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Destruction of polymer insulation and threshold amplitudes of current pulses of different temporal shapes for electric wires and cables in the low- and high-current circuits of pulse power engineering, electrical engineering and electronic devices

Goal. *Development of engineering method for settlement of threshold amplitudes I_{mpk} of single-pulse current $i_p(t)$ of different temporal shapes for electric wires and cables with polyethylene (PET), polyvinylchloride (PVC) and rubber (R) half-length insulation, used in modern pulsed power engineering, electrical engineering and electronics in their low- and high-current circuits.* ***Methodology.*** *Basis of the theoretical and applied electrical engineering, electrical power engineering, electrophysics bases of technique of high-voltage and large pulsed currents, bases of low- and high-current electronics, measuring technique, electromagnetic compatibility and standardization.* ***Results.*** *Development of engineering method is executed on close calculation determination of threshold amplitudes I_{mpk} of single-pulse axial-flow current $i_p(t)$ of different temporal shapes for electric wires and cables with copper (aluminum) current-carrying parts and PET, PVC and R half-length insulation, used in the ow- and high-current circuits of pulsed electrical power engineering, electrical engineering and electronics. Electrothermal resistibility of half-length insulation of the examined cable and wire products (CWP), proper maximum to the possible temperatures of heating of current-carrying and insulating parts of the probed wires and cables and shutting out the offensive of the phenomenon destruction in the indicated insulation of CWP, was fixed based on this method. Calculation analytical correlations are obtained for finding in probed CWP of threshold numeral values of I_{mpk} amplitudes of pulses of current $i_p(t)$, time-varying both on aperiodic dependence of type τ_f/τ_p with duration of their front τ_f and duration of their pulses τ_p and by law of exponential attenuation sinewave. It is shown that at $I_{mp}>I_{mpk}$ destruction of their half-length insulation, resulting in the decline of service life of CWP, will come from the thermal overheat of current-carrying parts of the examined electric wires and cables. The examples of practical application of the offered method are resulted upon settlement for a radiofrequency coaxial cable RC 50-4-11 with middle sizes is easily soiled with continuous PET insulation of threshold amplitudes of I_{mpk} of standard aperiodic pulses of current $i_p(t)$ from nano-, micro- and millisecond temporal ranges of shape of τ_f/τ_p=5 ns/200 ns, τ_f/τ_p=10 μs/350 μs and τ_f/τ_p=7 ms/160 ms. It is shown that with the proper growth of parameter $\tau_p>>\tau_f$ for flow on a continuous copper tendon and split copper shell of radiofrequency coaxial cable RC 50-4-11 with middle sizes is easily soiled indicated homopolar pulses of current $i_p(t)$ substantial diminishing of their threshold amplitudes of I_{mpk} (with 531,2 кA for the nanosecond pulse of current of type 5 ns/200 ns to 1.84 кA for the millisecond impulse of current of type of 7 ms/160 ms takes place).* ***Originality.*** *An engineering method is first developed for close settlement of threshold numeral values of I_{mpk} amplitudes of single-pulse axial-flow current $i_p(t)$ of arbitrary peak-temporal parameters for electric wires and cables with copper (aluminum) current-carrying parts and PET, PVC and R half-length insulation.* ***Practical value.*** *Application in electrical engineering practice of the offered engineering method for determination of threshold amplitudes I_{mpk} of the indicated pulses of axial-flow current $i_p(t)$ for the probed electric wires and cables will allow considerably to increase service life of examined CWP.* References 20, tables 2.

Key words: **electrical wires and cables with polymer insulation, electrothermal resistance of cable and wire products, destruction of insulation, threshold amplitudes of current pulses for wires and cables.**

Запропонована інженерна методика за розрахунковим визначенням порогових амплітуд I_{mpk} імпульсів струму $i_p(t)$ різної часової форми для електричних проводів і кабелів з поліетиленовою, полівінілхлоридною і гумовою ізоляцією, широко вживаних в галузі імпульсної енергетики, високовольтної сильнострумової техніки, вимірювальної техніки і електроніки, а також в системах імпульсного електроживлення, контролю, управління роботою і діагностики стану функціонування електротехнічних пристроїв різного загальногромадянського і військового призначення. В якості вихідного критеріального положення при виборі порогових амплітуд I_{mpk} імпульсів струму $i_p(t)$ довільних амплітудно-часових параметрів для вказаних проводів і кабелів була вибрана термічна стійкість їх поясної ізоляції, яка відповідає гранично допустимим короткочасним температурам нагріву мідних (алюмінієвих) і ізоляційних частин досліджуваних кабелів (проводів) і що не допускає настання явища деструкції в ізоляції даної кабельно-провідникової продукції. Приведені приклади практичного використання запропонованої методики за розрахунковим визначенням порогових амплітуд I_{mpk} стандартних аперіодичних імпульсів струму $i_p(t)$ часової форми 5 нс/200 нс, 10 мкс/350 мкс і 7 мс/160 мс для радіочастотного коаксіального середньогабаритного кабелю марки РК 50-4-11 зі суцільною поліетиленовою ізоляцією. Бібл. 20, табл. 2.

