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Electrical engineering equipment for generating and measuring of complete pulse current of artificial lightning in the conditions of high-voltage electrophysics laboratory

Goal. *Decision of problem scientific and technical task on the reliable generating and measuring in the conditions of high-voltage electrophysics laboratory basic component of complete pulse current of artificial lightning with the rationed amplitude-temporal parameters (ATPs) with the use of the modernized generator of current of lightning of type of UITOM-1.* ***Methodology.*** *Bases of the applied electrical engineering, electrodynamics and electrophysics, electrophysics bases of technique of high-voltage and high pulse currents, bases of high-voltage pulse technique and measuring technique.* ***Results.*** *Information, which specify on a decision at Research and Design Institute «Molniya» of National Technical University «Kharkiv Polytechnic Institute» problem scientific and technical task, related to the reliable generating and measuring in the conditions of high-voltage electrophysics laboratory of complete pulse current of artificial lightning, which contains pulse A- (repeated pulse D-), intermediate B- and long-term C- (shortened long C*-) components of this current, is resulted, ATPs which answer the hard technical requirements of normative documents of the USA of SAE ARP 5412: 2013, SAE ARP 5414: 2013 and SAE ARP 5416: 2013. Short information is indicated about the applied electrical circuits of separate high-voltage generators of pulse currents of condenser type of GIC-A (GIC-D), GIC-B and GIC-C (GIC-C*), which it is worked as synchronous appearance on the general electrical loading in composition the modernized powerful high voltage generator of complete pulse e current of artificial lightning of type of UITOM-1, and in-use high-voltage measuring facilities which contain the heavy-current low-resistance shunts of type of SHK-300 for simultaneous registration with their help on examinee on stability to lightning devices objects of aviation and space-rocket technique of ATPs proper component of complete i pulse current of artificial lightning. Technical examples are resulted and the row of results of practical application of the indicated domestic powerful high-voltage proof-of-concept electrophysics equipment is described at the tests of elements of some aircrafts (ACs) on resistibility to the direct action on them of complete pulse current of artificial lightning with rationed ATPs.* ***Originality.*** *A problem is formulated and having the important applied value in area of aviation and space-rocket technique for the leading countries of the world scientific and technical task on the reliable generating and measuring in the conditions of high-voltage electrophysics laboratory indicated component of complete pulse current of artificial lightning with rationed ATPs and concrete electro-technological ways and hardware are indicated for its successful decision.* ***Practical value.*** *The use of the modernized powerful high-voltage generator of complete pulse current of artificial lightning of type of UITOM-1 developed in practice and created in Ukraine will allow to conduct the real verification on resistibility to the action of lightning of different side systems, devices and construction elements, containing metallic and composition materials, both again developed and modernized ACs, that will be instrumental in the increase of vitality of such ACs in the extreme terms of their flight and stay in an electrical active earthly atmosphere with flowing in it storm electrical discharges.* References 30, tables 3, figures 20.

Key words: **pulse current of artificial lightning, modernized high-voltage generator of current of lightning, shunt, generating, measuring, components of current of lightning.**

Приведені дані, які вказують на вирішення в НДПКІ «Молнія» НТУ «ХПІ» проблемної науково-технічної задачі, пов'язаної з надійним генеруванням і вимірюванням в умовах високовольтної електрофізичної лабораторії повного імпульсного струму штучної блискавки, що містить імпульсну A- (повторну імпульсну D-), проміжну B- і тривалу C- (укорочену тривалу C-) компоненти даного струму, які відповідають технічним вимогам нормативних документів США SAE ARP 5412: 2013, SAE ARP 5414: 2013 і SAE ARP 5416: 2013. Вказані відомості про застосовані електричні схеми окремих високовольтних генераторів імпульсних струмів конденсаторного типу ГІС-A (ГІС-D), ГІС-B і ГІС-C (ГІС-C*), що синхронно працюють на загальне електричне навантаження у складі модернізованого потужного високовольтного генератора струму штучної блискавки типу УИТОМ-1, і використовувані високовольтні вимірювальні засоби, які містять удосконалені низькоомні шунти типу ШК-300 для одночасній реєстрації за їх допомогою на випробовуваних на блискавкостійкість пристроях об'єктів авіаційної і ракетно-космічної техніки амплітудно-часових параметрів (АЧП) відповідних компонент повного імпульсного струму штучної блискавки. Приведені технічні приклади і описані деякі результати практичного застосування вказаного модернізованого вітчизняного високовольтного електрофізичного обладнання при випробуваннях елементів вітчизняних літальних апаратів на стійкість до прямої дії на них основних компонент імпульсного струму штучної блискавки з нормованими АЧП.* Бібл. 30, табл. 3, рис. 20.

Ключові слова: **імпульсний струм штучної блискавки, модернізований високовольтний генератор струму блискавки, шунт, генерування, вимірювання, компоненти струму блискавки.**

Relevance of the topics. The direct (indirect) effect of powerful natural thunderstorm long spark discharges (lightning) on objects of aviation and rocket and space technology during their stay in the Earth's electrically active atmosphere can lead to accidental damage to their metal (composite) structural parts (elements) and irreversible failure of their electrical equipment and on-board systems (for example, computer equipment, control, navigation and communication systems), which can have catastrophic consequences [1-7]. No less dangerous are direct lightning strikes to ground technical objects (for example, TV and radio antennas, energy objects and their overhead power lines) [1, 3, 8]. Here, the main factors of damage to the specified objects are powerful electromagnetic disturbances arising from the propagation of a high-current plasma channel of lightning in the air and causing the appearance in the on-board (internal) electrical circuits of these objects of large electrical currents (overvoltages and shock currents caused by them), as well as large pulse currents flowing in the zone of local attachment of the lightning plasma channel on their surfaces and which are characterized by strong electrothermal and electrodynamic action [1, 3, 9]. In this regard, various electrotechnical approaches and surge protection devices are used for lightning protection of the specified technical objects [1-3, 10, 11].

According to [4-9], a reliable method of checking the used electrotechnical approaches and fail-safe devices when providing lightning protection equipment and systems for both aircrafts (ACs) and ground objects is their full-scale test for the direct (indirect) effect of powerful artificial thunderstorm spark discharges reproduced in the conditions of a high-voltage electrophysical laboratory. For the practical implementation of such electromagnetic tests of ACs and other technical objects, appropriate powerful high-voltage electrical test equipment is required.

In [7, 9], the circuit of a high-voltage electrical installation is indicated, which allows, in accordance with the technical requirements of the NATO Standard AESTR-500: 2016, to form an aperiodic current pulse of a time shape of 50 μs/500 μs with amplitude of up to ±10 kA on various devices and systems of ACs tested for lightning resistance at constant voltage of the electric charge of its capacitor bank up to ±2 kV. At the same time, in accordance with the technical requirements of US regulatory documents [12-14], other amplitude-time parameters (ATPs) of individual components of the full pulse current of artificial lightning are required during lightning resistance tests of on-board systems, component parts and elements of the aircraft (Table 1).

