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# THE TOOLING IN UKRAINE OF MODEL TESTS OF OBJECTS OF ENERGY, AVIATION AND SPACE-ROCKET ENGINEERING ON RESISTIBILITY TO ACTION OF PULSED CURRENT OF ARTIFICIAL LIGHTNING

***Purpose.** Presentation and analysis of the modern state of the tooling in Ukraine of model tests of objects of energy, aviation and space-rocket engineering on resistibility to the action of pulsed current of artificial lightning. **Methodology.** Electrophysics bases of technique of high-voltage and high pulsed currents, theoretical bases of electrical engineering, engineering of high electric and magnetic fields. Scientific methods of analysis of research and technical information. **Results.** Information regarding the modern consisting of Ukraine of high-voltage high-current pulsed engineering intended for the leadthrough of model tests of aircrafts and power objects on resistibility to the direct or indirect action on them of pulsed current of artificial lightning in accordance with the requirements of normative documents of the USA SAE ARP 5412: 2013, SAE ARP 5416: 2013 and International Standard IEC 62305-1: 2010. Basic technical descriptions are presented of developed and created in Ukraine for the aims of model tests of the technical objects marked higher on resistibility to lightning of two powerful high-voltage generators of current of lightning (GCL) of type of UITOM-1 and GTM-10/350, playback on the tested objects the pulses of current of artificial lightning with the rationed peak-temporal parameters in obedience to the indicated normatively-technical documents. Examples are resulted and the results of model tests are indicated on described domestic GCL of some elements and devices of the tested technical objects on resistibility to direct action on them of pulsed current of artificial lightning. It is shown that technical descriptions indicated domestic powerful GCL conform to the high requirements of operating in the leading countries of the world of normative documents to on resistibility to lightning objects of industrial energy, aviation and space-rocket engineering. **Originality.** First in the summarizing concentrated kind possibilities are shown developed and created domestic scientists and specialists of unique high-voltage high-current electrophysics equipment for the aims of leadthrough of integration model tests on resistibility and fire safety of aircrafts and power objects at lightning strike. **Practical value.** Application in practice of model tests of objects of industrial energy, aviation and space-rocket engineering on complex resistibility and fire safety to the striking action on them of pulsed current of artificial lightning, generated in discharge circuits of two described powerful domestic GCL, will be instrumental in the successful decision of global in the world problem of protecting from lightning of air and surface technical objects and being in them personnel.* References 20, tables 2, figures 15.
*Key words*: **domestic powerful high-voltage high-current generators of current of lightning, objects of energy, aviation and space-rocket engineering, results of model tests of some technical objects on resistibility to the direct action of pulsed current of artificial lightning.**

***Изложено современное состояние инструментального обеспечения в Украине натурных испытаний объектов промышленной энергетики, авиационной и ракетно-космической техники на стойкость к прямому (косвенному) воздействию на них импульсного тока искусственной молнии. Показано, что подобные испытания технических объектов на молниестойкость могут проводиться в полевых условиях на уникальном отечественном высоковольтном сильноточном электрооборудовании в соответствии с требованиями нормативных документов США SAE ARP 5412: 2013, SAE ARP 5416: 2013 и международного стандарта IEC 62305-1: 2010. Описаны основные технические характеристики разработанных и созданных в Украине для целей натурных испытаний отмеченных выше технических объектов на молниестойкость двух мощных высоковольтных генераторов тока молнии (ГТМ) типа УИТОМ-1 и ГТМ-10/350, воспроизводящих на испытываемых объектах импульсы тока искусственной молнии с нормированными амплитудно-временными параметрами согласно указанных технических документов. Приведены примеры и указаны результаты натурных испытаний на описанных ГТМ некоторых устройств технических объектов на стойкость к прямому воздействию на них импульсного тока искусственной молнии.*** Библ. 20, табл. 2, рис. 15.
*Ключевые слова*: **отечественные мощные высоковольтные сильноточные генераторы тока молнии, объекты энергетики, авиационной и ракетно-космической техники, результаты натурных испытаний некоторых технических объектов на стойкость к прямому действию импульсного тока искусственной молнии.**

**Introduction**. Technical progress in modern society objectively leads to the complication of the various techniques used by people and the active use in it of low-current electronics sensitive to the action of external powerful electromagnetic interference (PEMI) on it [1]. One source of such PEMI is a long spark discharge in the air atmosphere of the Earth of a thundercloud (lightning) into the ground, a neighboring cloud, a protected aircraft or a ground object [2-4]. The frequency of such discharges in the terrestrial troposphere is numerically in average of about 100 $s^{-1}$ [2, 3]. The total electric charge accumulated in a thundercloud due to bipolar electrification processes in the warm ascending air flows of its fine-dispersed inclusions (for example, small droplets and water vapor, fine solid dielectric particles, small granules and ice crystals [5, 6] of ±(50-200) C at the indicated discharge of a thunderstorm cloud causes a powerful pulsed current of a complex time shape in the plasma channel to flow with amplitude up to ± (30-200) kA [2, 3]. Thus, the US technical guidelines SAE ARP 5412: 2013 [7] and SAE ARP 5416: 2013 [8] define the requirements for the normalized amplitude-time parameters (ATP) of artificial lightning current pulses, generated by powerful high-voltage generators of currents of lightning (GCL) and used for field testing of aviation and rocket and space equipment for lightning resistibility. International Standard IEC 62305-1: 2010 [9] regulates the current requirements for normalized ATPs of generated by a powerful high-voltage GCL aperiodic current pulse of artificial lightning with a time shape of 10/350 μs characteristic of a short thunderstorm strike in a protected ground facility and applied in field tests of many industrial facilities of power engineering for lightning resistibility. The development, creation and practical application of these GCLs are topical tasks in the world.

