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ANALYSIS OF CHARACTERISTICS AND POSSIBILITIES OF HIGH-VOLTAGE ELECTRICAL ENGINEERING COMPLEX SCIENTIFIC-&-RESEARCH PLANNING-&-DESIGN INSTITUTE «MOLNIYA» OF NTU «KHPI» FOR THE TESTS OF OBJECTS OF ENERGY, ARMAMENT, AVIATION AND SPACE-ROCKET TECHNIQUE ON ELECTRIC SAFETY AND ELECTROMAGNETIC COMPATIBILITY

Purpose. Implementation of analysis of basic technical descriptions and new possibilities of separate electric options of unique high-voltage electrical engineering complex Scientific-&-Research Planning-&-Design Institute «Molniya» of NTU «KhPI», intended for testing objects of industrial energy (IE) on electric safety, action on them of standard storm and interconnect pulses of voltage (current), and also objects of armament and military technique (OAMT), aviation (AT) and space-rocket (SRT) technique on electromagnetic compatibility (EMC) and resistibility at direct action on them of the rationed pulses of current of artificial lightning and row of no-spread temporal functions of pulses of current (high-voltage). Methodology. Basis of the applied electrical engineering, electroenergy and electromechanics, electrophysics bases of technique of high-voltage and large pulse currents, bases of the applied instrument-making, high-voltage measuring technique and standardization. Results. Description of basic technical descriptions and new possibilities of component parts of unique high-voltage electrical engineering complex Scientific-&-Research Planning-&-Design Institute «Molniya» of NTU «KhPI», intended for testing different objects of IE on electric safety, their resistibility to direct (indirect) action of standard aperiodic storm and interconnect pulses of voltage (current), and also OAMT, AT and SRT on EMC and resistibility to lightning at a direct action on them of the rationed pulses of current of artificial lightning. It is shown that these tests can be conducted in accordance with the requirements of normative documents of the USA of SAE ARP 5412: 2013, SAE ARP 5414: 2013, SAE ARP 5416: 2013, RTCA DO-160G: 2011, military Standards of the USA of MIL-STD-464C: 2010, MIL-STD-461G: 2015, Standards of NATO AECTP-500: 2016, AECTP-250: 2014, International Standards of IEC 62305-1: 2010, IEC 61024-1: 1990 and intergovernmental Standard GOST 1516.2-97 on the domestic high-voltage options of type of UITOM-1, GTM-10/350, GKIN-2, TI-CS115 (NCS08), TI-CS116 (NCS09), G-NCS10, MV 1000 and IK-1U with the rationed descriptions. Examples and results of tests of row of technical objects are resulted on indicated high-voltage little- and heavy-current electric options. Originality. First in a complex kind basic technical descriptions and proof-of-concept possibilities of unique high-voltage electrical equipment of Scientific-&-Research Planning-&-Design Institute «Molniya» of NTU «KhPI» are presented, being in Ukraine head organization in area of development, creation and practical application of the indicated high-voltage technique in behalf of domestic industries of IE, airplane and rocket production, and also defense industries of industry. Practical value. Application of the described domestic high-voltage proof-of-concept electrical equipment at tests on electric safety, EMC and resistibility to lightning of different objects of IE, OAMT, AT and SRT will be instrumental in the increase of reliability of their functioning in the conditions of striking (destabilizing) action on them of powerful electromagnetic hindrances of natural and artificial origin. References 39, tables 9, figures 30.

Key words: **high-voltage generators of voltage and current pulses, objects of industrial energy, armament, aviation and space-rocket technique, standards of tests, results of tests of technical objects on electric safety, electromagnetic compatibility and resistibility to lightning.**

Виконаний аналіз основних технічних характеристик і нових можливостей складових частин унікального високовольтного електротехнічного комплексу НДПКІ «Молнія» НТУ «ХПІ», призначеного для проведення випробувань об'єктів промислової енергетики на електробезпеку, їх стійкість до дії стандартних аперіодичних грозових і комутаційних імпульсів напруги (струму), а також об'єктів озброєння і військової техніки, авіаційної і ракетно-космічної техніки на електромагнітну сумісність і блискавкостійкість при прямій дії на них нормованих імпульсів струму штучної блискавки. Показано, що дані випробування можуть проводитися відповідно до вимог нормативних документів США SAE ARP 5412: 2013, SAE ARP 5414: 2013, SAE ARP 5416: 2013, RTCA DO-160G: 2011, військових стандартів США MIL-STD-464C: 2010, MIL-STD-461G: 2015, стандартів НАТО AECTP-500: 2016, AECTP-250: 2014, міжнародних стандартів IEC 62305-1: 2010, IEC 61024-1: 1990 і міждержавного стандарту ГОСТ 1516.2-97 на оригінальних вітчизняних високовольтних установках УИТОМ-1, ГТМ-10/350, ГКИН-2, TI-CS115 (NCS08), TI-CS116 (NCS09), G-NCS10, МВ 1000 і ИК-1У з нормованими характеристиками. Приведені приклади і результати випробувань ряду технічних об'єктів на вказаних високовольтних слабко- і сильнострумних електроустановках. Бібл. 39, табл. 9, рис. 30.

Ключові слова: **високовольтні генератори імпульсів напруги і струму, об'єкти промислової енергетики, озброєння, авіаційної і ракетно-космічної техніки, стандарти випробувань, результати випробувань технічних об'єктів на електробезпеку, електромагнітну сумісність і блискавкостійкість.**

Выполнен анализ основных технических характеристик и новых возможностей составных частей уникального высоковольтного электротехнического комплекса НИПКИ «Молния» НТУ «ХПИ», предназначенного для проведения испытаний объектов промышленной энергетики на электробезопасность, их стойкость к воздействию стандартных апериодических грозовых и коммутационных импульсов напряжения (тока), а также объектов вооружения и военной техники, авиационной и ракетно-космической техники на электромагнитную совместимость и молниестойкость при прямом действии на них нормированных импульсов тока искусственной молнии. Показано, что данные испытания могут проводиться в соответствии с требованиями нормативных документов США SAE