Ключові слова: **електричні проводи і кабелі з полімерною ізоляцією, електротермічна стійкість кабельно-провідникової продукції, деструкція ізоляції, порогові амплітуди імпульсів струму для проводів і кабелів**.

Предложена инженерная методика по расчетному определению пороговых амплитуд I_{mpk} импульсов тока $i_p(t)$ различной временной формы для электрических проводов и кабелей с полиэтиленовой, поливинилхлоридной и резиновой изоляцией, широко применяемых в области импульсной энергетики, высоковольтной сильноточной техники, измерительной техники и электроники, а также в системах импульсного электропитания, контроля, управления работой и диагностики состояния функционирования электротехнических устройств различного общегражданского и военного назначения. В качестве исходного критериального положения при выборе пороговых амплитуд I_{mpk} импульсов тока $i_p(t)$ произвольных амплитудно-временных параметров для указанных проводов и кабелей была выбрана термическая стойкость их поясной изоляции, соответствующая предельно допустимым кратковременным температурам нагрева медных (алюминиевых) и изоляционных частей исследуемых кабелей (проводов) и не допускающая наступления явления деструкции в изоляции *рассматриваемой кабельно-проводниковой продукции. Приведены примеры практического использования предлагаемой методики по расчетному определению пороговых амплитуд I_{mpk} стандартных апериодических импульсов тока $i_p(t)$ временной формы 5 нс/200 нс, 10 мкс/350 мкс и 7 мс/160 мс для радиочастотного коаксиального среднегабаритного кабеля марки РК 50-4-11 со сплошной полиэтиленовой изоляцией.* Библ. 20, табл. 2.

Ключевые слова: **электрические провода и кабели с полимерной изоляцией, электротермическая стойкость кабельно-проводниковой продукции, деструкция изоляции, пороговые амплитуды импульсов тока для проводов и кабелей.**

State-of-the-art and urgency of the problem. In the field of traditional electric power engineering, there is an electrical engineering approach to the engineering selection of the cross-sections S_C of electrical wires and cables with polymer insulation, used for both long-term and short-term modes of their operation [1]. This approach is based on the thermal stability of such a cable and wire product (CWP) under conditions of direct exposure to it of short-circuit (SC) current with specified amplitude-temporal parameters (ATPs). In this case, the thermal resistance of electric cables (wires) of any design is limited by the maximum permissible short-term temperature θ_{lS} of heating of their metal and insulating parts in the mode of one-, two and three-phase SC in the electrical network [1]. According to electrical data from [1], the specified temperature θ_{lS} should not exceed for those used in power circuits with alternating current of power frequency 50 Hz of non-insulated (bare) copper and aluminum buses (wires) in the SC mode of the highest level of 250 °C and 200 °C, and for cables (insulated wires) with copper (aluminum) cores, polyvinylchloride (PVC), rubber (R) and polyethylene (PET) insulation – respectively, the temperature level of 150 °C and 120 °C. In addition, it is known that in the field of industrial power engineering, the long-term permissible heating temperature θ_{ll} of conductive (insulating) parts of various electrical wires and cables is limited by the conditions of reliable operation of electrical contacts and contact connections of their circuits, as well as by the operating conditions of their insulation [1]. Here, the maximum long-term permissible heating temperature θ_{ll} for the main types of bare wires (buses) and cables (wires) with PVC, R and PET insulation, which are under current load in industrial electric power circuits, should not numerically exceed the level of 70 °C and 65 °C, respectively [1]. Taking into account the above electrical data and the fulfillment of those initial conditions that the cable (wire) before the AC current acts on it was fully electrically loaded and had temperature θ_{ll}, and upon the onset of the SC mode, it heated up to temperature θ_{lS}, in [1] to select the minimum permissible cross-section $S_{l\min}$ of the electric wire (cable), the following calculated analytical relationship is recommended:

$$S_{l\min} = B_k^{1/2} / C_k\,, \tag{1}$$

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 its duration t_k of flow in the CWP, $A^2 \cdot s$; C_k is the constant coefficient, $A \cdot s^{1/2}/m^2$.

We point out that the engineering method for calculating the Joule integral B_k in (1) and the numerical values of the coefficient C_k corresponding to the indicated operating conditions of wires and cables in power electric circuits for the CWP are given in [1]. The values of the cross-sections $S_{l\min}$ of the CWP found by (1) will correspond to the operating mode in the electric power circuits of wires and cables when the heating temperature of their current-carrying and insulating parts does not exceed the maximum permissible short-term temperature θ_{lS} and when the thermal resistance of the indicated CWP is ensured.