**The goal** of the paper is to describe and analyze the current state of tooling in Ukraine for testing power engineering, aviation and rocket and space equipment for resistibility to the action of pulsed current of artificial lightning.

**1. General information and basic ATPs for pulsed current of artificial lightning.** According to [10], when analyzing the scientific and technical problems we are considering, the notion of «*resistibility*» of an object to lightning includes the following three definitions:

- «*electromagnetic resistibility*» of the object, which means the ability of the object under investigation to resist the action of pulsed voltages and currents induced from the flow of linear lightning in the electrical circuits of its constituent elements to a certain level, while maintaining its operative state;
- «*electrothermal resistibility*» of the object, which means the ability of the object under investigation to resist the effect of the temperature of the heating of the materials of its structural elements arising in the dynamic mode from the current of the linear lightning, to its specified level, while maintaining its operative state;
- «*electromechanical resistibility*» of the object, which means the ability of the object under investigation to resist the dynamic effect of mechanical stresses arising from the flow of linear lightning current in the materials of its structural elements to a certain level, while maintaining its operative state.

In this connection, when carrying out the corresponding complex tests of technical facilities for lightning resistibility with the help of powerful high-voltage high-current GCL, it is necessary to comply with all the technical requirements of normative documents [7-9] in order to determine the above-mentioned types of resistibility based on the results of these tests. Sometimes by the test program and technique of testing technical objects for lightning resistibility the rest team can also be limited to the experimental determination of their most critical resistibility to the effect of artificial lightning current with given normalized ATPs [10]. As a rule, tests for the lightning resistibility of technical objects according to [7-9] are carried out by direct action of the plasma channel of the simulated lightning discharge to the test elements of the object. It is also possible to test objects by indirectly action the indicated discharge channel to the elements of the object located near the lightning passage.

According to the current technical requirements [7, 8], when testing aircraft and rocket and space equipment for lightning resistibility, the following components of artificial lightning current generated in high-voltage high-current GCL circuits can be used: pulse *A*- (or repetitive pulsed *D*-), intermediate *B*- and long-term *C*- (or shortened long-term *C**-) current components of artificial lightning. In the practice of tests for the lightning resistibility of various devices and systems of civil and military aircrafts, the following combinations of these lightning current components are most often used [7, 8, 11]: *A*-, *B*- and *C*-components; *A*-, *B*- and *C** -components; *D*-, *B*- and *C**-components. The main normalized by [7, 8] ATPs, typical for such components of the current of artificial lightning in the circuits of GCL, are summarized below in Table 1.

From the data of Table 1 and the practice of testing technical objects for lightning resistibility it follows that the values of $I_m$ and $\tau_f$ determine the electromagnetic and electromechanical resistibility of the tested elements of the object under the influence of the artificial lightning current component under consideration. At the same time, the values of $q_0$, $\tau_p$ and $J_a$ determine the thermal energy released on the test element of the technical object, and accordingly its electrothermal resistibility to the lightning current. It can be seen that the pulsed *A*- component and the long-term *C*- component of the lightning current are the main components in the total lightning current. It depends on them the lightning resistibility of the object being tested in the discharge circuits of a powerful GCL. It should be noted that in the practical implementation of a powerful GCL on the basis of high-voltage capacitive energy storage (capacitor banks), each of the listed in Table 1 component of artificial lightning current is formed on the electric load of the test element of the object by separate capacitor banks of different energy intensities having different charging voltages. In this regard, the task of synchronizing the operation of such batteries as part of a single GCL comes to the fore.

Table 1

Normalized ATPs of the main components of artificial lightning current [7, 8]

| Lightning current component | $I_m$, kA | $I_c$, kA | $q_0$, C | $J_a$, $10^6$ J/Ω | $\tau_f$, μs | $\tau_p$, 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 | – | – | $(0.25÷1)\cdot10^3$ |
| $C^*$ | – | 0.4 | 6÷18 | – | – | 15÷45 |
| *D* | 100±10 | – | – | 0.25±0.05 | ≤25 | ≤0.5 |

*Note*. $I_m$ –current pulse amplitude; $I_c$ – average current value; $q_0$ – amount of flowed charge; $J_a$ – current pulse action integral; $\tau_f$, $\tau_p$ – respectively, the duration of the pulse front between the levels $(0.1\text{-}0.9)I_m$ and the current pulse on the level $\le0.1I_m$.

In accordance with the requirements of the current standards [9, 12], power engineering facilities for lightning resistibility are tested by an aperiodic current pulse of the time shape of 10/350 μs of both polarities, generated by a special powerful GCL. Normalized ATPs of this test current pulse of artificial lightning, corresponding to a short lightning strike into the protected technical object, are given in Table 2.

From the data of Table 1, 2 it follows that the test pulse of the current of 10/350 μs on the energy parameters (primarily on the value of the integral of its action $J_a$) substantially exceeds the corresponding values for the pulsed *A*- and repetitive pulsed *D*- components of artificial lightning current used in aircraft lightning resistibility tests. Thus, for the level I of lightning protection of a ground object for the same values of the current amplitude $I_m$=±(200±20) kA, this difference with respect to the pulse *A*- component of the total current of artificial lightning is for the integral of the action of the current $J_a$ within five times.