ARP 5412: 2013, SAE ARP 5414: 2013, SAE ARP 5416: 2013, RTCA DO-160G: 2011, военных стандартов США MIL-STD-464C: 2010, MIL-STD-461G: 2015, стандартов НАТО AECTP-500: 2016, AECTP-250: 2014, международных стандартов IEC 62305-1: 2010, IEC 61024-1: 1990 и межгосударственного стандарта ГОСТ 1516.2-97 на оригинальных отечественных высоковольтных установках УИТОМ-1, ГТМ-10/350, ГКИН-2, TI-CS115 (NCS08), TI-CS116 (NCS09), G-NCS10, MB 1000 и ИК-1У с нормированными характеристиками. Приведены примеры и результаты испытаний ряда технических объектов на указанных высоковольтных слабо- и сильноточных электроустановках. Библ. 39, табл. 9, рис. 30.
Ключевые слова: **высоковольтные генераторы импульсов напряжения и тока, объекты промышленной энергетики, вооружения, авиационной и ракетно-космической техники, стандарты испытаний, результаты испытаний технических объектов на электробезопасность, электромагнитную совместимость и молниестойкость.**

Problem definition. Powerful electromagnetic interference (PEMI) of natural and artificial origin is a serious threat to the reliable functioning of modern technology, based on the use of various radio, electrical and electronic equipment [1]. The world experience in the operation of such equipment (for example, military and civilian aircraft, launch vehicles, thermal (TPP), nuclear (NPP) and hydraulic (HPP) power plants) indicates that low-current electronics, which is part of its information technology systems and computer control networks, is extremely sensitive to the action of PEMIs on it [2]. One of the sources of PEMIs is long spark discharges in the Earth's air atmosphere (lightning) arising from a thundercloud to the earth, neighboring clouds, aircraft and various objects located on the Earth's surface [3]. Therefore, the issues of electromagnetic compatibility (EMC) in the field of modern technology have gained increased importance in the world. General requirements for EMC of equipment are regulated by the relevant Technical Regulations of Ukraine, similar to EU Directive 2014/30/EU [4]. Types of tests and methods for their implementation are described in Ukrainian Standards, identical to EU Standards of the 61000 and 55000 series. In 2004, the KT-160D Standard [5], similar to the corresponding US Standard RTCA DO-160D, was introduced in Ukraine to test the onboard equipment of civilian aircraft. In 2011, the next edition of this RTCA DO-160G Standard [6] was released in the USA, which has a number of significant differences from the previous RTCA DO-160D Standard. Obviously, the capabilities of testing laboratories in Ukraine should be adapted to the requirements of the new edition of this Standard. Section 22 of this Standard focuses on onboard equipment (OBE) tests on transient susceptibility caused by lightning. In all versions of the Standards from RTCA DO-160D to RTCA DO-160G, the basic requirements for OBE tests for lightning resistance have not practically changed, with the exception of some refinements and adjustments. These basic requirements include [5, 6]:

- temporary shapes and amplitude values of lightning test currents and voltages;
- types of test lightning discharges;
- methods for introducing interference from lightning into the OBE;
- OBE test regulations.

Of fundamental importance for the implementation of the Concept of the State Target Program for the Reform and Development of the Military-Industrial Complex of Ukraine, which was approved by Order of the Cabinet of Ministers of Ukraine No. 19-r of 01.20.2016, is the implementation of NATO Standards in Ukraine (in particular, according to EMC). These standards regulate the requirements for EMC parameters for objects of armament and military technique (OAMT) and their components, taking into account the combat arms and destination. Ensuring the necessary level of immunity of the OAMT samples to the action of various PEMIs will increase the defense capability of Ukraine and will promote the promotion of products of national manufacturers on international markets. By order of the National Standardization Body of Ukraine dated December 26, 2017 No. 471, from February 1, 2018, the following two basic NATO Standards came into force in our country by confirmation method: DSTU-P STANAG 4370 AESTP-500 Ed. E: 2017 [7] and DSTU-P STANAG 4370 AESTP-250 Ed. C: 2017 [8]. It should be noted that the stringent requirements of these NATO Standards are largely consistent with the requirements of similar US military Standards [9, 10]. Therefore, the implementation in Ukraine of tests of OAMT in accordance with NATO Standards will actually provide an opportunity to assess the compliance of our OAMT with the requirements of US military Standards, which are the most common in the world. Taking into account the novelty of the requirements of NATO Standards, in the paper it is advisable to analyze the technical characteristics of a number of new generators recently developed and created at Scientific-&-Research Planning-&-Design Institute «Molniya» of NTU «KhPI» for testing the stability of OAMT equipment to external (internal) PEMIs.

No less dangerous for the operation of power electric power equipment is such a source of PEMIs as switching overvoltages arising in electric power systems and networks of various voltage classes during regular switching on and emergency switching off of electric power consumers in them [11, 12]. In this regard, the development and use for practical purposes in the field of modern electrical technologies in assessing the real resistance and electric strength of the external (internal) insulation of electric power facilities of generators that reproduce switching voltage pulses with an amplitude of hundreds and thousands of kilovolts at industrial power (IP) facilities is relevant in world applied task. Emergency modes in their electrical circuits, accompanied by the flow of short-circuit currents (SC) with an amplitude of up to several tens of kiloamperes, are also dangerous for the reliable operation of power electrical equipment and electronic devices of power facilities of PE, aviation (AT) and space-rocket (SRT) technique [1, 11]. An electric charge of up to ±(50-200) C accumulated in thunderclouds due to electrophysical processes in the Earth's atmosphere during spark discharges from these clouds (for example, to ground objects or to objects caught in flight in the Earth's atmosphere) causes flow in their plasma channels of a powerful pulse current of a complex temporal shape with amplitude of up to ±(30-200) kA [3]. In this regard, US guiding technical documents SAE ARP 5412: 2013 [13] and SAE ARP 5416: 2013 [14] define stringent requirements for the normalized amplitude-temporal parameters (ATPs) of artificial lightning current pulses generated by powerful high-voltage lightning current generators (LCG) and used in tests of AT and SRT objects for lightning resistance. The International Standard IEC 62305-1: 2010 [15] and the National Standard of the Russian Federation GOST R IEC 62305-1-2010 [16] regulate the current requirements for the standardized ATPs of the aperiodic pulsed current pulse of an artificial lightning of a temporary shape of 10 μs/350 μs generated by a powerful high-voltage LCG, typical for a short thunderstorm into ground-based power facilities and used in testing of various objects of IP for lightning resistance. The indicated high-voltage LCG allow determining the real EMC indicators and the resistance of IP, AT, and SRT objects to the direct effect of lightning strikes on them. Therefore, the development, creation and practical application of powerful high-voltage LCG are currently relevant applied scientific and technical tasks for the diverse infrastructure of industrialized countries of the world.