ATPs of current pulses $i_p(t)$ of nano-, micro- and millisecond time ranges generated and used in the field of high-voltage pulse technology (HPT) [2] and in other areas of modern pulsed low- and high-current power engineering, electrical engineering and electronics (for example, in equipment of pulse electrical technologies and accelerator technology [3]) to achieve various scientific and technological goals, usually do not correspond to ATPs of AC SC current in industrial power circuits. In this regard, the practical application of relationship (1) for the calculation determination of the cross-sections S_C of wires (cables) in low- and high-current electrical circuits of the indicated pulse technology is fundamentally impossible. In addition, the indicated electrical engineering approach to the choice in the industrial electric power industry of the cross-sections S_C of electric wires (cables) does not allow determining the threshold amplitudes I_{mpk} of pulse currents $i_p(t)$ with various ATPs, above which destructive processes in its polymer insulation will begin to manifest in the considered CWP. As is known, the phenomenon of destruction of such insulation, accompanied by irreversible violations of its electrical insulating properties, can be caused by an external (internal) damaging or destabilizing effect on wires and cables of various physical factors (for example, an alternating (pulsed) current flowing through their current-carrying parts, ionizing and electromagnetic radiation) [1, 4, 5]. Within the framework of the applied problem we are solving, only one destabilizing factor is considered, due to the pulse current $i_p(t)$ flowing through the electric wires and cables with various ATPs. At certain (threshold) values I_{mpk} of the amplitude I_{mp} of current pulses $i_p(t)$ of one or another temporal shape flowing through the current-carrying parts (inner core and outer shell) of the CWP, due to the intense Joule heating of these metal parts of the wires (cables), processes of thermal destruction in their belt insulation can occur [1, 6, 7]. It should be noted that at values of the amplitudes I_{mp} of pulse currents $i_p(t)$ of hundreds of kiloamperes, destructive processes in the polymer insulation of the studied CWP can also arise from the action of large electrodynamic forces on cables (wires) [2]. In practice, it is important to know such threshold values I_{mpk} of the amplitudes I_{mp} of current pulses $i_p(t)$ of various temporal shapes, leading to a violation of the electrical insulating properties of wires (cables) used in the field of HPT, measuring technology, electronics, in systems of power supply, control, operation control and diagnostics of the state of functioning of electrical devices, and a decrease in their service life.

At present, when developing and creating in the world new polymeric insulating materials with various nano- and microstructural structures of electrical engineering and other (including medical and biological) purposes, the issues of behaviour of polymer insulation under conditions of the action of destabilizing (damaging) physical factors are given increased attention [8-11].

The goal of the paper is the development of an engineering methodology for calculating the threshold amplitudes I_{mpk} of single current pulses $i_p(t)$ of various temporal shapes for electrical wires and cables with PET, PVC and R belt insulation used in modern pulsed power engineering, electrical engineering and electronics in their low- and high-current circuits.

Problem definition. Consider insulated wires and cables with copper (aluminum) inner cores (i=1) and outer shells (i=2), with PET, PVC and R belt insulation used in electrical circuits of HPT and other low- and high-current electrical engineering (electronics) [1, 12]. We assume that single current pulses $i_p(t)$ flow in their longitudinal direction along the round solid or split copper (aluminum) cores and shells of the indicated wires and cables of electrical circuits of pulsed electrical engineering (electronics) devices, the ATPs of which can correspond to nano-, micro- and millisecond time ranges with amplitudes I_{mp}, varying in a wide range from 1 A to 1000 kA [2, 3]. We assume that wires and cables of finite length l_0 are placed in the surrounding air with temperature equal to θ_0 = 20 °C [13]. Let us use the condition of the adiabatic nature of electrothermal processes flowing at the time of action of the pulsed axial current $i_p(t)$ no more than 1000 ms in the materials of the cores (shells) of the studied CWP, in which the effect of heat transfer from the surfaces of their current-carrying parts, having current temperature $\theta_{Ci} \geq \theta_0$, and their thermal conductivity of their electrically conductive materials and insulation for Joule heating of the metal parts of the cores (shells) of wires (cables) are neglected. We believe that the thermal resistance of wires (cables) of circuits of HPT and other above-mentioned electrical engineering (electronics) devices when exposed to pulse current $i_p(t)$ is limited by their maximum permissible short-term heating temperature θ_{CiS}, which depends on the degree of decrease in the mechanical strength of the core (shell) material and thermal conditions of operation of the insulation of the CWP in the mode of its short-term heating by current pulses of nano-, micro- or millisecond duration, flowing through their current-carrying parts. As in [14], we assume that the temperature value θ_{CiS} corresponds to the known from [1] maximum permissible short-term temperature θ_{lS} of heating of wires and cables by SC currents of power frequency. Then, in accordance with the data from [1], in the electrical low- and high-current circuits of the considered electrical engineering for their insulated wires (cables) with copper and aluminum conductors (shells) and PVC (R) insulation, the value θ_{CiS} will be numerically approximately $\theta_{CiS} \approx 150$ °C , and for their CWP with the indicated cores (shells) and PET insulation – $\theta_{CiS} \approx 120$ °C . It is required to calculate in an approximate form the threshold amplitudes I_{mpk} of single current pulses $i_p(t)$ of various ATPs from nano-, micro- and millisecond time ranges flowing through electrical wires and cables with copper (aluminum) cores (shells) and PET, PVC and R belt insulation.