Table 2

Normalized ATPs of an aperiodic pulse current of the time shape 10/350 μs [9, 12]

| Name of the current pulse parameter | Lightning protection level of the facility according to the standard IEC 62305-1: 2010 | | |
|---|---|---|---|
| | I | II | III-IV |
| Front duration $\tau_f$, μs | 10±2 | 10±2 | 10±2 |
| Pulse puration at half-descend $\tau_p$ (on the level $0,5I_m$), μs | 350±35 | 350±35 | 350±35 |
| Current amplitude $I_m$, kA | 200±20 | 150±15 | 100±10 |
| Action integral $J_a$, $10^6$ J/Ω | 10±3.5 | 5.6±1.96 | 2.5±0.875 |
| Charge $q_0$, C | 100±20 | 75±15 | 50±10 |

In this connection, testing of technical objects for lightning resistibility with the use instead of pulsed *A*-component of an artificial lightning of an aperiodic current pulse of a time shape of 10/350 μs (the case of a short lightning strike by [9, 12]) should be considered as more stringent than their lightning resistibility tests according to requirements [7, 8]. At the same time, one should not overlook the strong electrothermal effect on the metal and composite elements of the test object of the long-term *C*-current component of artificial lightning, according to [7, 8], which carries through its round support zone at the object of relatively small outer diameter (up to 6 mm [10]) the huge values of the electric charge $q_0$ (up to ±200 C).

**2. The generator of artificial lightning current type УИТОМ-1.** In 2007, a unique powerful high-voltage high-current GCL of the УИТОМ-1 type [11] was created by the staff of the Scientific-&-Research Planning-&-Design Institute «Molniya» of the NTU «KhPI» at its experimental range (Andreevka village, Kharkiv region) [11], capable of field testing the objects aviation and rocket and space technology for lightning resistibility in accordance with stringent requirements [7, 8]. The general view of this GCL is shown in Fig. 1, and its principal electrical circuit is shown in Fig. 2. It can be seen from this circuit that a powerful generator of the УИТОМ-1 type includes five separate high-voltage pulse current generators (PCG), which form the required normalized components of the artificial lightning current on the common electrical (as a rule, active-inductive) load. In this case, the types of current components determine the name of these generators: PCG-*A*, PCG-*B*, PCG-*D*, PCG-*C* and PCG-*C**.

The use of electrical jumpers in the circuit in Fig. 2 allows the combination of the current components required by [7, 8] to be obtained at the total load (TO). The generators PCG-*A* and PCG-*D* are equipped in parallel with high-voltage low-inductance capacitors of

Fig. 1. General view of a powerful high-voltage high-current generator of artificial lightning current of the type УИТОМ-1 (in the foreground there is a desktop with a high-voltage three-electrode air controlled switch with steel electrodes for a voltage of ±50 kV and pulsed sinusoidal lightning current up to ±220 kA, a tested sample of the skin of an aircraft and an air drawing system, and in the background – separate high-voltage pulse current generators for the corresponding current components *A*, *B*, *C*, *C** and *D*) [11]

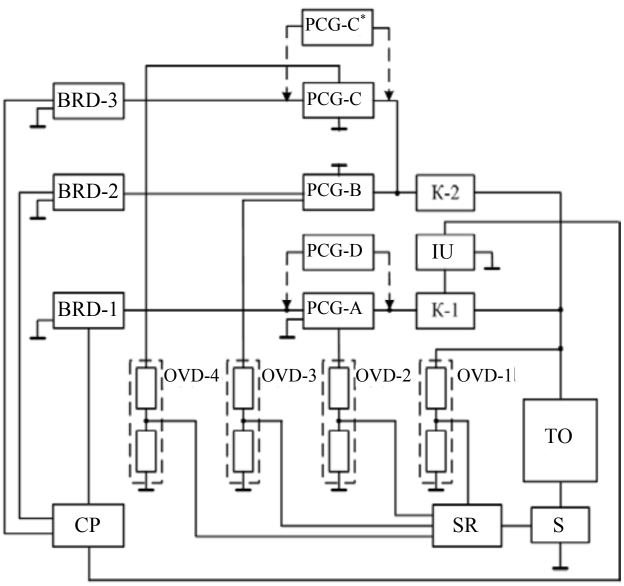


Fig. 2. Principal block electrical circuit for constructing a powerful lightning current generator of the type УИТОМ-1, containing individual pulse current generators PSG-*A*, *PSG*-B, PSG-*D*, PSG-*C* and PSG-*C** (К-1, К-2 – high-voltage air switches for ±50 and ±5 kV; IU – ignition unit for ±100 kV; BRD-1, BRD-2 and BRD-3 – boost-rectifying devices for charging high-voltage capacitors of generators PSG-*A*, PSG-*B*, PSG-*D*, PSG-*C* and PSG-*C**, CP – control panel, OVD-1, OVD-2, OVD-3 and OVD-4 – ohmic voltage dividers for voltage measurement on capacitors of generators PSG-*A*, PSG-*B*, PSG-*D*, PSG-*C* and PSG-*C**, SR – system for recording measured voltages and currents in the circuits of generators PSG-*A*, PSG-*B*, PSG-*D*, PSG-*C* and PSG-*C**; S – measuring shunt; TO – tested object) [11]

the type ИК-50-3 (rated voltage ±50 kV, nominal capacity 3 μF), respectively, in the amount of 111 and 36 pcs. At the same time, PCG-*A* is characterized by a nominal stored energy of 416 kJ, and PCG-*D* – 135 kJ. The generators PCG-*B*, PCG-*C* and PCG-*C** are equipped with parallel-connected high-voltage low-inductance capacitors of ИМ-5-140 type (rated voltage ±5 kV; nominal capacity 140 μF) in the amount of 18, 324 and 34 pcs., respectively.

In this regard, they have a nominal energy capacitance of 31.5, 567 and 59.5 kJ. As a result, the nominal energy capacitance of a powerful GCL of the УИТОМ-1 type is approximately 1.21 MJ [11]. Each capacitor of the generators PSG-*A*, PSG-*B*, PSG-*D*, PSG-*C* and PSG-*C** (with their total number of 523 pieces) from the emergency operation modes of these capacitor batteries (for example, electrical breakdown of one of the capacitors on the stage of charge or discharge) is equipped with a protective device mounted on its high-voltage terminal and made of several parallel-connected protective constant graphite-ceramic resistors of the ТВО-60 type of nominal of 24 or 100 Ω [13].