According to the analysis of observations of thunderstorm activity at 178 weather stations of the country, National Energy Company Ukrenergo established that the duration of thunderstorm activity in Ukraine is increasing by 100 hours annually. Over the past 5 years, about 350 emergency switches off have occurred on power lines of classes 220-750 kV as a result of a direct lightning strike, 50 of which were accompanied by SC. Therefore, lightning voltage (current) pulses are a serious threat to energy objects for their operation. The critical state in the reliability and safety of operation of energy facilities in Ukraine is confirmed by a number of major accidents due to malfunctions of their grounding devices (GDs). Among them: ignition of the power transformer of the Rivne NPP in 2019 due to SC with the subsequent operation of the protection and the erroneous disconnection of its power unit No. 3 from the Ukrainian power system; disconnection of a substation of voltage class of 330 kV in the south of the country due to a false actuation of its protection system; erroneous disconnection of power unit No. 1 of Zmievskaya TPP in 2019. In this regard, the diagnostics and modernization of the GDs of power facilities will ensure both the electrical safety of their maintenance personnel and other persons who may suffer from the removal of electrical potential outside the power facilities, as well as the normal operation of the equipment of TPPs, NPPs HPPs.

In contrast to the high-voltage test installations created in foreign countries in the field of electrical safety, EMC, and the resistance of technical facilities to the action of artificial lightning and PEMIs according to [4-10, 12-16], the high-current high-voltage test electric equipment available in Ukraine is characterized by the originality of constructing its discharge electric circuits with a global priority and made of domestic components, structural and insulating materials [17-24]. For well-known reasons, the acquisition of expensive foreign electrical installations is an unrealistic task for us. In this regard, it is necessary to rely on our own original developments and electrical installations that implement the requirements of [4-10, 12-16]. Electrical installations of Ukraine for the implementation of the requirements of a number of US and NATO Standards [4-10] have not been described in literature.

The goal of the paper is analysis of the main technical characteristics and new capabilities of individual electrical installations of the high-voltage electrical complex Scientific-&-Research Planning-&-Design Institute «Molniya» of NTU «KhPI» designed to test IP objects for electrical safety, the effect of standard lightning and switching voltage (current) pulses on them, as well as OAMT, AT and SRT on EMC and resistance to action on them of normalized current pulses of artificial lightning and a number of special temporary shapes of current pulses (voltage).

1. A generator of full current artificial lightning with amplitude of up to ±200 kA. In 2007, the staff of the Scientific-&-Research Planning-&-Design Institute «Molniya» of NTU «KhPI» at its scientific and experimental training ground (Andreevka, Kharkiv region) created a powerful high-voltage high-current LCG of the UITOM-1 type [17], capable of testing elements of AT and SRT objects on lightning resistance in accordance with international requirements [13, 14]. According to US technical requirements [13, 14], in laboratory tests of devices and elements of aviation and rocket and space technology for resistance to the direct effect of full current of artificial lightning on them, its following components generated in high-voltage high-current LCG circuits can be used: pulsed *A*-, repeated pulsed *D*-, intermediate *B*-, long-term C- and shortened long-term *C**- current components of artificial lightning. We point out that most often in the practice of lightning tests of various devices and systems of civil and military aircraft, the following combinations of the indicated lightning current components are used [13, 17]: *A*-, *B*- and *C*-components; *A*-, *B*- and *C**- components; *D*-, *B*- and *C**-components. The main ATPs normalized according to [13, 14], typical for such components of the artificial lightning current in the electrical circuits of the LCG, can be summarized in Table 1.

Table 1
Normalized ATPs of the main components of the total current of artificial lightning [13, 14]

Lightning current component	I_m, kA	I_C, kA	q_C, C	J_a, 10^6 J/Ω	τ_f, μs	τ_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) ×10^3
C^*	–	0.4	6-18	–	–	15-45
D	100±10	–	–	0.25±0.05	≤25	≤0.5

Note. I_m is the amplitude of the current pulse; I_C is the average current value; q_C is the amount of the flowing charge; J_a is the integral of the action of the current pulse; τ_f, τ_p are, respectively, the duration of the pulse front between the levels (0.1-0.9)I_m and the current pulse at the level ≤0.1I_m.

Figure 1 shows a general view of a powerful LCG of the UITOM-1 type, and Fig. 2 is a schematic electrical diagram of the construction of this artificial lightning full-current generator. In accordance with the data in Fig. 2, the UITOM-1 type generator includes five separate and synchronously operating high-voltage pulse current generators (GIT) of capacitive design, each of which (GIT-*A*, GIT-*D*, GIT-*B*, GIT-*S* and GIT-*C**) on common electric load – the test object (TO) forms the corresponding components of the total current of artificial lightning [17]. The required combination of lightning current components (and, accordingly, the necessary combination of GIT) on a common TO is implemented using electrical jumpers X1-X4 (see Fig. 2).

Fig. 1. General view of the high-voltage high-current LCG of the UITOM-1 type, which simulates the direct influence of the main components of the artificial lightning current on the TO (in the foreground there is a working table with a three-electrode controlled air switch F_1 for voltage of ±50 kV and an air exhaust system, and in the background there are powerful high-voltage generators GIT-*A*, GIT-*D*, GIT-*B*, GIT-*C* and GIT-*C**) [17, 18]

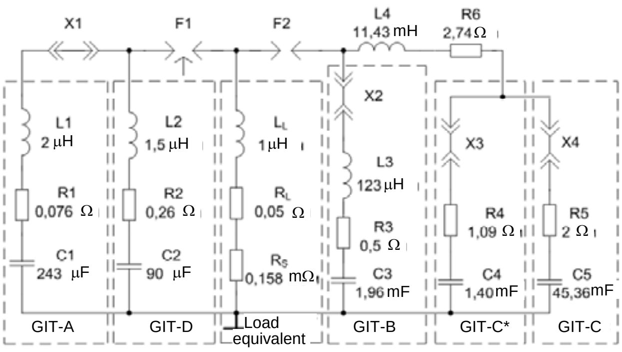


Fig. 2. Electrical circuits for the construction of discharge circuits of five high-voltage GITs (GIT-*A*, GIT-*D*, GIT-*B*, GIT-*C* and GIT-*C**) and UITOM-1 type LCG in general with one common electric $R_L L_L$ load (F_1, F_2 – three- and two-electrode high-current air switches for voltage ±50 kV and ±5 kV; *X*1-*X*4 – electrical jumpers; R_S=0.158 mΩ – active resistance of the measuring coaxial shunt ShK-300M1; *R*1-*R*5, *L*1-*L*3 – own electrical parameters of the circuits of GIT-*A*, GIT-*D*, GIT-*B*, GIT-*C** and GIT-*C*; *R*6, *L*4 – electrical parameters of the forming elements for the circuits of GIT-*C* and GIT-*C**) [18]