Table 1*

Normalized ATPs of the main components of the full pulse current of artificial lightning [12-14]

Lightning current component	I_{mL}, kA	I_c, kA	q_L, C	J_a, 10^6 J/Ω	τ_f, μs	τ_{p1}, ms
A	200±20	–	–	2±0,4	≤50	≤0,5
B	–	2±0,4	10±1	–	–	5±0,5
C	0,2-0,8	–	200±40	–	–	$(0,25\text{-}1)\cdot 10^3$
C*	–	≥0,4	6-18	–	–	15-45
D	100±10	–	–	0,25±0,05	≤25	≤0,5

*Note. I_{mL} – the amplitude of the lightning current pulse; $I_c \approx q_L/\tau_p$ – the average value of the pulse current; q_L – the amount of charge flowing in the current pulse; J_a – the integral of the action of the lightning current pulse; τ_f, τ_{p1} – respectively, the duration of the front of the current pulse between the levels (0.1-0.9) I_{mL} and the duration of the lightning current pulse at the level ≤0.1 I_{mL}

At the same time, it should be noted that, according to [12-14], depending on the AC's area affected by lightning in the Earth's atmosphere, its full pulse current may contain the following main components, the ATPs of which differ significantly from each other: pulse *A*- (repeated pulse *D*-), intermediate *B*- and long-term *C*- (shortened long *C**-) components. Moreover, in the practice of electromagnetic tests on the lightning resistance of technical devices and on-board systems of civil and military ACs, the following combinations of the specified components of the full pulse current of artificial lightning are most often used [9, 12-14]: *A*-, B- and *C*-components (area 3 of damage); *A*-, *B*- and *C**-components (area 1*A* of damage); *D*-, *B*- and *C**-components (area 2*A* of damage). The sequence of flow of these components of the lightning current for the corresponding zones of damage to the AC in the atmospheric air by the lightning discharge must correspond to the order indicated above, and each of the given components of the lightning current must monotonically transition into another one.

To meet the technical requirements [12-14], [15] shows a diagram of a powerful high-voltage electrical installation, which was intended for testing on-board systems and AC elements for lightning resistance. The practice of operating a powerful lightning current generator (LCG) according to [15] revealed a number of technical deficiencies in its construction circuits and operation: insufficient protection of the used high-voltage capacitors in a total number of several hundred pieces of pulse current generators (PCGs) of LCG from emergency shock currents with amplitude of up to ±500 kA in the microsecond time range; lack of recommendations for the simultaneous selection of the lengths h_1–h_3 of the insulating air gaps in the used high-voltage high-current commutators of PCG when changing the levels of their charging electric voltage U_c, as well as the length h_e of the air gap between the edge of the electrically explosive wire (EEW) and the tested sample (TS) of the AC; the presence of cases of non-synchronous parallel operation in the LCG circuits of its individual generators GIC-*A*, GIC-*D*, GIC-*B*, GIC-*C** and GIC-*C* on the total $R_L L_L$ – the load of the TS of the corresponding AC, which excludes obtaining the necessary according to the requirements [12-14] test pulses of artificial lightning current.

From the data in Table 1 for the indicated ATPs, the component of the full pulse current of artificial lightning and the application of the necessary for their practical production of the PCG, built on the basis of individual high-voltage LCG of the capacitor type, it follows that the development and creation of such PCG in the field of high-voltage pulse technology (HPT) is a complex scientific and technical task. At the same time, the one related to the simultaneous registration from one high-voltage measuring device at once of at least three components of the pulse current of artificial lightning with ATP, which are sharply different from each other, turns out to be an equally difficult task. One of the indirect confirmations of this is the fact that at present we do not know the electrotechnological construction circuits and technical designs of similar high-voltage PCGs and means for measuring lightning currents, which were given in the open literature of the leading countries of the world.

The goal of the article is to solve the problematic scientific and technical task of reliable generation and measurement in the conditions of a high-voltage electrophysical laboratory of the main components of the full pulse current of artificial lightning with normalized ATPs using a modernized PCG of the UITOM-1 type.

1. Electrotechnological circuits of the construction of a powerful UITOM-1 type PCG. Figure 1 shows the modernized electrical circuit of the construction of a powerful high-voltage PCG of the UITOM-1 type [16], which includes five separate high-voltage LCG (GIC-*A*, GIC-*D*, GIC-*B*, GIC-*C* and GIC-*C**) with the possibility of their parallel and reliable synchronous operation on a common low-impedance active-inductive $R_L L_L$ – load in the mode selected by the researcher for the formation of the corresponding components of the full pulse current of artificial lightning. The necessary combination of the components of the full pulse current of artificial lightning and the corresponding powerful high-voltage PCG, specified in accordance with the technical requirements of the specified regulatory documents [12-14], is carried out with the help of electrical switches X1-X4 (Fig. 1) and which allow them to be manually switched on or off from the electromagnetic circuit of TS tests.

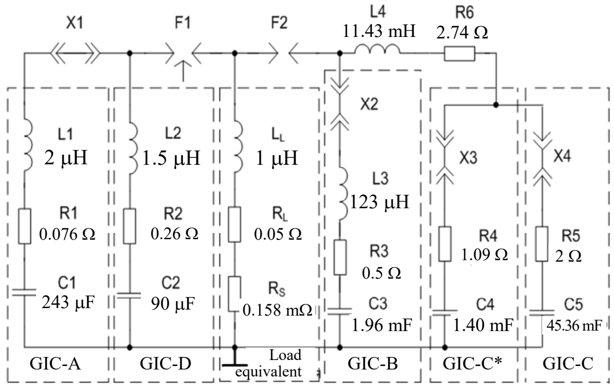


Fig. 1. Improved electrical circuit for the construction of a powerful high-voltage PCG of the UITOM-1 type with one common electric R_LL_L – load and discharge circuits of its separate high-voltage generators working in parallel GIC-*A*, GIC-*D*, GIC-*B*, GIC-*C* and GIC-*C** (F_1, F_2 – three- and two-electrode high-current air commutators for nominal constant voltage of ±50 kV and ±5 kV; X1-X4 – electrical switches; R_S ≈(0.158±0.005) mΩ – active resistance of the SHK-300M1 type measuring shunt; R1- R5, *R*1-*R*5, *L*1-*L*3 – intrinsic electrical parameters of discharge circuits of high-voltage generators GIC-*A*, GIC-*D*, GIC-*B*, GIC-*C** and GIC-*C*; *R*6, *L*4 – electrical parameters of forming *RL* elements for discharge circuits of high-voltage generators GIC-*C* and GIC-*C**) [16]

It should be noted that the GIC-*D* generator in the improved LCG circuit of the UITOM-1 type is assembled from 30 parallel-connected pulse capacitors of the IK-50-3 type, which are part of the GIC-*A* generator. In this regard, during the operation of GIC-*D* in the electrical circuit of the LCG, the switch X1 is removed and the GIC-*A* generator is switched off from the working circuit of the LCG (Fig. 1). This decision allows to significantly save time and material resources when creating this LCG.