Switching in high-current discharge circuits of the PSG-*A* and PSG-*D* generators is carried out by a controlled high-voltage air cascade type K-1 discharger (see Fig. 2) for a nominal voltage of ±50 kV [11, 14]. This discharger is controlled by feeding a high-voltage microsecond voltage pulse of a damped sinusoidal shape of amplitude of ±100 kV from a special starting generator of the ГВПИ-100 type (IU in Fig. 2) to its middle electrode. To switch the high-current discharge circuits of the PSG-*B*, PSG-*C* and PSG-*C** generators, a high-voltage air two-electrode K-2 discharger (see Fig. 2) is used for a voltage of ±5 kV, rectangular electrodes of which are made of erosion-resistant graphite brushes from a powerful electric machines [11, 14]. The discharger K-2 is triggered by a starting voltage pulse applied from the IU to the K-1 discharger.

Measurement of the ATPs of formed *A*-, *D*-, *B*-, *C*-, and *C**- components of artificial lightning current is carried out simultaneously with the help of one special high-current shunt (S) of the type ШК-300, which passed the state metrological certification [11, 15]. The GCL of the УИТОМ-1 type is equipped with several such measuring shunts having different $S_i$ conversion coefficients. Thus, to measure ATPs of the *A*- and *D*-components of the artificial lightning current, shunts with these coefficients approximately equal to $S_{iA}$≈11.26·10$^3$ A/V and $S_{iA}$≈25·10$^3$ A/V are used. When measuring ATPs of *B*-, *C*-, and *C**- components of artificial lightning current, the same shunts are used, but with the conversion coefficients of $S_{iC}$≈5.64·10$^3$ A/V and $S_{iC}$≈12.5·10$^3$ A/V.

Fig. 3, 4 show typical oscillograms of the pulsed *A*- and long-term *C*- components of the current of artificial lightning with normalized ATPs recorded in high-current discharge circuits of generators PCG-*A* and PCG-C of high-power GCL of the УИТОМ-1 type using the above-mentioned measuring shunts and digital storage oscilloscopes series Tektronix TDS 1012, located far from this GCL in the buried measuring bin.

Note that when obtaining the current oscillograms shown in Fig. 3, 4, the charging voltage of the capacitors in the high-power high-voltage generator PSG-*A* was approximately $U_{3A}$≈-29.7 kV, and in the powerful high-voltage generator PCG-*C* – $U_{3C}$≈ –4 kV. The lumped active-inductive load in this experimental case had the following electrical parameters: an active resistance of about 0.1 Ω, and an inductance of about 1 μH [10].

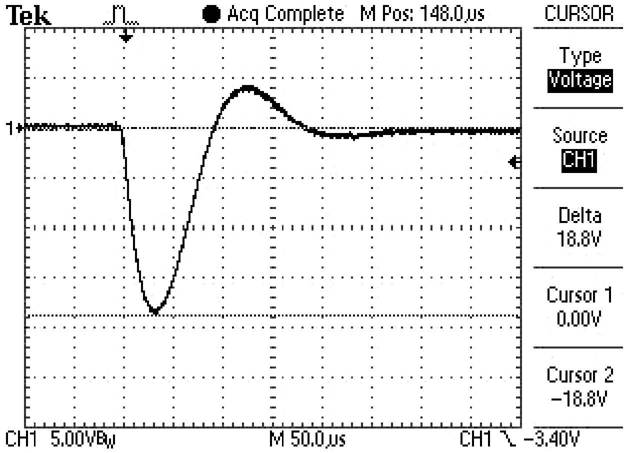


Fig. 3. Oscillogram of the pulsed *A*- component of the artificial lightning current with normalized ATPs in the high-current discharge circuit of the high-voltage generator PSG-*A* of the powerful domestic GCL of the УИТОМ-1 type ($U_{3A}$≈–29.7 kV; $I_{mA}$≈ –212 kA; $J_{aA}$≈2.09·10$^6$ J/Ω; $\tau_f$≈32 μs; $\tau_p$≈500 μs, vertical scale –56.3 kA/division, horizontal scale – 50 μs/division)

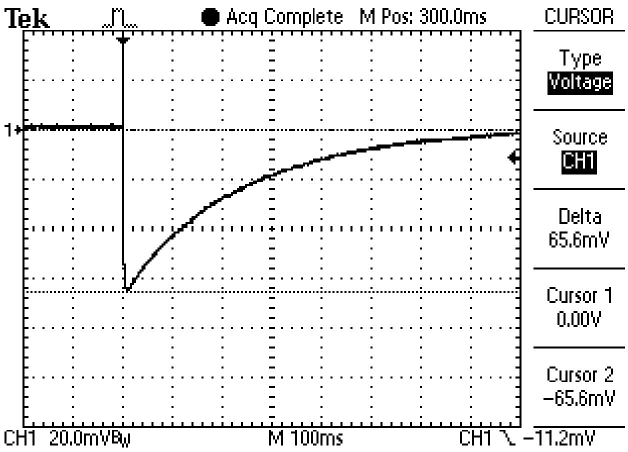


Fig. 4. Oscillogram of the long-term *C*- component of the artificial lightning current with normalized ATPs in the high-current discharge circuit of the high-voltage generator PCG-*C** of the powerful GCL of the УИТОМ-1 type ($U_{3C}$≈–4 kV; $I_{mC}$≈ –738 A; $q_{0C}$≈ –182 C; $\tau_f$≈9 ms; $\tau_p$≈1000 ms, vertical scale – 225 A/division, horizontal scale – 100 ms/division)

**2.1. Some examples and results of full-scale testing of technical facilities on a powerful GCL type УИТОМ-1.** Fig. 5, 6 show the results of direct action on the experimental model of the receiving and transmitting antenna of the domestic production aircraft of the pulsed *A*- component of the artificial lightning current, normalized by [7, 8], ATPs of which corresponded to the data shown in Fig. 3 ($I_{mA}$≈–212 kA; $J_{aA}$≈2.09·10$^6$ J/Ω; $\tau_f$≈32 μs; $\tau_p$≈500 μs).