Powerful GIT-*A* and GIT-*D* generators are equipped with parallel-connected high-voltage low-inductance capacitors of the type IK-50-3 (they are charged to constant voltage $\pm U_{CA}$ of not more than ±50 kV), and GIT-*B*, GIT-*C* and GIT-*C** generators with high-voltage low-inductance capacitors of the IM-5-140 type (the latter are charged, respectively, to constant voltage $\pm U_{CB}$ and $\pm U_{CC}$ not more than ±5 kV). As a result, the total nominal energy stored in the UITOM-1 type LCG capacitors is 1.21 MJ [18].

To measure the ATPs generated by these LCGs at the TO (according to Fig. 2 on the total lumped $R_L L_L$ load R_L≈50 mΩ и L_L≈1 μH) of all components of the pulsed lightning current, one measuring high-voltage coaxial shunt of the ShK-300M1 type, with active resistance of R_S=0.158 mΩ and passed the state metrological verification is used [18].

Table 2 shows the main technical characteristics of a measuring high-current coaxial shunt of the ShK-300M1 type, the high-resistance disk element of which 1 mm thick and outer diameter of 80 mm was made of 12X18H10T stainless steel [19]. The design of this measuring shunt is capable of withstanding repeated full currents of artificial lightning flowing through it, characterized by the action integral up to J_a≈10·10^6 J/Ω.

Table 2

Main technical characteristics of the measuring shunt type ShK-300M1 [18, 19]

Shunt name	Characteristic value		
	R_S, mΩ	K_S, A/V	Mass, kg
ShK-300M1	0.158±1 %	K_{SA}=12625	3.1
		K_{SC}=6312	

Note. K_S=2/R_S is the shunt conversion coefficient, A/V; K_{SA} is the shunt conversion coefficient when measuring in the LCG discharge circuit of the ATPs of *A*- and *D*- components of the artificial lightning current, A/V (from the 1:1 coaxial connector of the matching voltage divider (MVD) type SDN-300); K_{SC} is the shunt conversion coefficient when measuring in the LCG discharge circuit of the ATPs of *B*-, *C*- and *C**- components of the artificial lightning current, A/V (from the 1:2 coaxial connector of the SDN-300 voltage divider matched).

Figures 3-5 show typical oscillograms of pulsed *A*-, intermediate *B*- and long-term *C*- components of the artificial lightning current normalized according to [13, 14] ATPs previously recorded in high-current discharge circuits of high-voltage generators GIT-*A*, GIT-*B* and GIT-*C* of the powerful LCG *of* UITOM-1 type using the ShK-300 measuring shunt (K_{SA}=11261 A/V; K_{SC}=5642 A/V [17]) and Tektronix TDS 1012 digital storage oscilloscopes. Designs of the used ShK-300 and ShK-300M1 shunts, as well as the original schemes for constructing measuring channels in the UITOM-1 LCG allow simultaneously registering the required combinations of lightning current components [18].

In Fig. 4 interesting metrological features are almost ideal zones (time zones located on the horizontal time axis in the regions of 300 μs and 5 ms) of «joining» or «stitching» of the measured current curves corresponding to the *A*-, *B*- and *C*- components of the full current of artificial lightning generated by a powerful LCG of the UITOM-1 type [17, 18]. The practical implementation of this approach while simultaneously recording the indicated components of the artificial lightning current was carried out by using a single voltage divider type SDN-300 in the measuring path.

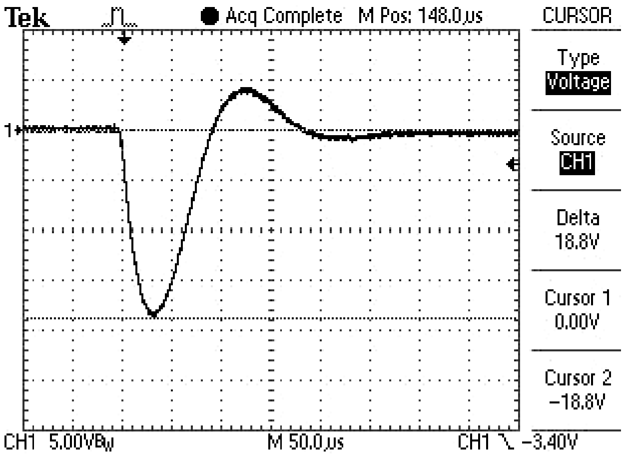


Fig. 3. Oscillogram of the pulsed *A*- component of the artificial lightning current with normalized ATPs in the high-current discharge circuit of the GIT-*A* generator of a powerful LCG of the UITOM-1 type (U_{3A}≈–29.7 kV; I_{mA}≈–212 kA; J_{aA}≈2.09·10^6 J/Ω; τ_f≈32 µs; τ_p≈500 µs; vertical scale – 56.3 kA/cell; horizontal scale – 50 µs/cell) [17]

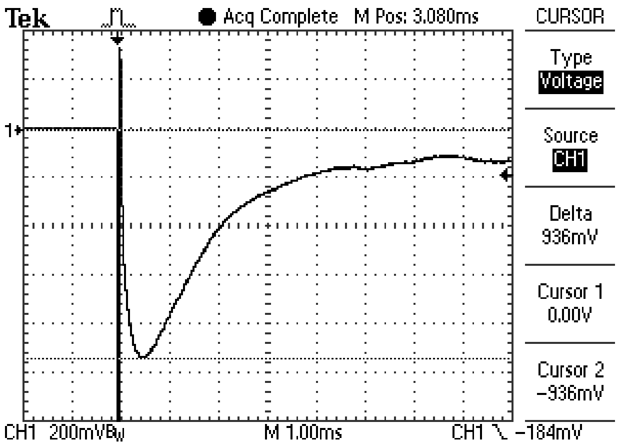


Fig. 4. Oscillogram of the intermediate *B*- component of the artificial lightning current with normalized ATPs in the high-current discharge circuit of the GIT-*B* generator of a powerful LCG of the UITOM-1 type (U_{3B}≈–4 kV; I_{mB}≈–5.28 kA; I_C≈2.08 kA; q_{CB}≈–10.4 C; τ_p≈5 ms; vertical scale – 1128.4 A/cell; horizontal scale − 1 ms/cell) [17]