Electrical engineering approach to the selection of the permissible minimum cross-sections S_{Cil} of wires and cables with pulse current of various ATPs. For the permissible minimum cross-sections S_{Cil} of the current-carrying conductors (shells) of the investigated electrical wires (cables) with pulse current $i_p(t)$ of arbitrary ATPs, from the equation of their heat balance in the adiabatic mode of the CWP operation in low- and high-current circuits, the following approximate calculated relationship can be obtained [14]:

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

where $J_{CiA} = \int_0^{t_p} i_p^2(t)dt$ – the action integral of a single current pulse $i_p(t)$ with its duration t_p and given ATPs, $A^2 \cdot s$; $C_l = (J_{ClS} - J_{Cll})^{1/2}$ is the constant coefficient, $A \cdot s^{1/2}/m^2$; J_{ClS}, J_{Cll} are the current integrals for current-carrying conductors (shells) of electrical wires (cables) of low-current and power circuits of various electrical devices, the permissible short-term and long-term permissible heating temperatures of the CWP material which correspond to the values adopted above: $\theta_{lS} = \theta_{CiS}$ and θ_{ll}, $A^2 \cdot s/m^4$.

To find the numerical values of the current integrals J_{ClS} and J_{Cll} included in (2), the following analytical expressions can be used [14]:

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

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

where γ_{0i}, c_{0i}, β_{0i} are, respectively, the specific electrical conductivity, specific volumetric heat capacity and thermal coefficient of specific electrical conductivity of the material of the core (shell) of the wire (cable) of the electric circuit before the impact on the considered CWP of the pulsed current $i_p(t)$ with arbitrary ATPs.

Table 1 shows the numerical values of the electrophysical parameters γ_{0i}, c_{0i} и β_{0i}, included in the calculation relationships (3), (4), at room temperature of the air surrounding the electrical wires and cables under consideration, equal to θ_0 = 20 °C [13].

Table 2 shows calculated according to (2) − (4) taking into account the quantitative data of Table 1 numerical values of the coefficient C_l for insulated wires and cables with copper (aluminum) cores (shells) with PVC, R and PET insulation for two cases possible in real practice of their exploitation: the case of their preliminary current load ($J_{Cll} \neq 0$) and the case of their complete de-energizing ($J_{Cll} = 0$).

Table 1

Basic electrophysical parameters of the material of current-carrying cores (shells) of insulated wires and cables in low- and high-current circuits of modern electrical engineering (electronics) at $\theta_0 = 20$ °C [13]

Material of the core (shell) of the wire (cable)	Numerical value of the parameter		
	γ_{0i}, $10^7\cdot(\Omega\cdot\text{m})^{-1}$	c_{0i}, $10^6\cdot\text{J}/(\text{m}^3\cdot{}^\circ\text{C})$	β_{0i}, $10^{-9}\cdot\text{m}^3/\text{J}$
Copper	5,81	3,92	1,31
Alunimum	3,61	2,70	2,14

Table 2

Numerical values of the coefficient C_l for insulated wires and cables with copper (aluminum) cores (shells) in low- and high-current circuits of modern electrical engineering (electronics) with nano-, micro- and millisecond current pulses $i_p(t)$ of various ATPs

Type of insulation in a wire (cable) of a low- and high-current circuit of electrical engineering and electronics	Material of the core (shell) of the wire (cable)	Numerical value of C_l, 10^8 A·s$^{1/2}$/m^2	
		J_{Cll}=0	J_{Cll}≠0
PVC, R	Copper	1,506	1,160
	Aluminum	0,972	0,745
PET	Copper	1,355	0,957
	Aluminum	0,877	0,616

As for the calculated definition in (2) of the action integral J_{CiA} of a single current pulse $i_p(t)$ with one or another ATPs, we first consider the case of a change in this type of electric current in time t according to the aperiodic law of the following form [2,15]:

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

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 the given ATPs, flowing in low- and high-current circuits of HPT, pulsed electrical engineering and electronics; $k_{p1} = [(\alpha_1/\alpha_2)^m - (\alpha_1/\alpha_2)^n]^{-1}$ is the normalizing factor; $m = \alpha_1/(\alpha_2 - \alpha_1)$; $n = \alpha_2/(\alpha_2 - \alpha_1)$; τ_f, τ_p are, respectively, the rise time at the level of (0.1–0.9) I_{mp} and the duration of the current pulse at the level of 0.5 I_{mp}; I_{mp} is the amplitude of the current pulse $i_p(t)$ flowing through the wire (cable).