From the experimental data of Fig. 5, 6 it follows that the experimental model of the receiving and transmitting antenna of aeronautical engineering of full-scale tests, developed and created without taking into account the requirements for lightning protection, according to the normative documents of the USA SAE ARP 5416: 2013 [7] and SAE ARP 5416: 2013 [8] could not stand: it was destroyed and is disabled [10].

Fig. 7 shows the results of direct simultaneous action in high-current discharge circuits of GCL type УИТОМ-1 on a prototype sheet sample of roofing of a technical structure made of 12X18H10T stainless steel with a thickness of 1 mm normalized by [7, 8], first of the pulsed $A$- component of artificial lightning current ($I_{mA}$≈–192 kA; $J_{aA}$≈1.9·10$^6$ J/Ω;$\tau_f$≈34 μs; $\tau_p$≈500 μs) and immediately behind it a long-term $C$- component of the current of the simulated lightning discharge ($I_{mC}$≈–804 A; $q_{0C}$≈–165 C; $\tau_f$≈9 ms; $\tau_p$≈448 ms).

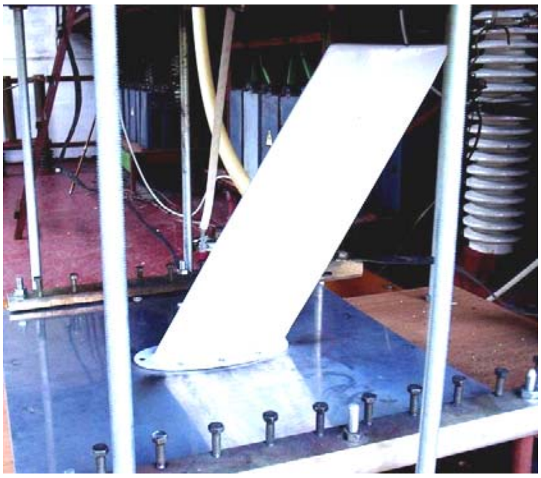

Fig. 5. External view of the experimental model of the aerial receiving and transmitting antenna prior to direct impact on it in the high-current discharge circuit of the PCG-$A$ generator of the powerful GCL of the УИТОМ-1 type of the pulsed $A$- component of the artificial lightning current with normalized [7, 8] ATPs [10]

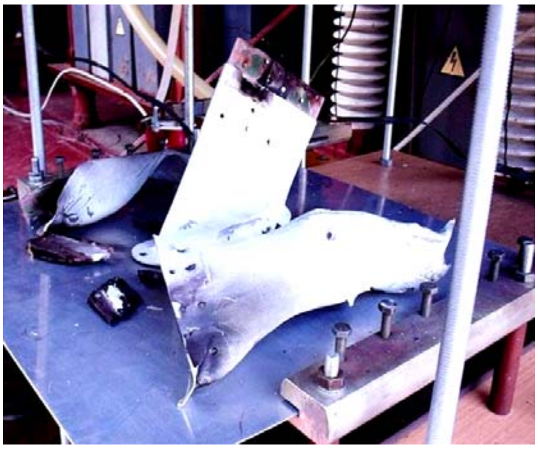

Fig. 6. External view of the experimental model of the aerial receiving and transmitting antenna after the direct impact on it in the high-current discharge circuit of the PCG-$A$ generator of the powerful GCL of the УИТОМ-1 type of the pulsed $A$- component of the artificial lightning current with normalized [7, 8] ATPs [10]

From the data in Fig. 7 it can be seen that at this current loading of the experimental steel sheet specimen, its rounded through melting with a diameter of up to 12 mm occurs due to the electrothermal effect of the long-term $C$- component of the current of the simulated lightning discharge used in the experiment [16, 17]. Due to the action on the considered experimental specimen made of the mentioned stainless steel of the pulsed $A$- component of the current of artificial lightning in the round zone with a diameter of up to 58 mm, a surface melting (up to a depth of 50 μm) with characteristic colors of tarnishing occurs [16, 17].

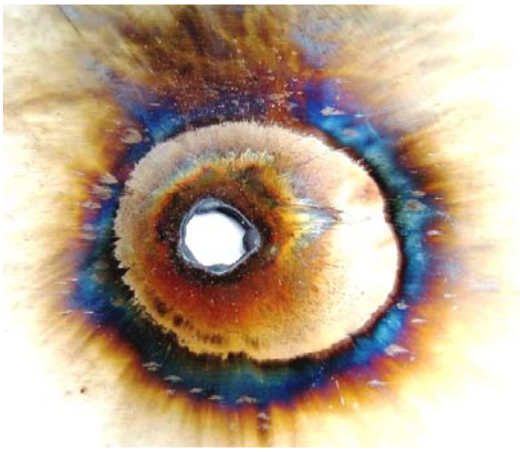

Fig. 7. General view of the affected area in an experimental sheet specimen made of stainless steel grade 12X18H10T of 1 mm thickness from the direct simultaneous action on it of a pulsed $A$-component ($I_{mA}$≈–192 kA; $J_{aA}$≈1.9·10$^6$ J/Ω; $\tau_f$≈34 μs; $\tau_p$≈500 μs) and a long-term $C$- component of the artificial lightning current ($I_{mC}$≈–804 A; $q_{0C}$≈–165 C; $\tau_f$≈9 ms; $\tau_p$≈448 ms) formed in high-current discharge circuits of the powerful high-voltage GCL of the УИТОМ-1 type [16]

