHIT circuits that are affected by a millisecond current pulse of temporal shape of 7 ms/160 ms varies from 100 A to 1000 A

Type of insulation in the wire (cable) of the HHIT power circuit	Material of the core (shell) of the wire (cable)	Value of the section S_{CCl}, mm^2			
		Amplitude I_{mp} of the current pulse 7 ms/160 ms, A			
		100	500	835	1000
Without insulation, PVC, R and PET insulation	Copper	0.077	0.387	0.647	0.775
	Aluminum	0.103	0.518	0.865	1.036

From the presented in Table 7 quantitative data, it follows that the estimated critical amplitudes of the densities δ_{CCi}≈I_{mp}/S_{CCi} of a millisecond aperiodic current pulse $i_p(t)$ of the shape 7 ms/160 ms with ATPs corresponding to the oscillogram in Fig. 2, for uninsulated wires with copper and aluminum cores, as well as wires (cables) with copper and aluminum cores (shells) having PVC, R and PET insulation, are approximately equal to 1.29 kA/mm^2 and 0.97 kA/mm^2, respectively.

6. Results of experimental verification of the calculation relations for the determination of the critical sections S_{CCi} and the current densities δ_{CCi} in the wires (cables) of the HHIT circuits. This functional test of the critical sections S_{CCi} of wires (cables) recommended for calculation determination by the relation (1) and the critical amplitudes of the pulse current densities $i_p(t)$ in their cores (shells) calculated by relation δ_{CCi}≈I_{mp}/S_{CCi} we carry out using a powerful high-current high-voltage LCG [13] which simulates the normalized by [10] ATPs of the pulsed *A*- components of the artificial lightning current (see Fig. 1) and is equipped with verified by the state metrological service appropriate measuring equipment [15]. To do this, we first realize on the specified generator the effect of this lightning current component with ATPs normalized by requirements [10] (I_{mp1}≈−205 kA; I_{mp3}≈−16.9 kA; T_p≈200 μs; Δ_p≈ln(I_{mp1}/I_{mp3})≈2.495; t_m≈38 μs; J_{CiA}≈2.17·10^6 A^2·s) previously obtained at the load equivalent (cable brand PK 75-17-31 with a copper core of section of 10.2 mm^2), on the test sample (TS) with length of 0.55 m wire of grade ПВ-2.5 with PVC insulation and a cross-section of a split copper core equal to S_{C1}≈2.5 mm^2. According to the above initial data for ATPs of the used damped sinusoidal current pulse of the microsecond range and (1), the critical section for the tested copper wire is approximately equal to S_{CC1}≈3.34 mm^2. At |I_{mp1}|≈205 kA, this critical section corresponds to the critical amplitude of the density of this current pulse, which is numerically equal to δ_{CC1}≈61.4 kA/mm^2. It is seen that $S_{C1}<S_{CC1}$. In this regard, it was possible to conclude before the planned experiment that the tested wire, when exposed to its copper core with cross section S_{C1}≈2.5 mm^2 of the pulsed *A*- component of the lightning current with normalized ATPs, should undergo the EE and fail. Indeed, this conclusion was confirmed by the corresponding electrophysical experiment carried out on the indicated high-current LCG under the conditions of the high-voltage laboratory, the results of which applied to the nature of the abrupt change in time *t* due to the EE of the copper core with section S_{C1}≈2.5 mm^2 of the tested wire of grade ПВ-2.5 with PVC insulation PVC insulation of the original current pulse $i_p(t)$ are presented in Fig. 3.

From the data in Fig. 3 it follows that the EE in the discharge circuit of the specified LCG of the copper core with cross section S_{C1}≈2.5 mm^2 of grade ПВ-2.5 wire with PVC insulation causes a sharp deformation of the current pulse $i_p(t)$ flowing through it compared to its original shape (see Fig. 1). From the oscillogram in Fig. 3 it follows that the experimental value of the critical amplitude of the density δ_{CC1} of the microsecond current pulse $i_p(t)$ in the conducted electrophysical experiment is approximately δ_{CC1}≈I_{mp}/S_{CC1}≈205 kA/3.34 mm^2≈61.4 kA/mm^2. Compared with the calculated value of the critical amplitude density δ_{CC1} used in the experiment the damped sinusoidal current pulse $i_p(t)$ which equals to δ_{CC1}≈I_{mp}/S_{CC1}≈205 kA/3.34 mm^2≈61.4 kA/mm^2, the obtained experimental value of the critical current density δ_{CC1} differs from it by about 8 %.