In this electrophysical case, the expression for the action integral J_{CiA} flowing in low- and high-current circuits of the considered technique of the current pulse $i_p(t)$ takes at $t_p = 3\tau_p$ according to (2), (5) the following approximate analytical form:

$$J_{CiA} \approx k_{p1}^2 I_{mp}^2 [0{,}658\tau_p - 0{,}633\tau_f]. \qquad (6)$$

Next, consider the electrophysical case when changes in time t of the pulse current $i_p(t)$ acting on the electric wires (cables) of the indicated circuits of electrical engineering (electronics) occur according to the law of a damped sinusoid [2, 13]:

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

where $\delta = \Delta_p/T_p$ is the current damping coefficient; $\omega = 2\pi/T_p$ is the circular frequency of current oscillations; T_p is the period of current oscillations; $\Delta_p = \ln(I_{mp1}/I_{mp3})$ is the logarithmic decrement of pulse current $i_p(t)$ oscillations with the first I_{mp1} and the third I_{mp3} amplitudes in electrical circuits; $k_{p2} = [\exp(-\Delta_p/2\pi\cdot\text{arcctg}\Delta_p/2\pi)\sin(\text{arcctg}\Delta_p/2\pi)]^{-1}$ is the normalizing factor for the damped sinusoidal current $i_p(t)$ flowing in the wire (cable).

For the temporal shape (7) of the change in the wire (cable) of the current pulse $i_p(t)$ at $t_p = 3T_p$ in (2), the calculation expression for the action integral J_{CiA} of the current pulse $i_p(t)$ flowing in the investigated low- and high-current circuits of modern electrical engineering takes the following approximate analytical form:

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

Knowing the numerical values of I_{mp}, I_{mp1}, τ_f, τ_p, Δ_p and T_p from regulatory documents or experimental data, taking into account the calculated estimate of the values of the normalizing coefficients k_{p1} and k_{p2} for the indicated temporal shapes of changes in the pulse current $i_p(t)$ according to (2) – (8) we can in approximate form calculate (with an error of no more than 5 %), the permissible minimum cross-sections S_{Cil} of cores (shells) of electrical wires and cables used in circuits of HPT, power electrical engineering and electronics.

With regard to the applied problem being solved, the threshold values I_{mpk} of the amplitude I_{mp} of the current pulse $i_p(t)$ of the given temporal shape will correspond to the permissible short-term heating temperature $\theta_{CiS} = \theta_{IS}$ with this pulse current $i_p(t)$ of the electric wire and cable with the selected insulation. Therefore, from (2), taking into account (6), (8) and the data of Table 2, when the relation $S_{Ci} = S_{Cil}$ is fulfilled, the calculated threshold values I_{mpk} of the amplitudes I_{mp} and I_{mp1} of the axial current pulses $i_p(t)$ for the time shapes indicated according to (5), (7) flowing along the investigated insulated wires and cables in low- and high-current circuits of electrical engineering and electronics can also be determined in the considered approximation.

Calculation estimation of threshold amplitudes I_{mpk} of current pulses $i_p(t)$ of various ATPs for electrical wires and cables. In accordance with the above expressions (2), (5), (6) for the threshold value I_{mpk} of the amplitude I_{mp} of the aperiodic (unipolar) pulse of the axial current $i_p(t)$, acting on the current-carrying and insulating parts of the investigated electrical wires (cables), under the condition $S_{Ci} = S_{Cil}$, the following approximate calculated analytical relationship can be obtained:

$$I_{mpk} \approx S_{Ci} C_l k_{p1}^{-1} [0{,}658\tau_p - 0{,}633\tau_f]^{-1/2}. \qquad (9)$$

From (9) it can be seen that for given temporal parameters of the front τ_f and duration τ_p of the current pulse $i_p(t)$, known structural characteristics of wires and cables (values of their cross-sections S_{Ci}) and the selected operating mode of the CWP with the studied polymer insulation and the specified materials of its cores and shells (the known value of the coefficient C_l according to the data in Table 2), finding the desired value of the amplitude I_{mpk} will be reduced to determining, according to (5), the numerical value of the normalizing coefficient $k_{p1}>1$.

From (2), (7), (8) under the condition $S_{Ci} = S_{Cil}$ for the threshold value I_{mpk} of the first amplitude I_{mp1} of the damped sinusoidal pulse current $i_p(t)$ in the insulated wire and cable, the following approximate calculated analytical expression follows:

$$I_{mpk} \approx S_{Ci} C_l k_{p2}^{-1} [T_p (4\Delta_p)^{-1} - \Delta_p T_p (4\Delta_p^2 + 16\pi^2)^{-1}]^{-1/2} . \quad (10)$$

Similarly to (9), using (10) to find the calculated value I_{mpk} for a particular wire (cable) with known characteristics S_{Ci} and C_l (see Table 2) at given temporal parameters Δ_p и T_p for the discharge pulse current $i_p(t)$ flowing through the CWP will actually be reduced to the calculation according to (7) of the numerical value of the normalizing coefficient $k_{p2} \geq 1$.

According to (9), (10), the threshold values I_{mpk} of the amplitudes I_{mp} of aperiodic and damped sinusoidal current pulses $i_p(t)$ are directly proportional to the cross-sections S_{Ci} of the metal cores (shells) of the electrical wires and cables under study. In addition, the sought values of I_{mpk} are actually inversely proportional to the temporal parameters $\tau_p^{1/2}$ и $T_p^{1/2}$ for current pulses ${}_p(t)$flowing through the CWP.