Fig. 8 shows the results of the damaging action of the pulsed $A$- component of the current of artificial lightning with the normalized [7, 8] ATPs indicated in Fig. 3 ($I_{mA}$≈–212 kA; $J_{aA}$≈2.09·10$^6$ J/Ω; $\tau_f$≈32 μs; $\tau_p$≈500 μs) on the sheet prototype of the composite plating of an airplane of 3 mm thickness and 500×500 mm in plan. In this case, the multilayered composite of the test sample in its composition had fiberglass with an epoxy matrix, carbon fiber with an epoxy phenol matrix and several thin planar metal meshes that act as a reinforcer of the investigated composite material [10, 18]. It can be seen that this sample does not withstand the given effect of the plasma channel of artificial lightning sample does not withstand.

Fig. 8. General view of the damage zone with a diameter of up to 100 mm with a through burn in an experimental sheet specimen of 3 mm thickness of the composite plating of an aircraft tested in the high-current circuit of the powerful GCL of the УИТОМ-1 type, at a direct action on it of normalized by [7, 8] pulsed $A$- components of artificial lightning current [10]

**3. Generator of current of artificial lightning of the type ГТМ-10/350.** In 2014, a unique powerful high-voltage high-current generator of the current of a lightning short-term shock of the type ГТМ-10/350 [19] was developed at the experimental site of the Scientific-&-Research Planning-&-Design Institute «Molniya» of the NTU «KhPI», indicated in section 2, where field tests can be performed for the ground objects of industrial power engineering for lightning resistibility in accordance with stringent requirements [9, 12]. A general view of this GCL is shown in Fig. 9, and Fig. 10 shows its principal electric circuit diagram. It can be seen that the composition of this GCL includes four powerful high-voltage pulsed current generators: PCG-1, PCG-2, PCG-3 and PCG-4. The PCG-1 − PCG-3 generators are equipped with high-voltage pulse capacitors of the type ИК-50-3 (rated voltage ±50 kV, nominal capacitance 3 μF), and the PCG-4 generator with high-voltage pulse capacitors of the ИМ2-5-140 type (rated voltage ±5 kV, nominal capacity 140 μF) [19]. In the generators PCG-1 − PCG-3, their capacitors (correspondingly in the amount of 16, 44 and 111 pcs.) are connected in parallel to a rated voltage of ±50 kV, and in the generator PCG-4, the capacitors (288 pcs.) are in series-parallel (by two series-connected capacitors in each of the 144 parallel sections) to a rated voltage of ±10 kV. In this regard, the nominal energy capacitance for these generators is for: PCG-1 – 60 kJ; PCG-2 – 165 kJ; PCG-3 – 416 kJ; PCG-4 – 504 kJ. As a result, the total nominal power capacitance of a powerful generator of artificial lightning current type ГТМ -10/350 is approximately equal to 1.15 MJ [19]. The lumped capacitances $C1 - C4$ for the PCG-1 − PCG-4 generators are 48, 132, 333 and 10080 μF, respectively (see Fig. 10). The intrinsic active resistances $R1 - R4$ of low-resistance discharge circuits of these generators are approximately equal to 375, 136, 57 and 83 mΩ, respectively. The intrinsic inductances $L1 - L4$ of the low-inductance discharge circuits of the mentioned PCG-1 − PCG-4 generators are approximately 1, 1.3, 2.5 and 1.5 μH, respectively. The forming inductances $L31$ and $L41$ (see Fig. 10) are chosen to be approximately equal to 40 and 7 μH.

Fig. 9. General view of a powerful high-current generator of artificial lightning current type ГТМ-10/350 (in the foreground there is its working table with placed on top of it a controlled high-voltage three-electrode air switch with graphite electrodes for voltage of ±50 kV and pulsed aperiodic lightning current of amplitude up to ±220 kA and the tested sample of cable-conductor products, and in the background – the electrical engineering elements of the charge-discharge circuits of its separate high-voltage pulsed current generators PCG-1, PCG-2, PCG-3 and PCG-4) [19]

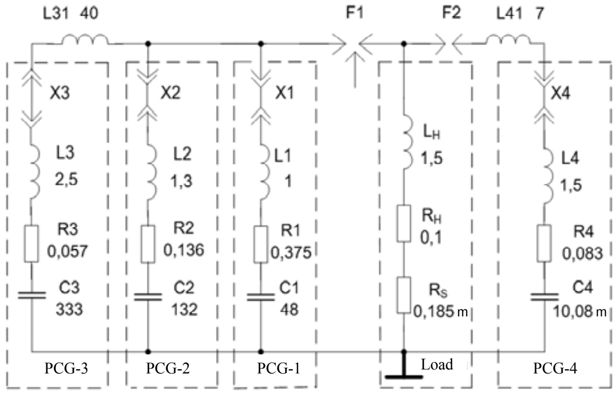


Fig. 10. Principal replacing electric circuit of high-current discharge circuits of four separate high-voltage generators PCG-1 – PCG-4 in the composition of a powerful current pulse generator 10/350 μs of artificial lightning of the type ГТМ-10/350 ($X1-X4$ − current-carrying jumpers of discharge circuits of generators PCG-1 − PCG-4) [19]

The active-inductive load in the circuit in Fig. 10 contains a lumped active resistance $R_H \approx 0.1$ Ω and a concentrated inductance $L_H \approx 1.5$ μH. In sequence with the electrical load parameters, the intrinsic resistance $R_S$ of the ШК-300 measuring shunt, numerically equal to about 0.185 mΩ [11, 15], is connected. Such a value of $R_S$ practically does not influence the electromagnetic processes in the discharge circuits of the GCL and the electrical circuits of the tested ground object.