With the selected electrical circuit for the formation of the necessary components, according to the requirements [12-14], the full pulse current of artificial lightning, reliable synchronization of the operation of the corresponding PCG in the LCG is ensured by the supply from a separate high-voltage pulse generator of the GVZI-100 type [16] to the middle control steel electrode of the three-electrode air switch F_1 (Fig. 2) for nominal constant voltage of ±50 kV of high-voltage rapidly decaying sinusoidal voltage pulse with amplitude of ±100 kV of microsecond duration, which causes activation of both air switch F_1 (see Fig. 1, 2) and two-electrode air switch F_2 (Fig. 3) for nominal DC voltage of ±5 kV. To ensure reliable operation of the three-electrode commutator F_1 of the improved LCG, the polarity of this voltage pulse from the GVZI-100 generator is selected opposite to the charge polarity of the capacitor batteries of the used PCG. Our modernized electrotechnological circuit for artificial lightning pulse current introduction into the TS contains, in accordance with the requirements of regulatory documents [12-14], a thin copper EEW with diameter of ~0.1 mm and length of l_e≈50 mm, separated from the surface of the TS by air gap of length h_e≈2 mm. During the electric explosion (EE) of a thin EEW above the surface of the TS in the local zone of introduction into it of the given components of the simulated lightning current from a powerful LCG, a low-temperature plasma is formed, through which the charges of the pre-charged high-voltage capacitor batteries of the LCG flow into the investigated TS. In Fig. 4 with the help of a Canon A-530 type digital camera, the moment of synchronous activation of the indicated air switches F_1 and F_2 and the explosion of the EEW in the formation circuit using an improved powerful UITOM-1 type LCG (see Fig. 1) of standardized *A*-, *B*- and *C**- components of the full current of artificial lightning (area 1*A*) was recorded in the TS of one of the devices of the domestic AC [17].

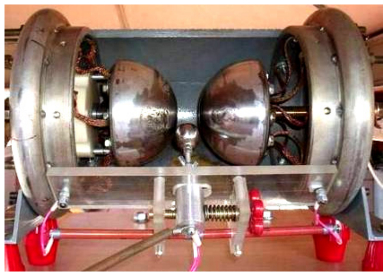


Fig. 2. General view of the high-voltage three-electrode high-current air commutator F_1 of cascade type with massive main hemispherical electrodes made of steel St. 3 grade at nominal constant voltage of ±50 kV and pulse current with amplitude I_{mL} up to ±300 kA [16]

Fig. 3. General view of the high-voltage two-electrode high-current air commutator F_2 with graphite electrodes of a rectangular shape for nominal constant voltage of ±5 kV and charge q_L up to ±300 C, which is placed in the discharge circuit of a powerful LCG of the UITOM-1 type [16]

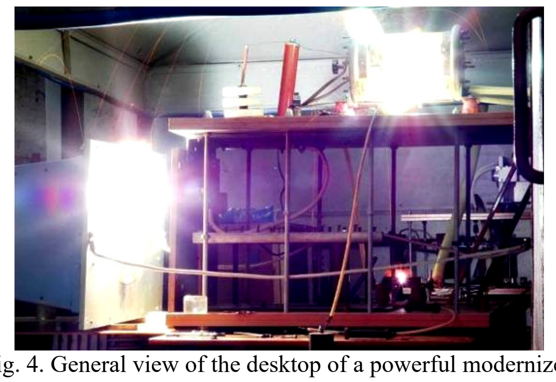


Fig. 4. General view of the desktop of a powerful modernized LCG of the UITOM-1 type at the moment of synchronous electrical activation of three charged powerful high-voltage test generators of pulsed currents GIC-*A*, GIC-*B* and GIC-*C** during lightning resistance tests (area 1A) of the TS of the device of the domestic LA [17]

Let us point out that when the charging constant voltage U_{c1} in powerful high-voltage generators GIC-*A* and GIC-*D* changes in the range $U_{c1} \approx \pm(28-33)$ kV in the three-electrode commutator F_1 (Fig. 2), the length of the air gaps between its steel (two main and one controlling) the electrodes should numerically be $h_1 \approx 4$ mm and $h_2 \approx 9$ mm, and when changing the charging DC voltage U_{c2} in high-voltage generators GIC-*B*, GIC-*C* and GIC-*C** in the range $U_{c2} \approx \pm(3.6-4.5)$ kV in the two-electrode commutator F_2 (Fig. 3), the length of the air gap between its graphite electrodes is chosen equal to $h_3 \approx 3$ mm [16]. At the same time, the physical conditions for atmospheric air must correspond to [18]: pressure $P_a \approx (1.013 \pm 0.015) \cdot 10^5$ Pa; absolute temperature $T_a \approx (293.15 \pm 10)$ K; relative humidity $\beta_a \approx (45 \pm 25)$ %.

Note that in Fig. 4, on the left is the TS of the AC device with the corresponding copper EEW, which glows brightly when its EE is in the discharge circuit of a powerful LCG and which is connected to the non-potential (grounded) steel electrode of the commutator F_1 (Fig. 1); above, we can see the F_1 commutator of a powerful LCG with a high-current pulse spark that glows brightly, rigidly fixed on the desktop; at the bottom of the LCG desktop, the F_2 commutator is shown with its pulse spark channel, which also glows brightly.

Figure 4 visually illustrates the correctness of the electrotechnological solutions proposed and indicated by us above to ensure reliable synchronous parallel operation of individual high-voltage generators GIC-*A* (GIC-*D*), GIC-*B* and GIC-*C* (GIC-*C**) when creating a modernized powerful UITOM-1 type LCG.

Table 2 shows the main electrical characteristics of individual high-voltage generators GIC-*A*, GIC-*B*, GIC-*C*, GIC-*C** and GIC-*D*, which are part of the improved powerful UITOM-1 type LCG.

Table 2

Technical characteristics of the generators GIC-*A*, GIC-*B*, GIC-C, GIC-*C** and GIC-*D*, which are included in the UITOM-1 type LCG

PCG name	Number of capacitors	Type of capacitors	Total capacity C_g, mF	Energy intensity W_g, kJ
GIC-*A*	111	IK-50-3	0,333	416,2
GIC-*B*	14	IM-6-140	1,96	24,5
GIC-*C*	324	IM-5-140	45,36	567,0
GIC-*C**	10	IM-6-140	1,4	17,5
GIC-*D*	30	IK-50-3	0,09	112,5

From the data in the Table 2 it follows that the total number of high-voltage pulse capacitors with a metal case of three types (IK-50-3, IM-6-140 and IM-5-140 [19]) in a powerful UITOM-1 type LCG is 489. At the same time, the total nominal electrical energy $W_{g\Sigma}$ stored by the high-voltage pulse capacitors of this LCB is equal to $W_{g\Sigma} \approx 1.25$ MJ. At the price of 1 kJ of electric energy stored by powerful high-voltage electrophysical equipment of the capacitor type, equal to the application case of its formation on an electrical load of pulse currents of micro- and millisecond duration of approximately \$1000 [20-22], the cost of construction of such a powerful high-voltage LCB will be at least \$1.25 million. As we can see, the development and creation of a powerful high-voltage, high-current LCB of the UITOM-1 type (Fig. 5) is associated not only with significant scientific and technical difficulties, but also with large financial costs.

Fig. 5. General view of the improved powerful high-voltage LCB of the UITOM-1 type (in the foreground is a work table with a three-electrode switch F_1 for nominal constant voltage of ±50 kV and an air extraction system, and in the background is an individual high-voltage powerful generators GIC-*A* (GIC-*D*), GIC-*B*, GIC-*C* and GIC-*C**)

It is important to point out that in the improved LCB of the UITOM-1 type, all high-voltage pulse capacitors of generators GI*S*-*A*, GIC-*D*, GIC-*B*, GIC-*C* and GIC-*C** are equipped with resistive systems to protect them from the action of emergency shock currents in the LCB [23].