Note that the calculated relations (9), (10) for determining the threshold values I_{mpk} of the amplitudes I_{mp} of the axial current pulses $i_p(t)$, varying in time t according to (5), (7) according to the aperiodic dependence and the law of the exponentially decaying sinusoid, cover a wide nomenclature of temporary shapes and ATPs of used in electrophysical practice single current pulses $i_p(t)$ flowing through current-carrying parts of wires and cables with PVC, R and PET belt insulation in modern pulsed power engineering, electrical engineering and electronics.

In low- and high-current circuits of the considered power engineering, electrical engineering and electronics with the temporal shapes of current pulses $i_p(t)$ flowing through their CWP used according to (5), (7) at $I_{mp}>I_{mpk}$, thermal overheating of the current-carrying parts of wires and cables will lead to destruction of their insulation, which reduces the working life of the CWP used in them.

Calculation estimation of the heating temperature θ_{Ci} of electrical wires and cables by current pulses $i_p(t)$ of various ATPs. For the purpose of computational verification of the formulas (9), (10) for choosing the threshold amplitudes I_{mpk} of the pulse current in the considered CWP, let us estimate the temperature θ_{Ci} of the Joule heating of the current-carrying parts of cables (wires) through which single current pulses $i_p(t)$ with specified ATPs flow. For this, we use the well-known nonlinear dependence of the electrical conductivity γ_{0i} of the material of the core (shell) of the wire (cable) on its current temperature θ_{Ci} [13]:

$$\gamma_{0i} \approx \gamma_{20i}\left[1 + c_{0i}\beta_{0i}(\theta_{Ci} - \theta_0)\right]^{-1} , \quad (11)$$

where γ_{20i} is the specific electrical conductivity γ_{0i} of the conductive material of the current-carrying parts of the CWP at the temperature of the surrounding air $\theta_{Ci}=\theta_0=20$ °C (for copper and aluminum these values of γ_{20i} are indicated in Table 1).

For used in CWP of pulsed power engineering, electrical engineering and electronics basic metals, (11) describes the temperature changes in their parameter γ_{0i} with an error of no more than ±5 % [13].

Taking into account (11) and data from [13], the solution of the inhomogeneous differential equation of thermal conductivity applied to the metal parts of the investigated cables (wires) of the adopted length l_0 with pulse current $i_p(t)$ of various ATPs for the current temperature θ_{Ci} of their Joule heating by the specified current under the initial condition $[\theta_{Ci}|_{(t=0)}-\theta_0] = 0$ can be written in the following approximate form:

$$\theta_{Ci} \approx \theta_0 + (c_{0i}\beta_{0i})^{-1}[\exp(J_{CiA}\gamma_{20i}^{-1}\beta_{0i} / S_{Ci}^2) - 1] . \quad (12)$$

It follows from (12) that the current temperature θ_{Ci} of heating by pulsed current $i_p(t)$ of various ATPs of current-carrying cores (shells) of the considered CWP is inversely proportional to the specific volumetric heat capacity c_{0i} (heat capacity per unit volume of metal) of their conductive materials, which for most metals in the solid phase varies depending on their temperature within ±10 % of its average numerical value [13]. We point out that for the thermophysical parameter c_{0i}, an equality of the form [13] is fulfilled: $c_{0i}=c_{\rho i}\cdot\rho_i$, where $c_{\rho i}$ is the heat capacity per unit mass of the homogeneous conductive material of the CWP (J/kg·°C) with its density ρ_i (kg/m^3). Therefore, in the investigated electrophysical case, we can say that the overall parameters of the CWP (except for the cross-section S_{Ci} of its cores and shells) at given ATPs of current pulses i $i_p(t)$ flowing through its metal parts do not affect the heating of cables (wires). This thermal process is attended, according to (12), by mainly the specific thermophysical parameters of the CWP (γ_{0i}, c_{0i} and β_{0i}) and the ATPs of the pulsed current $i_p(t)$ [13]. For short (with extremely small values of τ_p and T_p) current pulses $i_p(t)$, the heating zone of the CWP will be localized in very thin layers of its metal cores and shells. Taking into account the accepted assumptions and (12), we can conclude that in the considered adiabatic approximation, the length l_0 of the cable (wire) and, accordingly, the total mass of the metal parts of the CWP at $t \leq 3\tau_p$ or $t \leq 3T_p$ does not have a noticeable effect on the pulse heating temperature θ_{Ci} of these parts of the CWP. This influence on the temperature level θ_{Ci} will increase after the passage of the considered current pulses $i_p(t)$ through the current-carrying parts of the CWP, when, due to the thermal conductivity of their metal, the temperature will begin to equalize along the thickness of these parts.