The switching of the high-current discharge circuits of the PCG-1 − PCG-3 generators as part of a powerful current generator of a short-time thunder-storm strike type ГТМ-10/350 is performed by a three-electrode air controlled switch with graphite electrodes (Fig. 11) specially designed for this purpose [19].

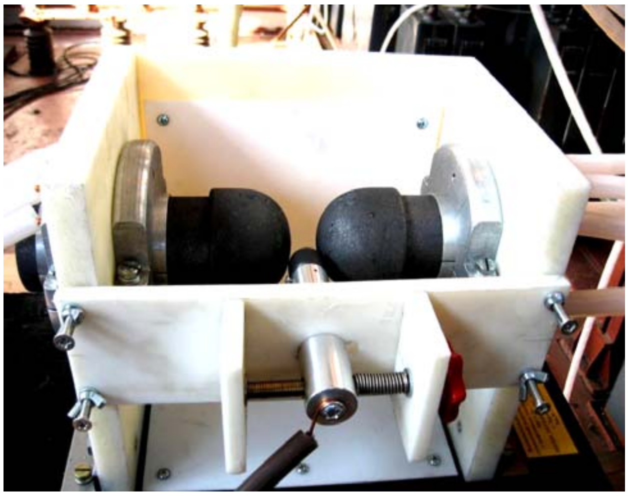

Fig. 11. External view of the high-voltage three-electrode air controlled switch $F1$ with graphite electrodes at a rated DC voltage of ±50 kV and a pulsed current of artificial lightning of the time shape of 10/350 μs with amplitude up to ±220 kA in the GCL circuit [19]

As for the switching of the discharge circuit of the PCG-4 generator, it is performed using a two-electrode $F2$ air switch with graphite electrodes for a rated voltage of ±10 kV and a pulse current of up to ±100 kA. The switch $F2$ is started by the pulse overvoltage that occurs on the electrical load when the switch $F1$ is activated and the pulse discharge current from the PCG-1 − PCG-3 generators begins to flow in it.

Fig. 12 shows the oscillogram of obtained in the discharge circuit of the ГТМ-10/350 generator with a low-resistance active-inductive load ($R_H$≈0.1 Ω; $L_H$≈1.5 μH) aperiodic current pulse of artificial lightning with normalized [9, 12] ATPs.

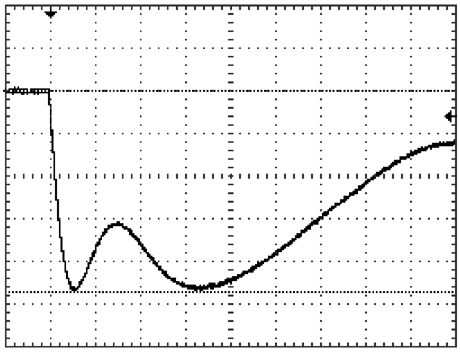

Fig. 12. Oscillogram of an aperiodic current pulse of the time shape of 15/340 μs in the high-current discharge circuit of the powerful high-voltage generator of artificial lightning current type ГТМ-10/350 with a low-resistance *RL*-load ($U_{C1-3}$≈−15 kV; $U_{C4}$≈−2.25 kV; $I_m$≈−106 kA; $J_a$≈3.03·$10^6$ J/Ω; $q_0$≈52.2 C ; $\tau_f$≈15 μs; $\tau_p$≈340 μs; $R_H$≈0.1 Ω; $L_H$≈1.5 μH; vertical scale - 22.52 kA/division; horizontal scale -50 μs/division) [19]

The charging voltage $U_{C1-3}$ of the negative polarity of all the capacitors for the PCG-1 − PCG-3 generators in this case was about 15 kV, and the charging voltage $U_{C4}$ of the same polarity of the individual capacitors for the PCG-4 generator was about 2.25 kV.

**3.1. Some examples and results of full-scale tests of energy facilities on a powerful generator of artificial lightning current type ГТМ-10/350.** Fig. 13 shows the working table of the generator type ГТМ-10/350 with the prepared according to the requirements [9, 12] for the tests on the electrothermal resistivity to the direct action of the artificial lightning current pulse 10/350 μs the pilot sample of the radio frequency coaxial cable of the РК 50-7-11 type with the belt polyethylene insulation having a split copper core of section $S$≈3.2 mm$^2$.

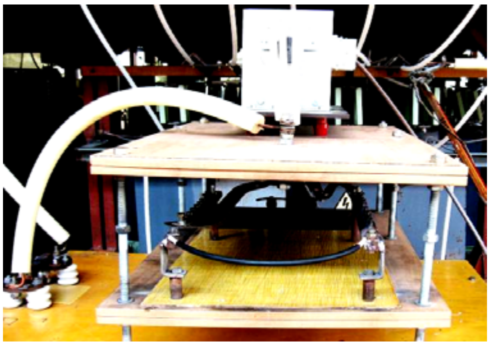

Fig. 13. External view of the working table of the generator of artificial lightning current type ГТМ-10/350 with fixed on its steel electrodes a splintered round copper core of 3.2 mm$^2$ cross section and of 0.5 m length of the radio frequency coaxial cable of РК 50-7-11 type with solid polyethylene insulation and its «drowned» external copper braiding before the action of an aperiodic current pulse of 17/310 μs of a lightning discharge by an amplitude of ~82.9 кА [20]

This cable could not stand the direct action in a high-current discharge circuit of a powerful generator of the type ГТМ-10/350 of the aperiodic current pulse 17/310 μs ($I_m$≈82.9 kA; $J_a$≈1.59·$10^6$ J/Ω; $q_0$≈36.3 C; $\tau_f$≈17 μs; $\tau_p$≈310 μs) on its copper core. At a current density in the copper core of about $\delta_m$≈$I_m$/$S$≈25.9 кA/mm$^2$, an electric explosion (EE) occurred, which led to the destruction of the cable and its failure.