The data of the system of reliable protection of impulse capacitors in the modernized LCB are based on the use of high-voltage constant graphite-ceramic resistors of the TVO-60 type with nominal value of 24 Ω and 100 Ω [24], which sharply limit the operation of the LCB in emergency modes (for example, in the event of an electrical breakdown of the internal or external insulation of its pulse capacitors) shock pulse currents and dissipate the thermal energy released at the same time on them.

Thanks to:

- performed modernization in accordance with the technical solution [23] of resistive circuits for protection against emergency shock pulse currents with calculated amplitude of up to ±500 kA of high-voltage pulse capacitors of separate powerful generators GIC-*A* (GIC-*D*), GIC-*B*, GIC-*C* and GIC-*C** (Table 2),
- improvement of the circuit of controlled electric start from a separate high-voltage generator type GVZI-100 [16] of the three-electrode air commutator F_1 (Fig. 2) and the two-electrode air commutator F_2 (Fig. 3),
- recommended simultaneous selection of the lengths h_1-h_3 of the air gaps in the used high-voltage commutators F_1 and F_2 of the high-current discharge circuits of the specified LCBs and the length h_e of the air gap between the edge of the EEW and the TS of the object, the modernized PCG of the UITOM-1 type, despite the similarity of the electrotechnological circuits used earlier in the PCG [15] for the construction of discharge circuits of the corresponding LCGs (Fig. 1), has a significant difference from the PCG, which was proposed in [15]. This difference of powerful high-voltage PCG ensures more reliable operation of the modernized PCG of the UITOM-1 type in comparison with PCG [15] when generating pulses of full current of artificial lightning (Table 1) according to technical requirements [12-14].

2. Results of measurement of the main components of artificial lightning current in the discharge circuit of a powerful UITOM-1 type PCG. In [25, 26], the main methods of measuring ultra- and high-pulse voltage in electrical installations during tests of various electrical engineering and electric power equipment are given. As for the methods of measuring high pulse currents (HPC) in the field of HPT, certain technical techniques and means for this were given in [20-22, 27, 28]. Unfortunately, for the practical implementation of complex metrological tasks related to the simultaneous measurement of a number of components of the full pulse current of lightning in a powerful PCG of the UITOM-1 type, given in [20-22, 27, 28], materials and data on high-voltage measuring devices designed for simultaneous registration with the help of one meter, both HPC (with amplitude I_{mL} of tens and hundreds of kiloamperes) and relatively weak pulse currents (with amplitude I_{mL} of hundreds and tens of amperes) in a wide time interval of their flow in the discharge circuits of its series of parallel operating LPC (from units microseconds to hundreds of milliseconds), was not enough. In connection with this, the authors had to independently develop, create and modernize non-standardized high-voltage high-current meters of similar electric pulse currents, which are able to reliably register the necessary components of the pulse current of artificial lightning on the total electric R_LL_L – load when individual high-voltage LCG of this PCG is activated [16, 17, 29, 30].

Figures 6-10 show the main typical oscillograms of pulse *A*-, intermediate *B*-, long-term *C*-, shortened long *C**- and repeated pulse *D*- components of the full pulse current of artificial lightning with normalized ATPs according to [12-14], which were obtained in a high-current discharge circuit of a powerful high-voltage PCG of the UITOM-1 type, which contains the lightning resistance-tested TS made of aluminum alloy D16 of the fuel tank skins of one of the modernized domestic aircraft «An» [17].

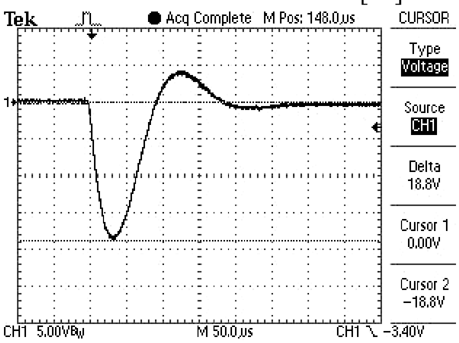


Fig. 6. Oscillogram of the pulse *A*- component of the artificial lightning current with normalized ATP in the discharge circuit of the GIC-*A* generator of the powerful UITOM-1 type PCB (U_{c1}≈–29.7 kV; I_{mA1}≈–211.7 kA; J_{aA}≈2.09·10^6 J/Ω; t_{mA1}≈32 – time corresponding to the first amplitude I_{mA1}; τ_{fA}≈t_{mA1}/1.6≈20 µs; τ_{p1A}≈500 µs; vertical scale – 56.3 kA/div; horizontal scale – 50 µs/div)

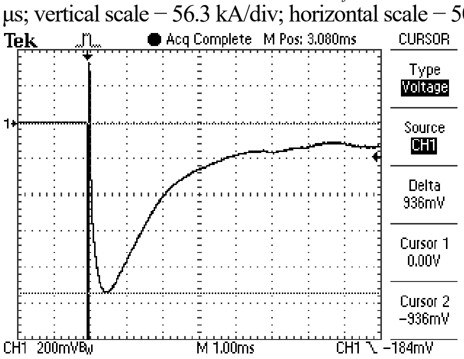


Fig. 7. Oscillogram of the intermediate *B*- component of the artificial lightning current with normalized ATP in the high-current discharge circuit of the high-voltage generator GIC-*B* of the powerful PCG type UITOM-1 (U_{c2}≈–4 kV; I_{mB}≈–5.27 kA; I_{cB}≈–2.08 kA; q_{LB}≈–10.4 C; τ_{p1B}≈5 ms; vertical scale – 1126 A/div; horizontal scale – 1 ms/div)

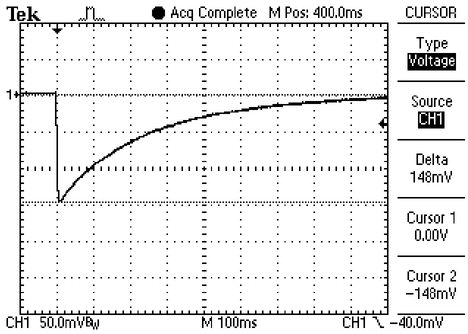


Fig. 8. Oscillogram of the long-term *C*- component of the full current of artificial lightning with normalized ATP in the discharge circuit of the high-voltage GIC-*C* generator of the powerful PCG of the UITOM-1 type (U_{c2}≈–4 kV; I_{mC}≈–833 A; q_{LC}≈–186.2 C; τ_{fC}≈7 ms; τ_{p1C}≈1000 ms; vertical scale – 281.5 A/div; horizontal scale – 100 ms/div)

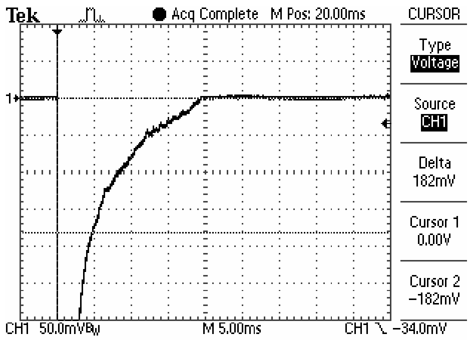


Fig. 9. Oscillogram of the shortened long-term *C**- component of the full pulse current of artificial lightning with normalized ATP in the discharge circuit of the high-voltage generator GIC-*C** of the powerful PCG type UITOM-1 (U_{c2}≈–4 kV; I_{mC*}≈–1148 A; τ_{pC*}≈14.8·ms; q_{LC*}≈–6.16 C; I_{cC*}≈q_{LC*}/τ_{pC*}≈–416 A)