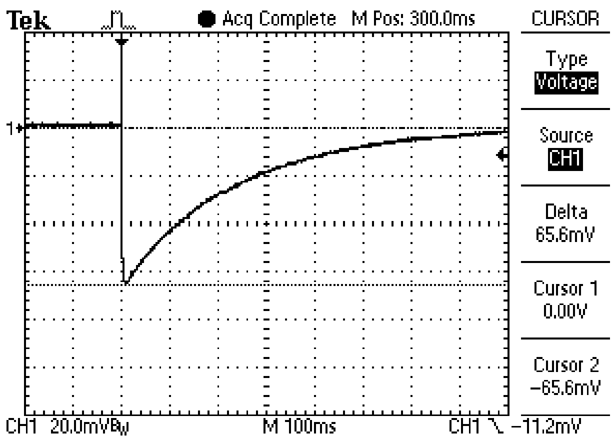
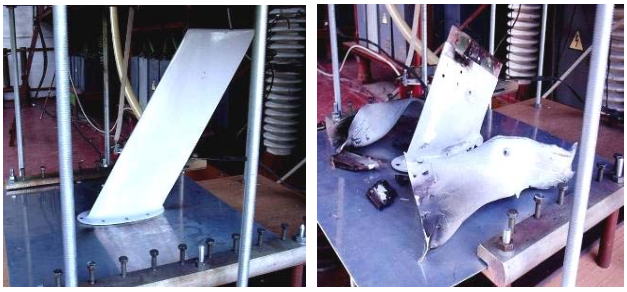


Fig. 5. Oscillogram of the long-term *C*- component of the artificial lightning current with normalized ATPs in the high-current discharge circuit of the GIT-*C* generator of a powerful LCG of the UITOM-1 type (U_{3C}≈–4 kV; I_{mC}≈–0.74 kA; q_{CC}≈–182 C; τ_f≈9 ms; τ_p≈1000 ms; vertical scale – 225.6 A/cell; horizontal scale − 100 ms/cell) [17]

Figure 6 shows the results of direct exposure to a pilot model of a domestic-produced aircraft receiving-transmitting antenna of only one pulsed *A*- component of the artificial lightning current, normalized according to [13, 14] the ATPs of which corresponded to the technical data indicated on the current oscillogram of Fig. 3 (I_{mA}≈–212 kA; J_{aA}≈2.09·10^6 J/Ω; τ_f≈32 µs; τ_p≈500 µs) [20].

The data in Fig. 6 clearly shows that the experimental model of the receiving-transmitting antenna of a domestic aircraft, designed and manufactured without fully taking into account the international requirements for lightning resistance given in the US regulatory documents [13, 14], underwent its complete destruction after direct exposure to its radio elements of pulsed *A*- artificial lightning current components with normalized ATPs.



a *b*

Fig. 6. External view of the experimental model of the receiving-transmitting antenna of a domestic aircraft before (*a*) and after (*b*) the direct impact on it in a high-current discharge circuit of a high-voltage generator GIT-*A* of a powerful LCG type UITOM-1 of only one pulsed *A*- component of the artificial lightning current with normalized ATPs (I_{mA}≈–212 kA; J_{aA}≈2.09·10^6 J/Ω; τ_f≈32 µs; τ_p≈0.5 ms) [20]

The UITOM-1 powerful high-voltage lightning current generator based on schemes for constructing and synchronizing the parallel operation of the discharge circuits of its five separate GITs, stored in capacitor banks electric energy, generated on the tested $R_L L_L$ load normalized ATPs of the components of the artificial lightning current and its comparatively low cost does not have foreign analogues [17].

2. A current pulse generator of a temporary shape 10/350 µs of artificial lightning with amplitude of up to ±200 kA. In 2014, at the indicated scientific and experimental training ground of the Scientific-&-Research Planning-&-Design Institute «Molniya» of NTU «KhPI», we created a unique powerful high-voltage high-current generator of current of short-term lightning strike of the GTM-10/350 type [21], on which tests of various ground-based IP objects can be carried out on lightning resistance to the direct action on them of an aperiodic current pulse of artificial lightning of a temporary shape τ_f/τ_p=(10±2) µs/(350 ± 35) µs of both polarities in accordance with the technical requirements set forth in international regulatory documents [15, 16]. The main normalized ATPs of this powerful test pulse of artificial lightning current, corresponding to a short shock of a thunderstorm high-current discharge into a protected electric power object (TO), are given in Table 3. From the data of Table 1, 3 it follows that the powerful test current pulse of a short thunderstorm high-current discharge of a temporary shape of 10/350 μs in terms of its energy indicators (first of all, by the value of the corresponding integral of the current action J_a) significantly exceeds the corresponding numerical indicators for pulsed *A*- and repeated pulsed *D*-component of the artificial lightning current (see section 1) used in testing of various objects of AT and SRT for lightning resistance in accordance with the regulatory documents in force [13, 14].

Table 3

Normalized ATPs of an aperiodic current pulse of a temporary shape 10 μs/350 μs [15, 16]

Name of the current pulse parameter	Lightning protection level according to the Standard IEC 62305-1: 2010		
	I	II	III-IV
Front duration τ_f, μs	10±2	10±2	10±2
Pulse duration τ_p at the level $0.5I_m$, μs	350±35	350±35	350±35
Current amplitude I_m, kA	200±20	150±15	100±10
Current action integral J_a, 10^6 J/Ω	10±3.5	5.6±1.96	2.5±0.875
Charge q_C, C	100±20	75±15	50±10

Figure 7 shows a general view of the generator type GTM-10/350, and Fig. 8 shows the electrical circuits for constructing (replacing) of its four separate high-voltage GITs (GIT-1 – GIT-4, synchronously working on one common electric R_LL_L load) and this generator as a whole.