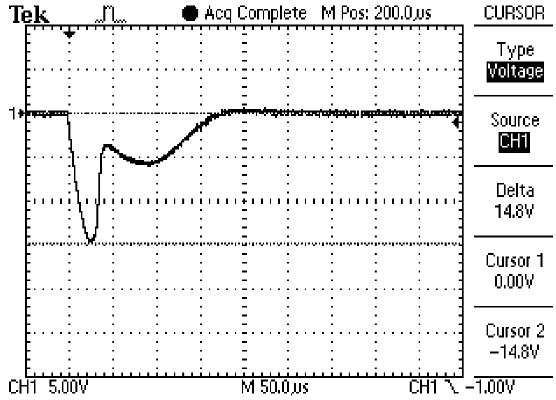

Fig. 3. Oscillogram of the pulsed *A*- component of the artificial lightning current, deformed by the EE process in the LCG discharge circuit of a split copper core with S_{C1}≈2.5 mm^2 section of the tested TS of grade ПВ-2,5 wire, 0.55 m long with PVC insulation (I_{mp1}≈−166.7 kA; δ_{CC1}≈|I_{mp1}|/S_{C1}≈66.7 kA/mm^2; vertical scale – 56.3 kA/division; horizontal scale – 50 μs/division) [1, 14]

Figure 4 shows a general view of a desktop of a high-voltage high-current LCG, on which a tested on electrothermal resistibility to the action of pulsed *A*- component of an artificial lightning current with ATPs normalized by [10, 11] (I_{mp1}≈−205 kA; I_{mp3}≈−16.9 kA; T_p≈200 μs; t_m≈38 μs; Δ_p≈ln(I_{mp1}/I_{mp3})≈2.495; J_{CiA}≈2.17·10^6 A^2·s) TS of the radio frequency cable brand PK 75-4-11 with length of 0.55 m with solid copper core with section S_C =0.407 mm^2 and copper braid with section S_{C2}=2.44 mm^2 is fixed prior to exposure on it of the specified microsecond pulse current $i_p(t)$. The inner copper core and the outer copper shell-braid at the edges of this cable were connected in parallel and connected together to the discharge circuit of a high-current high-voltage LCG [14].

Fig. 4. General view of the desktop of the LCG with 0.55 m length rigidly fixed on its massive aluminum electrodes the tested radio frequency cable brand PK 75-4-11 with a solid copper core with section S_{C1}=0.407 mm^2 and a copper shell-braid with section S_{C2}=2.44 mm^2 prior to the impact on it of the pulsed *A*- component of the artificial lightning current with normalized ATPs (the core and the shell-braid at the ends of this cable were connected to the high-current discharge circuit of the LCG in parallel) [1, 14]

Figure 5 shows an oscillogram of the pulsed *A*- component of the artificial lightning current used in the experiment deformed by the EE of the copper current-carrying parts of the tested TS of the radio frequency cable of the PK 75-4-11 brand with a total cross section of the core and braid, equal to $(S_{C1}+S_{C2})\approx 2.85$ mm^2.

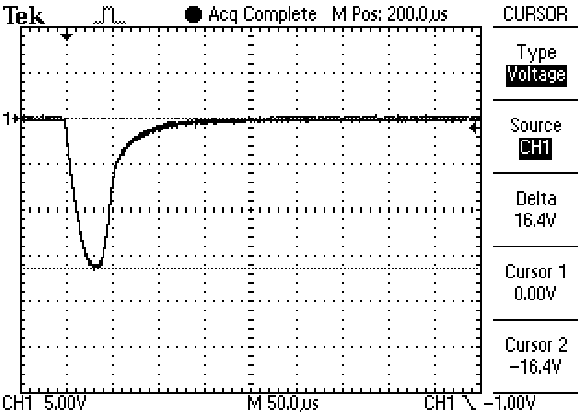

Fig. 5. Oscillogram of a pulsed *A*- component of an artificial lightning current deformed by EE in a discharge circuit of a LCG of a solid copper core with $S_{C1}\approx 0.407$ mm^2 section and a copper braid with S_{C2}=2.44 mm^2 section of a tested TS of a 0.55 m in length radio frequency cable PK 75-4-11 brand with PET insulation ($I_{mp1}\approx -184.7$ kA; $\delta_{CCi}\approx|I_{mp1}|/(S_{C1}+S_{C2})\approx 64.8$ kA/mm^2; vertical scale – 56.3 kA/division; horizontal scale − 50 µs/division) [1, 14]

Figure 6 shows the external view of the LCG desktop immediately after the impact of the specified current pulse $i_p(t)$ on the tested in its high-current discharge circuit TS of the cable of the brand PK 75-4-11 with PET insulation and full cross section of its copper current-carrying parts $(S_{C1}+S_{C2})\approx 2.85$ mm^2. Due to the phenomenon of the EE of its solid copper core and hollow copper shell-braid, which occurred in the TS of the cable, sublimation of its copper current-carrying parts occurred with the destruction of the belt and protective PET insulation of the test cable sample. Insulating and metal elements of the LCG were subjected to active metallization with brown-red copper vapor (see Fig. 6). On this desktop in the EE zone of the tested TS of the cable, there is the presence of small melted and charred fragments of its protective PET insulation.