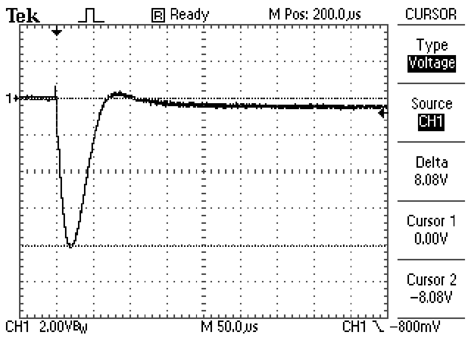


Fig. 10. Oscillogram of the repeated pulse *D*- component of the full pulse current of artificial lightning with normalized ATP in the discharge circuit of the GIC-*D* generator of the powerful high-voltage PCG of the UITOM-1 type (U_{c1}≈–33 kV; I_{mD1}≈–102 kA; t_{mD1}≈20 µs – time, which corresponds to the amplitude I_{mD1}; τ_{fD}≈t_{mD1}/1.6≈12.5 µs; τ_{p1D}≈500 µs; J_{aD}≈0.26·10^6 J/Ω)

The powerful high-voltage PCG of the UITOM-1 type is equipped with several high-current meters (improved disk coaxial low-resistance shunts of the ShK-300 type) of artificial lightning pulse current components, the main technical characteristics of which are given in Table 3.

The novelty of shown in Fig. 6-10 oscillograms consists in the fact that they are obtained on the specified TS with the help of modernized electrotechnological circuits for the formation of these components of the full pulse current of artificial lightning in the discharge circuit of the UITOM-1 type PCG, as well as high-voltage measuring devices, which are based on high-current low-resistance shunts of the type ShK-300 (Table 3). Note that for the simultaneous measurement of several components of the full pulse current of artificial lightning, generated in the discharge circuit of the improved high-voltage PCG of the UITOM-1 type, it was necessary to develop and create a measuring matching special voltage divider (SVD), which is connected at the output of the used in similar high-voltage measurements of the cable communication line (Fig. 11).

The modernization of the measuring instruments carried out by us was to exclude, when measuring in the discharge circuit of a high-voltage PCG of the UITOM-1 type of the corresponding components of the artificial lightning current, a high electric potential enters the channels of digital storage oscilloscopes (DSOs). As it is known, applying such a potential to the input of the DSO leads to its failure. The following new technical solution was proposed: the radio-frequency coaxial cable of the length l_c of the communication line, which connects the measuring shunt of the ShK-300 type with the SVD and the DSO, must be placed in an additional copper braid screen, which must be securely grounded before the SVD.

Fig. 11. General view of a high-voltage measuring shunt of the ShK-300M type, connected to the input of an additionally shielded radio-frequency coaxial cable of the RK 75-7-11 brand l_c≈70 m long, the output of which is connected to the input of the SPN-300 shielded matching voltage divider with two output coaxial 1:1 and 1:2 connectors for the coordinated connection of the measuring channels of three DSOs to them (for example, Tektronix TDS 1012 series) with simultaneous registration in the discharge circuit of a powerful UITOM-1 type PCG at once of three components of the full pulse current of artificial lightning with different ATPs [16]

Table 3*

Main technical characteristics of high-voltage high-current shunts of the ShK-300M, ShK-300M1 and ShK-300M2 type

Shunt name	Value of the characteristic			
	R_S, mΩ	K_S, A/V	L_S, nH	Mass, kg
ShK-300M	0,178±0,005	K_{SA}≈11260 K_{SC}≈5630	10±0,3	3,0
ShK-300M1	0,158±0,005	K_{SA}≈12625 K_{SC}≈6312	10±0,3	3,1
ShK-300M2	0,080±0,003	K_{SA}≈25000 K_{SC}≈12500	10±0,3	3,2

*Note. R_S, L_S – the active resistance (mΩ) and inductance (nH) of the shunt; K_S≈2/R_S – the shunt conversion factor, A/V; K_{SA} – the shunt conversion factor when measured in the discharge circuit of the UITOM-1 type PCG the ATPs of *A*- and *D*- components of the artificial lightning current, A/V (from the 1:1 connector of the SPN-300 type divider [16]); K_{SC} – the shunt conversion factor when measured in the discharge circuit of the UITOM-1 type PCG of the ATPs of *B*-, *C*- and *C**- component of the artificial lightning current, A/V (from the 1:2 connector of the SPN-300 type divider [16]).

Figure 12 shows the electrical diagram of the coordinated connection of the high-voltage shunt of the ShK-300M1 type with its measuring coaxial resistor (MCR) to the measuring coaxial cable (MCC), SVD and the corresponding DSO.

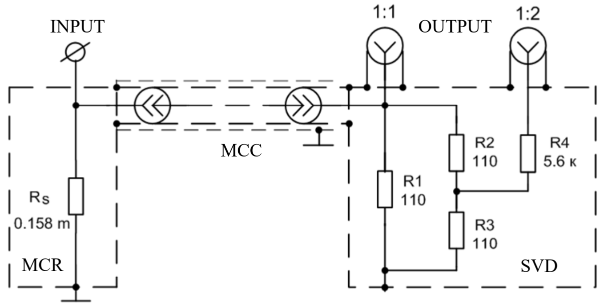


Fig. 12. Schematic electrical diagram of connecting a high-voltage shunt of the SHK-300M1 type to a low-voltage measuring circuit of a communication cable line and DSO (the shunt MCR with an active resistance R_S≈0.158 mΩ, which is connected to the input of the communication line cable; MCC brand RK 75-7-11 of the triaxial communication line; SVD, which coordinates the operation of the shunt, MCC and DSO inputs and is connected to the output of the MCC, which transmits an electrical signal from the zone of the steel disk of the shunt to the SVD and DSO)

According to Fig. 12, we can see that at the output of the MCC cable, the additional copper cylindrical shield of which is reliably grounded before the SVD, the SVD is connected, which coordinates the operation of the shunt, the MCC and the inputs of the DSO and which is made of concentrated resistors R1−R3 with nominal value of 110 Ω with total active resistance equal to the wave resistance of the MCC cable Z_c ≈ 75 Ω. The task of the SVD applied in the circuit of the high-voltage shunt of the ShK-300M1 type is to ensure not only the agreed mode of operation of the measuring circuit of this shunt, but also the simultaneous registration of several oscillograms of the corresponding components of the full current of artificial lightning of micro- and millisecond duration with amplitude values that differ sharply. For this purpose, this SVD was equipped with two output coaxial connectors 1:1 and 1:2 (Fig. 12).