Fig. 7. General view of a powerful high-voltage high-current generator of artificial lightning type GTM-10/350 (in the foreground there is its desktop with a controllable high-voltage three-electrode air switch placed on top of it with graphite electrodes for voltage ±50 kV and pulsed aperiodic lightning current with amplitude up to ±220 kA and a test sample of cable and wire products, and in the background there are the electrical elements of the charge-discharge circuits of its individual high-voltage pulse current generators GIT-1, GIT-2, GIT-3 and GIT-4) [21]

Note that the GIT-1 – GIT-3 generators are equipped with high-voltage low-inductance pulse capacitors type IK-50-3 (rated voltage ±50 kV; rated capacitance 3 μF), and the GIT-4 generator is equipped with high-voltage pulse capacitors of the IM2-5-140 type (rated voltage ±5 kV; rated capacitance 140 μF) [21]. In the GIT-1 – GIT-3 generators, their capacitors (respectively, in the amount of 16, 44 and 111 pcs.) are connected in parallel to the rated voltage of ±50 kV, and in the GIT-4 generator its capacitors (in the amount of 288 pcs.) – in series in parallel (two series-connected capacitors in each of the 144 parallel-connected sections) for rated voltage of ±10 kV. As a result, the total nominal energy stored in a high-voltage high-current generator of artificial lightning type GTM-10/350 is approximately equal to 1.15 MJ [21].

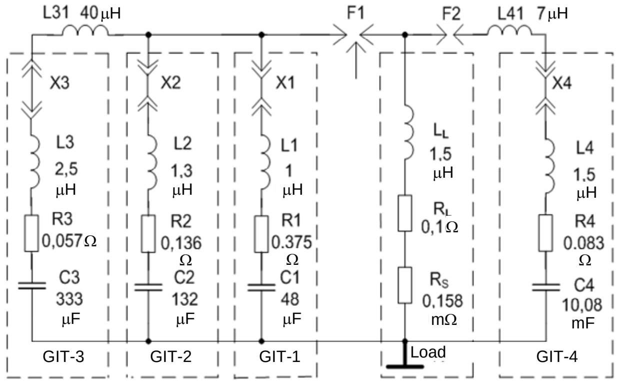


Fig. 8. Electrical equivalent circuits of high-current discharge circuits of four separate high-voltage generators GIT-1 – GIT-4 as parts of a high-power current pulse generator 10/350 μs of artificial lightning type GTM-10/350, working on one common electric R_LL_L load ($X1 - X4$ – conductive jumpers of discharge circuits of GIT-1 – GIT-4; $R1$-$R4$, $L1$-$L4$ – own electrical parameters of circuits of GIT-1 – GIT-4; $L31$, $L41$ – electrical parameters of forming reactive elements for discharge circuits of generators GIT-3 and GIT-4) [21, 22]

Figure 9 shows an oscillogram of a powerful aperiodic current pulse of a temporary shape of 10/350 μs with normalized ATPs obtained in a high-current discharge circuit of a high-voltage generator of the GTM-10/350 type with a low-resistance active-inductive load (R_L≈0.1Ω; L_L≈1.5 μH).

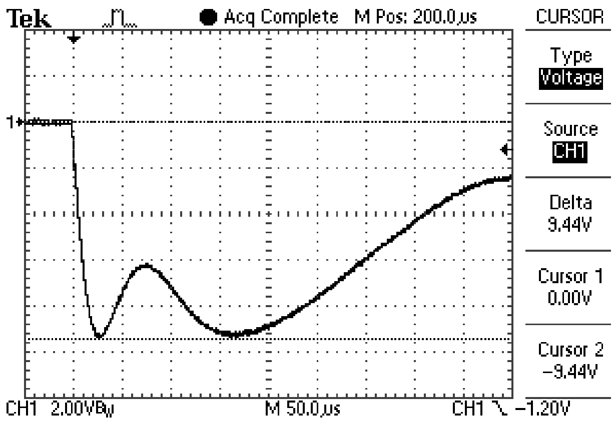


Fig. 9. Oscillogram of an aperiodic current pulse of negative polarity in a high-current discharge circuit of a high-voltage generator GTM-10/350 with an active-inductive load (R_L≈0.1 Ω; L_L≈1.5μH; U_{31-3}=−15 kV; U_{34}=−2.25 kV; I_m≈–106 kA; J_a≈3.03·10^6 J/Ω; q_C≈–52.2 C; τ_f≈15 μs; τ_p≈340 μs; vertical scale – 22.52 кA/cell; horizontal scale − 50 μs /cell) [22]

The ATPs of the aperiodic current pulse of artificial lightning (see Fig. 9), formed in the discharge circuit of the GTM-10/350 generator, was measured using a ShK-300 type coaxial shunt (K_S = 11261 A/V [17]) and digital storage oscilloscope series Tektronix TDS 1012. The charging voltage $U_{C1\text{-}3}$=$U_{31\text{-}3}$ of negative polarity of the capacitors for the generators GIT-1 – GIT-3 in this case was about 15 kV, and the charging voltage U_{C4}=U_{34} of the same polarity of the individual capacitors for the generator GIT-4 was 2.25 kV.

Figure 10 shows the results of the impact on a solid aluminum core with cross section of 6 mm^2 of АППВнг2×6 network cable with polyvinylchloride (PVC) insulation of an aperiodic current pulse of a short shock of a lightning discharge of a temporary shape of 17/265 μs with amplitude I_m≈ –83.8 kA obtained in a discharge circuit of GTM-10/350 [23].

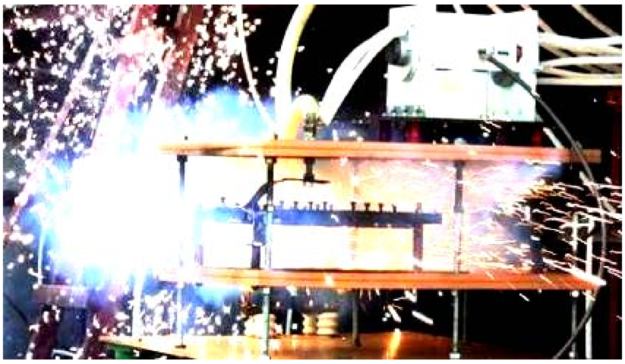


Fig. 10. Results of the electrothermal action in the discharge circuit of the GTM-10/350 type artificial lightning current generator of a normalized aperiodic current pulse of a short thunderstorm discharge of a temporary shape of 17/265 μs with amplitude of I_m≈ –83.8 kA on the test sample of the АППВнг2×6 network cable with PVC insulation and solid aluminum core of cross section of 6 mm^2 [23]