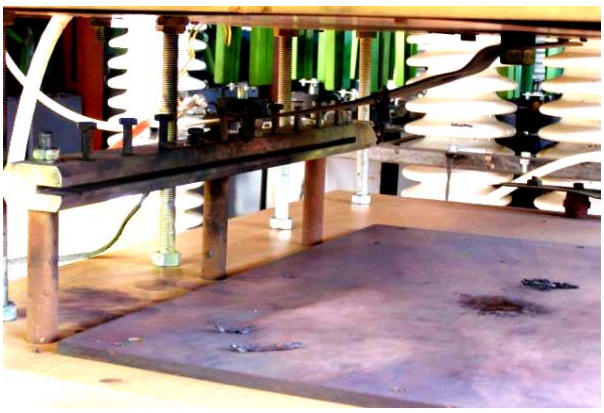

Fig. 6. External view of the desktop of the LCG after the EE of the current-carrying parts of the tested in its high-current discharge circuit TS of 0.55 m long of the RF cable of the PK 75-4-11 brand with PET insulation and connected in the gap of the discharge circuit of a high-voltage generator with total cross section of its copper core and copper braid equals to $(S_{C1}+S_{C2})\approx 2.85$ mm^2 ($I_{mp1}\approx -184.7$ kA; $\delta_{CCi}\approx|I_{mp1}|/(S_{C1}+S_{C2})\approx 64.8$ kA/mm^2) [1, 14]

Due to the fact that for the tested cable of brand PK 75-4-11, the following inequality is fulfilled $(S_{C1}+S_{C2})<S_{CCi}$, its current-carrying copper parts together with PVC insulation were destroyed by the apparent in the carried out experiment the EE of the solid round core and hollow braid-shell of the selected size of the CCP. At the calculated by (1) value of a critical section for this type of cable, equal to $S_{CCi}\approx 3.34$ mm^2, the calculated critical amplitude of the density δ_{CCi} of the used in the experiment a microsecond current pulse $i_p(t)$ for it was numerically $\delta_{CCi}\approx I_{mp}/S_{CCi}\approx 61.4$ kA/mm^2. From the oscillogram in Fig. 5 it follows that the experimental value of the critical density amplitude δ_{CCi} of the specified current pulse $i_p(t)$ is numerically equal in module to $\delta_{CCi}\approx I_{mp}/(S_{C1}+S_{C2})\approx 64.8$ kA/mm^2. It can be seen that the obtained experimental value for the value of the critical amplitude of the density δ_{CCi} of a current pulse of microsecond duration in the cable under study differs from its corresponding calculated value by no more than 6%. Thus, experimental studies for a microsecond current pulse $i_p(t)$ performed on a high-current high-voltage LCG have confirmed the performance of the proposed calculation relations for determining the critical sections S_{CCi} and critical amplitudes of current densities δ_{CCi} for the specified time range in the current-carrying parts of the wires and cables of HHIT power circuits.

Conclusions. 1. The proposed electrical engineering approach allows for the condition of EE in atmospheric air of the current-carrying parts of the CCP to carry out an approximate calculation of the critical cross sections S_{CCi} and amplitudes of current densities δ_{CCi} for uninsulated wires with copper (aluminum) cores, as well as for insulated wires and cables with copper (aluminum) cores (shells) with PVC, R and PET insulation, through which the pulse current $i_p(t)$ flows, the ATPs of which varies in the nano-, micro- and millisecond time ranges.

2. On the basis of the obtained approximate calculated relations, specific capabilities of the proposed electrical engineering approach for selecting critical cross sections S_{CCi} and amplitudes of current densities δ_{CCi} in the indicated wires and cables of HHIT power circuits, in current-carrying parts of which large pulse currents $i_p(t)$ varying in time t according to aperiodic law or damped sinusoid law with the first current amplitude I_{mp1}, are demonstrated.

3. It has been determined by calculation that the critical amplitudes of densities $\delta_{CCi}\approx I_{mp1}/S_{CCi}$ of pulse current $i_p(t)$ for its considered temporal shapes in copper (aluminum) cores of uninsulated wires and insulated wires and cables with copper (aluminum) cores (shells), PVC, R and PET insulation for the nanosecond time range are numerically approximately 1176 (878) kA/mm^2, for the microsecond time range 64 (48) kA/mm^2, and for the millisecond time range 1.29 (0.97) kA/mm^2.

4. Experiments carried out using high-current high-voltage LCG with regard to the effect on the current-carrying parts of the ПВ-2,5 grade wire with PVC insulation and the cable of the PK 75-4-11 grade with PET insulation of a microsecond damped sinusoidal current pulse of artificial lightning with normalized ATPs in accordance with the requirements of acting the field of lightning protection of aerospace technology objects of

the USA SAE ARP 5412: 2013 document confirmed the performance of the recommended calculation relations for determining the critical sections S_{CCi} and amplitudes of current densities δ_{CCi} in indicated wires and cables of the HHIT circuits.

5. The results obtained for the critical cross sections S_{CCi} and current densities δ_{CCi} can also be used in the practice of implementation in the atmospheric air with the help of HHIT electrical installations of the EE phenomena of uninsulated thin metal conductors (wires) used in a number of modern applied electrophysical technologies.

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