To strengthen the mutual decoupling of coaxial connectors 1:1 and 1:2 in the SVD by increasing the input resistance of the output connector 1:2, an additional concentrated resistor R4 with nominal value of 5.6 kΩ is electrically connected to its potential electrode (see Fig. 12). At the same time, the SVD is performed in the form of a separate low-voltage device that is connected to the output of the MCC coaxial cable of an additionally shielded triaxial communication line and is placed in a shielded metal case (see Fig. 11), which must be reliably isolated from the grounded edge of the additional copper cylindrical screen of the MCC.

The SPN-300 type voltage divider (Fig. 11) has two coaxial connectors 1:1 and 1:2, which are designed for the coordinated connection of the corresponding outputs to the inputs of the measuring channels of the DSO. At the same time, according to Table 3, the specified connectors 1:1 and 1:2 of SPN-300 are characterized by different conversion factors K_S of the used measuring shunts when registering with their help ATPs as *A*- and *D*- components of artificial lightning current (in this case they are denoted as K_{SA}), as well as *B*-, C- and *C**- components of artificial lightning current (in this case they are designated as K_{SC}).

Figure 13 shows a general view of the improved measuring high-current disk shunt of the ShK-300M1 type, used in the discharge circuit of the powerful UITOM-1 type PCG.

Fig. 13. General view of a high-voltage measuring shunt of the ShK-300M1 type, connected to the collector of a high-current discharge circuit of a powerful UITOM-1 type PSG

Coaxial designs of measuring shunts of the ShK-300 type (Table 3), which are used as part of a powerful high-voltage PSG of the UITOM-1 type, are characterized by small values of their own electrical parameters – inductance L_S (no more than 11 nH) and active resistance R_S (no more than 0.2 mΩ), which ensures a small influence of the R_SL_S − parameters of the measuring shunts on the electromagnetic processes occurring in the R_LL_L − load (see Fig. 1).

Figure 14 schematically shows the design of the measuring high-voltage high-current shunt of the ShK-300M2 type in its longitudinal section.

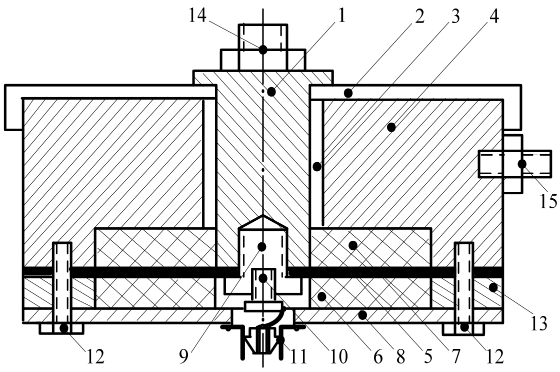


Fig. 14. Schematic representation of the improved design of the high-voltage coaxial disk shunt of the ShK-300M2 type in its longitudinal axial section (1 − massive internal cylindrical brass electrode; 2, 3 − insulating bushings made of fluoroplastic; 4 − massive external cylindrical brass electrode; 5 − measuring high-resistance steel disc of thickness h_S =2 mm; 6, 7 − massive pressing insulating discs; 8 − banded brass disc; 9, 10, 12 − steel fastening screws; 11 − output coaxial connector type SR-75; 13 − massive brass clamping ring; 14, 15 − input (potential) and output (grounded) elements of the brass bolt connection of the shunt to the high-current discharge circuit of the powerful UITOM-1 type PSG

A significant difference between the improved designs of high-voltage high-current shunts of the ShK-300M1 and ShK-300M2 type [16, 29, 30] from the ShK-300M shunt specified in [15] is the use of a high-resistance manganin disc instead of a thin-walled (thickness h_S≈0.3 mm) disc. which is subjected to huge electrothermal and electrodynamic shocks measured in the discharge circuit of the LCG of powerful pulses of the full current of artificial lightning and from which the drop of the pulse voltage U_S from the passage of the corresponding components of the pulse current of artificial lightning through it is removed, a disk with thickness of h_S = (1-2) mm of stainless steel grade 12X18H10T. The practice of operating a measuring shunt of the ShK-300M type with a manganin disc as part of the LCG according to [15] showed that after ~100 measurements, its disc cannot withstand the further action of powerful electrothermal loads and it fails.

Using the data of Table 3 and the numerical indicators (in fractions or units of volts) registered on the DSO screen using a high-voltage measuring shunt of the corresponding type of pulse voltage drop U_S, the desired value of the pulse current I_L of artificial lightning, which is generated and measured in laboratory conditions in the LCG circuit, is determined in the form: $I_L \approx K_S \cdot U_S$.

When deciphering the oscillograms (Fig. 6-10) obtained in the discharge circuit of a powerful PCG type UITOM-1 of the main components of the pulse current of artificial lightning and determining the numerical values of their ATPs, the following calculation analytical relationships can be used:

- for sinusoidal decaying current in the discharge circuit of a modernized PCG of the UITOM-1 type:

- when calculating the action integrals J_{aA} and J_{aD}, respectively, for *A*- and *D*- components of the artificial lightning current:

$$J_{aA} \approx k_A^2 I_{mA1}^2 [T_A (4\Delta_A)^{-1} - \Delta_A T_A /(4\Delta_A^2 + 16\pi^2)]; \quad (1)$$

$$J_{aD} \approx k_D^2 I_{mD1}^2 [T_D (4\Delta_D)^{-1} - \Delta_D T_D /(4\Delta_D^2 + 16\pi^2)], \quad (2)$$

where $I_{mA1}(I_{mD1})$, $I_{mA3}(I_{mD3})$, $T_A(T_D)$, $\Delta_A(\Delta_D)$ are, respectively, the first and third current amplitudes $I_A(I_D)$, the period and the logarithmic decrement of oscillations for the pulse *A*- and repeated pulse *D*- components of the artificial lightning current; $\Delta_A = \ln(I_{mA1}/I_{mA3})$, $\Delta_D = \ln(I_{mD1}/I_{mD3})$ are, respectively, the logarithmic decrement of oscillations for the pulse *A*- and repeated pulse *D*- components of the artificial lightning current; $k_A = [\exp(-0{,}5\pi^{-1}\Delta_A \mathrm{arcctg}\, 0{,}5\pi^{-1}\Delta_A)\sin(\mathrm{arcctg}\, 0{,}5\pi^{-1}\Delta_A)]^{-1}$, $k_D = [\exp(-0{,}5\pi^{-1}\Delta_D \mathrm{arcctg}\, 0{,}5\pi^{-1}\Delta_D)\sin(\mathrm{arcctg}\, 0{,}5\pi^{-1}\Delta_D)]^{-1}$ are, respectively, the normalizing coefficients for the pulse *A*- and repeated pulse *D*- components of the full pulse current of artificial lightning;

- when calculating electric charges q_{LA} and q_{LD}, respectively, for the sinusoidal *A*- and *D*- components of the full pulse current of artificial lightning:

$$q_{LA} \approx 2\pi k_A I_{mA1} T_A /(\Delta_A^2 + 4\pi^2)\,; \quad (3)$$

$$q_{LD} \approx 2\pi k_D I_{mD1} T_D /(\Delta_D^2 + 4\pi^2)\,. \quad (4)$$

- for aperiodic pulse current in the discharge circuit of a powerful PCG at $R_{1(2)} \geq 2[L_{1(2)}/C_{1(2)}]^{1/2}$:

- when calculating the action integrals J_{aA} and J_{aD} for the aperiodic *A*- and *D*- components of the lightning current:

$$J_{aA} \approx k_A^2 I_{mA}^2 [0{,}658\tau_{pA} - 0{,}633\tau_{fA}]; \quad (5)$$

$$J_{aD} \approx k_D^2 I_{mD}^2 [0{,}658\tau_{pD} - 0{,}633\tau_{fD}]\,, \quad (6)$$

where $I_{mA}(I_{mD})$ are, respectively, the amplitudes of the aperiodic pulse *A*- and repeated pulse *D*- components of the full current of artificial lightning; $\tau_{fA}(\tau_{fD})$ is, respectively, the duration of the pulse front of *A*- and *D*- components of the full lightning current at their level (0.1-0.9)$\cdot I_{mA}$ or (0.1-0.9)$\cdot I_{mD}$; $\tau_{pA}(\tau_{pD})$ is the duration of pulses of A- and D- components of the full artificial lightning current at their level of $0{,}5I_{mA}$ or $0{,}5I_{mD}$, respectively; $k_A=[(\alpha_{1A}/\alpha_{2A})^n-(\alpha_{1A}/\alpha_{2A})^m]^{-1}$, $k_D=[(\alpha_{1D}/\alpha_{2D})^l-(\alpha_{1D}/\alpha_{2D})^k]^{-1}$ are, respectively, normalizing coefficients for aperiodic pulse A- and repeated pulse D- component of the full pulse current of artificial lightning; $\alpha_{1A}\approx0{,}76/\tau_{pA}$; $\alpha_{2A}\approx2{,}37/\tau_{fA}$; $\alpha_{1D}\approx0{,}76/\tau_{pD}$; $\alpha_{2D}\approx2{,}37/\tau_{fD}$; $n=\alpha_{1A}/(\alpha_{2A}-\alpha_{1A})$; $m=\alpha_{2A}/(\alpha_{2A}-\alpha_{1A})$; $l=\alpha_{1D}/(\alpha_{2D}-\alpha_{1D})$; $k=\alpha_{2D}/(\alpha_{2D}-\alpha_{1D})$;

- when calculating electric charges q_{LA} and q_{LD}, respectively, for aperiodic A- and D- components of the full pulse current of artificial lightning:

$$q_{LA}\approx k_A I_{mA}[1{,}315\tau_{pA}-0{,}422\tau_{fA}]; \quad (7)$$

$$q_{LD}\approx k_D I_{mD}[1{,}315\tau_{pD}-0{,}422\tau_{fD}]. \quad (8)$$

Let us point out that formulas (7), (8) can be used in the calculations of the corresponding ATPs for intermediate B-, long-term C- and shortened long-term C*- components of the full pulse current of artificial lightning.

3. Technical examples and results of tests on lightning resistance of some AC devices on a powerful UITOM-1 type PCG. Figure 15 shows the results of the direct shock simultaneous action in the high-current discharge circuit of the modernized PCG of the UITOM-1 type on the TS of the sheet cladding of the AC made of aluminum alloy of the AMr2M brand with thickness of h = 1 mm of the pulse A- and long-term C- components of the pulse current of artificial lightning with normalized ATPs.

Fig. 15. General view of the outer rounded zone of through burning with radius $r_e\approx13$ mm of a sheet TS when testing on the lightning resistance of the AC cladding of the aluminum alloy of the AMr2M brand with thickness of h=1 mm from the simultaneous action on it in the discharge circuit of a powerful PCG type UITOM-1 of pulse A- ($I_{mA1}\approx-216$ kA; $t_{mA1}\approx32$ µs – time corresponding to the first amplitude I_{mA1} of the current pulse; $\tau_{p1A}\approx500$ µs; $J_{aA}\approx2{,}19\cdot10^6$ J/Ω) and the long-term C- ($I_{mC}\approx-869$ A; $t_{mC}\approx11$ ms – time that corresponds to the current pulse amplitude I_{mC}; $\tau_{fC}\approx7$ ms; $\tau_{p1C}\approx1000$ ms; $q_{LC}\approx-194.3$ C) component of the full current of artificial lightning with normalized ATP

Figure 16 shows the results of the indicated according to Fig. 15 the destructive electrothermal effect on the TS of the sheet covering of the AC made of aluminum alloy of the AMr2M brand with thickness of h = 1 mm of the pulse A- and long-term C- components of the current of artificial lightning with the corresponding normalized ATP from its inner surface.

Figure 17 shows the results of tests on lightning resistance (damage area 1A) in the discharge circuit of a powerful high-voltage PCG of the UITOM-1 type with thickness h = 1.2 mm of a flat duralumin panel of the fuel tank lining of the domestic aircraft «An».

Fig. 16. General view of the inner rounded zone of the through burning of the sheet TS during the lightning resistance test of the AC cladding of the aluminum alloy of the AMr2M brand with thickness of h = 1 mm from the combined action on it in the discharge circuit of a powerful high-voltage PCG of the UITOM-1 type of pulse A- and long-term C- components of the full current of artificial lightning with normalized ATP

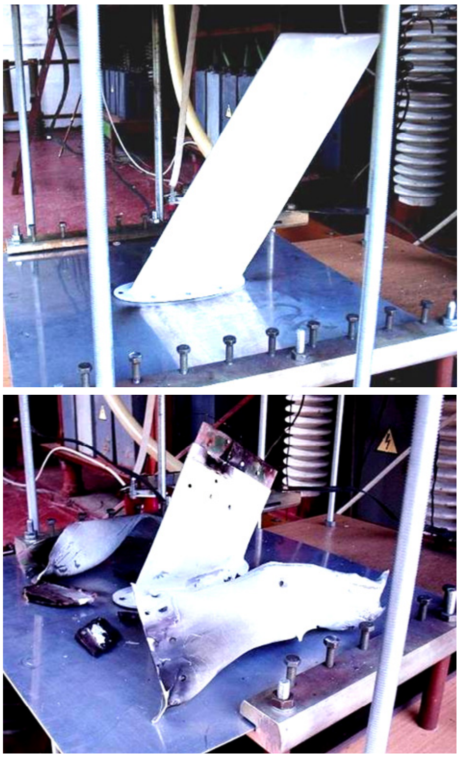
Fig. 17. General view from the side of the anchoring zone of the results of through burning on the outer surface of the TS of the flat duralumin panel with thickness of h=1.2 mm of the fuel tank lining of the domestic aircraft «An» of the plasma channel simulated in the discharge circuit of a powerful high-voltage PCG of the UITOM-1 type of artificial thunderstorm discharge with radius $r_e\approx3.7$ mm of its wall from the direct action of normalized A- $I_{mA1}\approx-199.5$ kA; $t_{mA1}\approx42$ µs; $\tau_{p1A}\approx500$ µs; $J_{aA}\approx1.99\cdot10^6$ J/Ω), B- ($I_{mB}\approx-6.16$ kA; $I_{cB}\approx-2220$ A; $q_{LB}\approx-11.1$ K; $\tau_{p1B}\approx5$ ms) and C*- ($I_{mC*}\approx-1112$ A; $\tau_{p1C*}\approx13.6\cdot$ms; $q_{LC*}\approx-5.79$ K; $I_{cC*}\approx q_{LC*}/\tau_{p1C*}\approx-426$ A) components of the full pulse current of artificial lightning (damage area 1A) [17]

Figure 18 presents the results of direct action in the discharge circuit of a powerful high-voltage PCG of the UITOM-1 type, only of the pulse A- component of artificial lightning with the ATP normalized according to the requirements [12-14] on the TS of the composite skin of the aircraft.