From the data in Fig. 10 it is shown that the test sample of АППВнг2×6 network cable with PVC insulation (TO) could not stand the indicated electrothermal effect of normalized to [15, 16] aperiodic current pulse of artificial lightning. Its continuous round aluminum core with cross section of 6 mm^2 together with its PVC insulation due to the onset of an electric explosion (EE) in it (the core) underwent sublimation and complete destruction. Note that the EE of the tested in the discharge circuit of the GTM-10/350 for thermal resistance to the indicated powerful current pulse of artificial lightning of a test sample of the network cable with a current-carrying aluminum part causes a noticeable deformation of the current pulse acting on it. In this case, the values of τ_f increase and the values of τ_p decrease. A powerful high-voltage lightning current generator of the type GTM-10/350 has no foreign analogues according to the schemes for constructing and synchronizing the parallel operation of the discharge circuits of four separate GITs, stored in capacitor banks of electric energy, generated at the R_LL_L load the normalized ATPs of a lightning current pulse of a short shock and its relatively low cost [21].

3. A generator of standard switching aperiodic voltage pulses with amplitude of up to ±2 MV. To test the electrical strength of the insulation of objects at the scientific and experimental training ground of the Scientific-&-Research Planning-&-Design Institute «Molniya» of NTU «KhPI», in 2012 a powerful generator of switching voltage pulses (GSVP) was created, which allows generating on the electrical load with a capacitive characteristic (for example, on insulators, high voltage bushings , disconnectors, capacitors, transformers, etc.) standard aperiodic voltage pulses of positive (negative) polarity of the temporal shape T_g/τ_p≈205 μs/1900 μs, where T_g, τ_p are, respectively, the rise time and duration at the level of 0.5 U_m of the voltage pulse, at their amplitude U_m up to ±2 MV [12, 24]. Figure 11 is a general view of this ultra-high-voltage generator.

Fig. 11. General view of GSVP of GKIN-2 type, which forms a standard aperiodic switching pulse of voltage of a temporary shape T_g/τ_p ≈205/1900 μs with amplitude U_m up to 2 MV on the tested electric power facility (the modernized generator GIN-4 is placed on the right, and an insulating support 11 m high with load capacitance C_l≈13.3 nF for 3 MV, to the upper potential electrode of which from the GIN-4 generator forming R_f≈4.28 kΩ and from the load capacitance – current-limiting R_l ≈4.59 kΩ resistors are connected) [24]

Figure 12 shows a circuit diagram of an ultra-high-voltage generator GKIN-2, assembled on the basis of using a modernized by us in 2012 for generating on test objects (TO) at electric power facilities in accordance with the requirements of [12] of a standard switching aperiodic voltage pulse of a temporary shape (250±50) μs/(2500±750) μs of a pulse voltage generator (PVG) for rated voltage of 4 MV and stored electric energy up to 1 MJ [25], built on the indicated training ground (field stand) of the Institute in the 1970s according to the classical Arkadyev-Marx scheme [26]. Note that GIN-4 (see Fig. 12) has a bookcase structure and contains 16 cascades, each of which (with the exception of the first cascade from the ground) includes one uncontrolled air two-electrode ball spark gap F with diameter of 125 mm and eight high-voltage capacitors C in the metal case KBMG-125/1 (rated voltage ±125 kV; capacitance 1 μF) of our own design [25, 27].

The first cascade of the GIN-4 generator from the ground is equipped with a high-voltage controlled air three-electrode spark gap (trigatron) F_1 of diameter of 125 mm, started from a special start-up pulse generator (SPG) of own design of the Scientific-&-Research Planning-&-Design Institute «Molniya» of NTU «KhPI», which supplies damped pulses microsecond duration to the trigatron F_1 electrodes, characterized by voltage amplitude of up to ±10 kV [28].

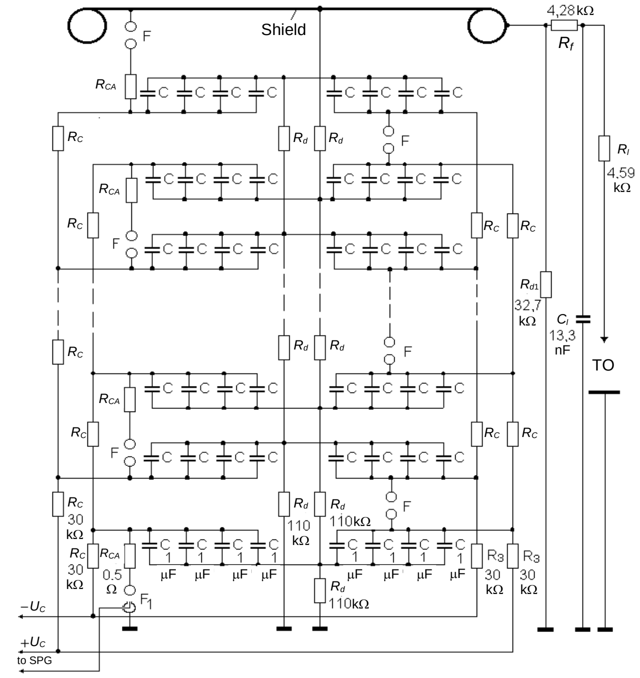


Fig. 12. Schematic diagram of the ultra-high-voltage GKIN-2 generator, assembled on the basis of the modernized powerful bipolar generator GIN-4 for rated voltage of 4 MV, connected to the proposed circuit for the formation of standard switching aperiodic voltage pulses on the TO (two-electrode needle-plane system with a long air discharge gap) containing an additional discharge resistor R_{d1}=32.7 kΩ, forming resistor R_f =4.28 kΩ, load capacitance C_l= 13.3 nF and current-limiting resistor R_l=4.59 kΩ [24]

The GIN-4 modernized by us in each of the charge branches of positive and negative polarities to constant voltage $\pm U_C$ of capacitors C with porcelain insulators (see Fig. 12) contains instead of low-resistance charging resistors with nominal value of 500 Ω the high-resistance charging resistors R_C=30 kΩ with a total of 32 pcs.