Fig. 14 shows a visual demonstration of the EE phenomenon of a continuous aluminum core with a cross section of 6 mm$^2$ of the network wire АППВнг2×6 with polyvinyl chloride insulation, which occurred at supply to it in the discharge circuit of the powerful generator of the type ГТМ-10/350 an aperiodic current pulse of the time shape of 17/265 μs of positive polarity ($I_m$≈83,8 kA; $J_a$≈1.41·$10^6$ J/Ω; $q_0$≈31.7 C; $\tau_f$≈17 μs; $\tau_p$≈265 μs) [20]. We point out that the current density in the aluminum core of the wire was then $\delta_m$≈$I_m$/$S$≈14 кA/mm$^2$.

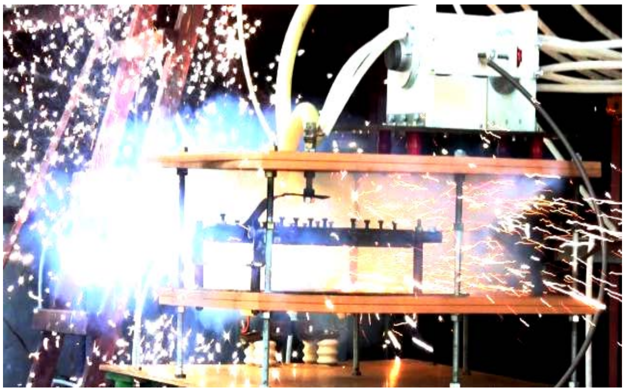

Fig. 14. General view of the EE phenomenon of a solid round aluminum core of 6 mm$^2$ cross-section of the АППВнг2×6 network cable with polyvinyl chloride insulation in the high-current discharge circuit of the powerful high-voltage generator type ГТМ-10/350 ($U_{C1-3}$≈15 kV; $U_{C4}$≈2.1 kV; $I_m$≈83.8 kV; $J_a$≈1.41·$10^6$ J/Ω; $q_0$≈31.7 C; $\tau_f$≈17 μs; $\tau_p$≈265 μs) [20]

Fig. 15 shows the oscillogram of this test pulse of the current of a short-term lightning strike.

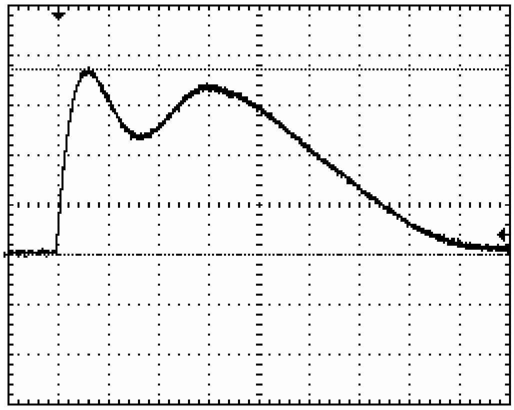

Fig. 15. Oscillogram of the aperiodic current pulse of 17/265 μs of artificial lightning in the high-current discharge circuit of the powerful high-voltage generator ГТМ-10/350 at EE of a solid round aluminum core with cross section of 6 mm$^2$ and length of 0,5 m of a network wire АППВнг2×6 with polyvinyl chloride insulation ($U_{C1-3}$≈15 kV; $U_{C4}$≈2.1 kV; $I_m$≈83.8 kV; $J_a$≈1.41·$10^6$ J/Ω; $q_0$≈31.7 C; $\tau_f$≈17 μs; $\tau_p$≈265 μs; vertical scale – 22.52 kA/division; horizontal scale – 50 μs/division) [20]

From a comparison of the data in Fig. 12, 15 it follows that the electrophysical processes in the elements of the tested object that proceed during the tests on the lightning resistibility according to the requirements of [9, 12] can substantially deform the first of all the falling part of the current pulse of artificial lightning. This is particularly evident in the EE of current-carrying elements of the object, which interrupt the current flow of the simulated lightning discharge current from the generator of the type ГТМ-10/350.

**Conclusions.**

1. Analysis of the current state in Ukraine of tooling for full-scale testing of industrial power engineering facilities, aircraft and rocket and space equipment for lightning resistibility shows that on domestic high-voltage high-current electrical equipment, including unique powerful generators such as УИТОМ-1 and ГТМ-10/350, developed and created at the Scientific-&-Research Planning-&-Design Institute «Molniya» of the NTU «KhPI» certification electromagnetic tests of the elements and systems of indicated objects on a direct or indirect effect of pulsed current of artificial lightning, meeting the requirements of the current US regulatory documents SAE ARP 5412: 2013, SAE ARP 5416: 2013 and the International Standard IEC 62305-1: 2010, can be conducted in the field.
2. The presented results and the world experience of the damaging effect on the technical and biological objects of linear lightning that develops and flows in the air troposphere of our planet unequivocally point to the necessity of carrying out the considered full-scale tests of structural elements and engineering networks of aircrafts and ground power facilities for complex resistibility to pulse lightning current.
3. Real actual tests for lightning resistibility and fire safety of objects of domestic and foreign aviation equipment (for example, onboard receiving and transmitting radio engineering devices, metal and composite elements of the frames of the aircrafts of the Antonov and Boeing) conducted in recent years on powerful generators of the УИТОМ-1 and ГТМ-10/350 types and industrial power engineering (for example, prototypes of multi-layer panels with an outer layer of thin sheet stainless steel of an expensive large-size protective containment of the 4th power unit of the Chernobyl Nuclear Power Plant) testify to the full compliance of the technical characteristics of domestic generators of artificial lightning current with the high requirements of the normative documents in force in the leading countries of the world.

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