Figures 15-18 clearly indicate that the indicated experimental sheet metal and composite samples of ACs cannot withstand high-energy electrothermal action from the high-current channel of artificial lightning with normalized ATPs of its main current components.

In order to reflect the complex nature of the performed full-scale electromagnetic research on the modernized UITOM-1 type PCG, Fig. 19,a,b show the results of the direct action in the discharge circuit of this high-voltage, high-current PCG on a factory-made pilot model of a domestically produced aircraft receiving-transmitting antenna of a powerful pulse A- component of the artificial lightning current with normalized ATPs.

Fig. 18. General view of the damage zone with diameter up to 100 mm with through burning in sheet TS with thickness h=2.9 mm of the experimental composite cladding of the aircraft, tested for lightning resistance in the discharge circuit of a powerful high-voltage PCG of the UITOM-1 type, when it is directly affected by only the pulse A- component of the artificial lightning current with normalized ATP (I_{mA1}≈–212 kA; t_{mA1}≈32 μs; τ_{p1A}≈500 μs; J_{aA}≈2.11·10^6 J/Ω) [16]



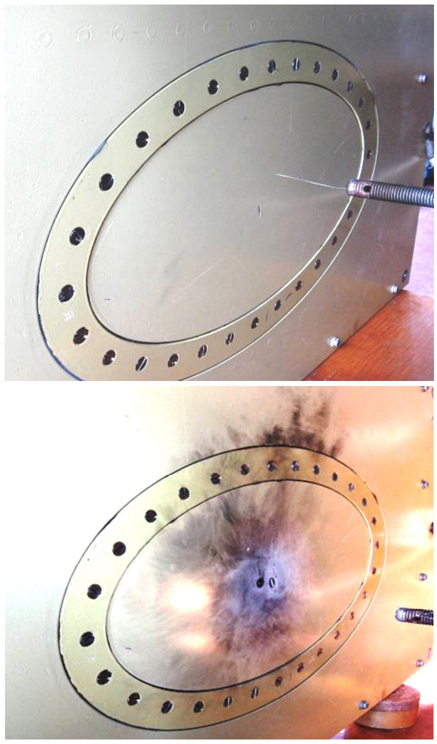
a

b

Fig. 19. General view of the experimental model of the aviation receiving-transmitting antenna of the AC before (a) and after (b) direct action on it in the high-current discharge circuit of the modernized powerful PCG of the UITOM-1 type of the pulse A-component of the artificial lightning current with normalized ATP (I_{mA1}≈–211.9 kA; t_{mA1}≈32 μs; τ_{p1A}≈500 μs; J_{aA}≈2,1·10^6 J/Ω) [16]

From the experimental data of Fig. 19, it follows that the experimental model of the receiving-transmitting antenna of the domestic aviation equipment, developed and created without taking into account the current requirements for lightning protection, cannot withstand lightning resistance tests according to the requirements of US regulatory documents [12-14]. Here, it was destroyed and disabled due to the specified impact of the powerful pulse A- component of the artificial lightning current (see Fig. 19,b).

Figures 20,a,b show the results of the test of the TS panel of the fuel tank of the «An» design aircraft with a hatch cover made of D16 aluminum alloy for lightning resistance (to sparks in its middle from a lightning strike in the aircraft) for area 1A under direct action on this TS with the help of a copper EEW from pulse current generators (GIC-A, GIC-B and GIC-C*) of a powerful modernized high-voltage PSG of the UITOM-1 type, of the necessary A-, B- and C*- components of the artificial lightning pulse current with standardized ATPs (U_{c1}≈–30 kV; U_{c2}≈–4 kV) to the corresponding points directly on its duralumin cover of the hatch.



a

b

Fig. 20. External view of the TS of the panel of the domestic aircraft with hatch cover and D16 aluminum alloy fuel tank ring with stiffeners and various variants of their metallization before (a) and after (b) direct simultaneous action on it in the discharge circuit of the modernized powerful high-voltage PCG of the UITOM-1 type of normalized A- (I_{mA1}≈–196 kA; t_{mA1}≈42 μs; τ_{p1A}≈500 μs; J_{aA}≈2.13·10^6 J/Ω), B- (I_{mB}≈–7.32 kA; I_{cB}≈–2431 A; q_{LB}≈–12.4 C; τ_{p1B}≈5.1 mc) and C*- (I_{mC*}≈–1032 A; τ_{p1C*}≈15·ms; q_{LC*}≈–7.2 C; I_{cC*}≈q_{LC*}/τ_{p1C*}≈–480 A) components of the full pulse current of artificial lightning (the zone of damage to the AC in atmospheric air by lightning discharge 1A)

Obtained according to Fig. 20 experimental data indicate that for damage area 1A, the action of A-, B-, and C*- components of the lightning current with standardized ATPs on the TS of the panel of the cladding of the AC fuel tank made of aluminum alloy D16 with hatch cover leads to the penetration of the corresponding electric discharge products (black soot around the sealing perimeter of the lid of this hatch and sparks recorded by our camera) from the direct action of lightning discharges simulated in laboratory conditions to the area of its inner surface, which can lead to an explosion of steam in the fuel tank of the AC and its catastrophe.

From the experimental data obtained in the open air in the conditions of a high-voltage electrophysical laboratory (see Fig. 15-20), despite their fragmentary nature, the conclusion follows that the metal (composite) elements of the aircraft structure and the receiving and transmitting radio technical devices of the AC before their manufacture and implementation in practice, should be checked in the conditions of a high-voltage electrophysical laboratory for electromagnetic compatibility and resistance to direct action on them of the corresponding components of the full pulse current of artificial lightning (see Table 1).

Conclusions. Currently, Research and Design Institute «Molniya» of National Technical University «Kharkiv Polytechnic Institute» has at its disposal a powerful, modernized high-voltage PCG of the UITOM-1 type with improved high-voltage high-current measuring devices included in its composition, which are capable of reliably generating and measuring the main components in the conditions of a high-voltage electrophysical laboratory full pulse current of artificial lightning operating in the open air and to test the lightning resistance of various on-board devices (systems) of objects of aviation and rocket and space technology. It is shown that in the high-current discharge circuit of the indicated powerful high-voltage PCG, the pulse *A*- (repeated pulse *D*-), intermediate *B*- and long-term *C*- (shortened long-term *C**-) components of the full pulse current of artificial lightning are simulated, the ATPs of which satisfy the strict technical requirements of regulatory documents of the USA SAE ARP 5412: 2013, SAE ARP 5414: 2013 and SAE ARP 5416: 2013. Field electromagnetic tests of aviation and rocket-space equipment being developed and modernized for resistance to direct action on its main on-board devices (systems) and structural elements with metal and composite materials of the specified main components of the full pulse current of artificial lightning will contribute to increasing the survivability of the aircrafts in the conditions of their flight and stay in the electrically active Earth's atmosphere with powerful lightning pulse spark discharges.

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Conflict of interest. The authors declare no conflict of interest.

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