In the case when the relation $S_{Ci} = S_{Cil}$ is fulfilled for the current-carrying metal parts of the cables and wires under consideration, taking into account (2), expression (12) is simplified and takes the following form:

$$\theta_{Ci} \approx \theta_0 + (c_{0i}\beta_{0i})^{-1}[\exp(\gamma_{20i}^{-1}\beta_{0i}C_l^2) - 1] , \quad (13)$$

where C_l is the constant coefficient, the numerical values of which for the considered polymer insulation of cables (wires) and the specified operating modes of their electrical circuits are given in Table 2.

Relation (13) can be just used in the calculated verification of the obtained expressions (9), (10) to find the numerical values of the threshold amplitudes I_{mpk} of the pulse current $i_p(t)$ in the considered CWP. According to the conditions we have adopted, at $S_{Ci} = S_{Cil}$, the calculated according to (13) temperature θ_{Ci} of heating of the current-carrying parts of the studied CWP should not exceed the accepted normalized permissible short-term temperature θ_{CiS} for it.

Examples of calculating the threshold amplitudes I_{mpk} of current pulses $i_p(t)$ of nano-, micro- and millisecond temporal ranges. As the investigated CWP, we choose a short radiofrequency coaxial medium-sized cable with solid PET insulation, brand RC 50-4-11 [12], having, at $l_0 \leq 10$ m, a round solid copper core with diameter of 1.37 mm ($S_{C1} \approx 1.474$ mm^2) and tinned braided copper shell (braid with twisting density of at least 95 %) with inner diameter of 4.6 mm and wall thickness of 0.15 mm ($S_{C2} \approx 2{,}059$ мм^2). We assume that this cable is placed in an air atmosphere at room temperature $\theta_0 = 20$ °C with the fulfillment of the condition for the current integral $J_{Cll} = 0$ in its electrical circuit (without preliminary current load of the cable at $\theta_{ll} = \theta_0$). From the given design data, it can be seen that the copper core of the selected RF cable brand RC 50-4-11 with cross-section $S_{C1} \approx 1.474$ mm^2 in comparison with its reverse external current conductor (copper braid with cross-section $S_{C2} \approx 2.059$ mm^2) will be less resistant to the electrothermal action of a current pulse $i_p(t)$ longitudinally flowing through them in opposite directions with specified ATPs. Let a single current pulse $i_p(t)$ flowing through the current-carrying parts of the adopted coaxial cable has an aperiodic temporal shape. Therefore, the specified core of the cable of the RC 50-4-11 brand can be an internal local hotbed of overheating of the current-carrying parts of this cable. In this regard, the continuous belt PET insulation adjacent to the copper core of the RC 50-4-11 radiofrequency cable may experience the effect of increased levels of the temperature field caused by the Joule heating of this copper core by the adopted current pulse $i_p(t)$ flowing through it. It is the copper core and the adjacent cylindrical zone of PET insulation of the RF cable of the adopted in applied calculations values I_{mpk} that will be the weak «links» in a possible chain of destructive processes in the cable under consideration. Taking into account the above, it can be concluded that the calculation estimation of the threshold values I_{mpk} of the amplitude I_{mp} of the used current pulse $i_p(t)$ of a given time shape for a radiofrequency cable of the brand RC 50-4-11 should be tied to the electrothermal state of a single-wire round copper core ($S_{C1} \approx 1.474$ mm^2) of this cable experiencing the thermal effect of an aperiodic current pulse $i_p(t)$.

1. First, we use a standard nanosecond current pulse of a temporal shape $\tau_f/\tau_p = 5$ ns/200 ns, which was used in a number of countries when simulating in high-current discharge electric circuits of HPT with multi-wire air systems of field formation and, accordingly, in their working air volumes with those tested for electromagnetic compatibility (durability) technical objects of various dimensions of a powerful electromagnetic pulse of a high-altitude nuclear explosion [4, 16]. From (5) we find that for this calculation case, the shape factors α_1 and α_2 of the nanosecond 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, for a given temporal shape of a unipolar current pulse $i_p(t)$, the normalizing factor k_{p1} according to (5) turns out to be approximately equal to $k_{p1} \approx 1.049$. Then from (9) at $k_{p1} \approx 1.049$, $C_l = 1.355 \cdot 10^8$ A·s$^{1/2}$/m^2 (see the corresponding data in Table 2) and $S_{Ci} = S_{C1} = 1.474$ mm^2 (cross-section of the copper cable core) for the threshold numerical value I_{mpk} the amplitude I_{mp} of the considered aperiodic current pulse $i_p(t)$ of the temporal shape $\tau_f/\tau_p = 5$ ns/200 ns in relation to the RF coaxial cable of the brand RC 50-4-11, we find that $I_{mpk} \approx 531.2$ kA.

2. Next, consider the standard microsecond aperiodic current pulse $i_p(t)$ of the time shape $\tau_f/\tau_p = 10$ µs/350 µs, which is now used in accordance with the requirements of the current International Standard IEC 62305-1-2010 [17] when testing power electrical equipment for resistance to the direct action of powerful short lightning electric discharges on it [18]. From (9) at $k_{p1} \approx 1.054$ ($\alpha_1 \approx 2.17 \cdot 10^3$ s^{-1}; $\alpha_2 \approx 2.37 \cdot 10^5$ s^{-1}), $C_l = 1.355 \cdot 10^8$ A·s$^{1/2}$/m^2 and section of a solid copper core $S_{Ci} = S_{C1} = 1.474$ mm^2 of the RC 50-4-11 RF cable under study for the threshold numerical value I_{mpk} of the amplitude I_{mp} of the considered aperiodic pulse of the axial current $i_p(t)$ of the time shape $\tau_f/\tau_p = 10$ µs/350 µs in the adopted cable we find that $I_{mpk} \approx 12.66$ kA.

3. At the end of the examples of applied calculations of threshold amplitudes I_{mpk} for the CWP, we use the standard millisecond aperiodic current pulse $i_p(t)$ of the temporal shape $\tau_f/\tau_p = 7$ ms/160 ms, which is now used in accordance with the requirements of the current US regulatory document SAE ARP 5412: 2013 [19] during full-scale electromagnetic tests of the main units and systems of aviation equipment for lightning resistance to direct exposure to them by the long-term component of the artificial lightning current [20]. For this current pulse $i_p(t)$in accordance with (9) at $k_{p1} \approx 1.078$ ($\alpha_1 \approx 4.75$ s^{-1}; $\alpha_2 \approx 3.38 \cdot 10^2$ s^{-1}), $C_l = 1.355 \cdot 10^8$ A·s$^{1/2}$/m^2 and a given cross-section of a copper core $S_{Ci} = S_{C1} = 1.474$ mm^2 of a radiofrequency coaxial cable of the RC 50-4-11 brand, it follows that the threshold numerical value I_{mpk} of the amplitude I_{mp} of the specified axial current pulse $i_p(t)$ of the temporal shape $\tau_f/\tau_p = 7$ ms/160 ms for it will be equal to about $I_{mpk} \approx 1.84$ kA.

One of the indicators of the reliability of the electrical engineering approach used by us and the approximate calculated relationship (9) obtained on its basis, used in the above examples of determining the threshold values I_{mpk} of the amplitudes I_{mp} of unipolar current pulses $i_p(t)$ of nano-, micro- and millisecond duration for a radiofrequency coaxial cable brand RC 50-4-11, is that the performance according to (13) in relation to these practical cases of finding the numerical values I_{mpk} of the estimated calculation of the heating temperature θ_{Ci} (at $\theta_0 = 20$ °C and $J_{Cll} = 0$) of the round solid copper core of the specified cable leads to a result equal to $\theta_{Ci} \approx 119.9$ °C. It can be seen that the calculated temperature level θ_{Ci} of Joule heating of the CWP in the cases under study does not exceed the permissible short-term temperature $\theta_{CiS} \approx 120$ °C, which is typical for electrical cables with PET insulation.

Conclusions.

1. An engineering technique has been developed for the approximate calculation of the threshold amplitudes I_{mpk} of single pulses of axial current $i_p(t)$ of various temporal shapes for electrical wires and cables with copper (aluminum) current-carrying parts and PET, PVC and R belt insulation used in low- and high-current pulse circuits of power engineering, electrical engineering and electronics. This technique is based on the electrothermal resistance of the polymer insulation of the considered CWP, which corresponds to the permissible short-term heating temperatures of current-carrying and insulating parts of its wires and cables and does not allow the occurrence of the phenomenon of thermal destruction in the belt insulation of the CWP.

2. Calculation analytical relationships (9), (10) are obtained for finding the threshold numerical values I_{mpk} of the amplitudes I_{mp} of the current pulses $i_p(t)$, which vary in time t according to the aperiodic dependence and according to the law of the exponentially decaying sinusoid, in the studied CWP. It is shown that at $I_{mp}>I_{mpk}$, due to thermal overheating of the current-carrying parts of the wires and cables under consideration, destruction of their belt insulation will occur, leading to a decrease in the service life of the CWP.

3. Examples of practical application of the proposed engineering methodology for the calculation definition for a radiofrequency coaxial medium-sized cable of the RC 50-4-11 brand with solid PET belt insulation of threshold amplitudes I_{mpk} of standard aperiodic current pulses $i_p(t)$ from nano-, micro- and millisecond temporal ranges of the shape τ_f/τ_p=5 ns/200 ns, τ_f/τ_p=10 μs/350 μs, and τ_f/τ_p=7 ms/160 ms are presented. It was found that with a corresponding increase in the parameter $\tau_p>>\tau_f$ for the indicated unipolar single pulses of current $i_p(t)$ flowing through a round solid copper conductor and a hollow split tinned copper braid of this cable, there is a significant decrease in their threshold amplitudes I_{mpk} (from 531.2 kA for a nanosecond current pulse of 5 ns/200 ns to 1.84 kA for millisecond current pulse of 7 ms/160 ms).

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