Each of the 16 GIN-4 cascades for a rated voltage of 250 kV is equipped with one soothing resistor R_{CA}=0.5 Ω. The parallel charge of capacitors C in GIN-4 to the corresponding constant voltage $\pm U_C$=$\pm U_3$ is carried out from two powerful high-voltage chargers of the GKIN-2 through four chains of series-connected charging R_C=30 kΩ (16 pcs. for each of two bipolar branches of charge) and two chains of series-connected discharging R_d=110 kΩ (8 pcs. each with a total discharge resistance of GIN-4 equal to 440 kΩ) resistors, each of which was calculated for rated voltage of 500 kV. The GIN-4 construction at the top contains a rectangular steel shield with round edges connected to its discharge circuit, to which shown in Fig. 12 forming elements and the required TOs are galvanically connected.

Figure 13 shows an oscillogram of a full standard switching aperiodic voltage pulse of positive polarity of a temporary shape T_g/τ_p≈205/1900 µs with amplitude U_m≈783.2 kV, obtained using the discharge of the described ultra-high-voltage generator GKIN-2 for an electrical load (TO), made in the form a long air gap (about 3 m long) in a two-electrode needle-plane system (Fig. 14, a steel rod was used for the «needle», and 5×5 m galvanized sheets were used for the «plane»).

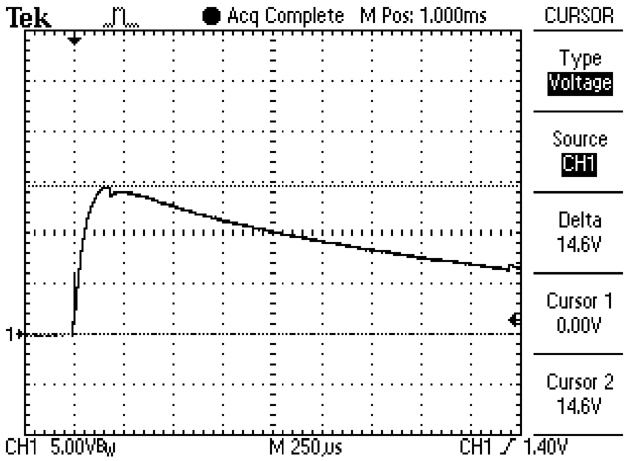


Fig. 13. Oscillogram of a full switching aperiodic voltage pulse of positive polarity on a needle-plane two-electrode system with an air gap of 3 m (U_3≈±40 kV; U_m≈783.2 kV; T_g≈205 µs; τ_p≈1900 µs; vertical scale – 268.2 kV/cell; horizontal scale – 250 µs/cell) [29]

Fig. 14. General view of the TO – a two-electrode needle-plane system with an air gap of 3 m, to the upper electrode of which GKIN-2 and the measuring ohmic divider of the pulse voltage ODN-2 to rated voltage of ±2.5 MV are galvanically connected [29]

Note that when measuring the ATPs of switching pulses of voltage of a temporary shape T_g/τ_p≈205/1900 µs, formed in the discharge circuit of the GKIN-2 in the TO shown in Fig. 14, an ODN-2 type ultra-high-voltage ohmic pulse voltage divider [29] matched in the measuring circuit having a division ratio K_d ≈ 53650 and a shielded cable transmission line from the TO of a useful electrical signal up to 60 m in length, and a Tektronix digital storage oscilloscope TDS 1012, located away from the considered GKIN-2 in a buried shielded measuring hopper, were used.

Figure 15 shows an oscillogram of a positive-polarity aperiodic switching voltage pulse of amplitude

U_m≈1030 kV cut off at the front obtained with GKIN-2 during electrical breakdown of air insulation of 3 m in length in the needle-plane two-electrode discharge system shown in Fig. 14. It can be seen that in this case, the cutoff time is T_C≈90 µ.

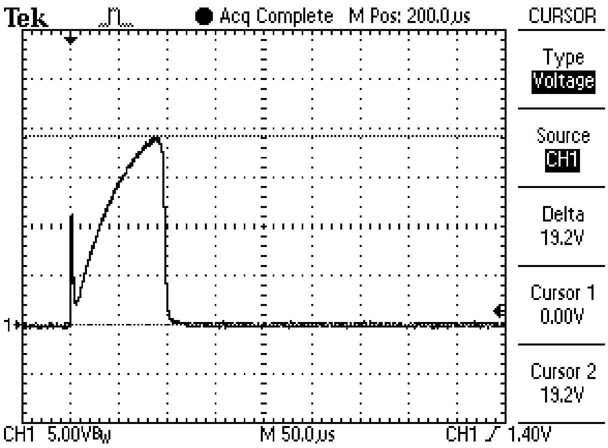


Fig. 15. Oscillogram of a cut off ultra-high-voltage switching aperiodic voltage pulse of positive polarity on a two-electrode needle-plane system with an air gap of 3 m ($U_З$≈±60 kV; U_m≈1030 kV; T_C≈90 µs; vertical scale – 268.2 kV/cell; horizontal scale – 50 µs /cell) [29]

We indicate that from the data in Fig. 13, 15 it follows that at the front of the switching aperiodic voltage pulse of the temporary shape T_g/τ_p≈205/1900 µs generated by the GKIN-2, a peak-like burst of up to 7 µs duration is observed [24], due to the operation peculiarity of the GKIN-4 ultra-high-voltage generator used in the test circuit, associated with the presence in it of a steel roof-top screen with area of up to 60 m^2 and a fast charge-discharge of its parasitic electric capacitance in the process of a powerful discharge to forming electrical elements and TO according to the diagram in Fig. 12 of power capacitors C = 1 µF of all GIN-4 cascades (with the capacitance «in the discharge» of this PVG equal to approximately 0.125 µF) when its high-voltage spark gaps F_1 and F are triggered. The GKIN-2 powerful ultra-high-voltage generator of aperiodic switching voltage pulses does not have foreign analogues today [24] according to the schemes for constructing its charge-discharge circuits (cascades) and normalized ATPs of the standard aperiodic switching pulse of 250/2500 µs voltage generated at the test object.

4. A generator TI-CS115 (NCS08). This generator is designed to test the components of the OAMT for conductive susceptibility to pulsed currents of the form CS115 [9] and NCS08 [7]. Test currents are supplied into the TO by feeding them into cable bundles through injectors. A general view of this generator is shown in Fig. 16.

The test current pulse generated by the TI-CS115 (NCS08) type generator on an electric load has a trapezoidal shape with a rise time of the front T_F≈2 ns, a fall time T_D≈2 ns and a horizontal section duration T≈30 ns. Figures 17-19 show typical oscillogram of a test current pulse of the shape required by [9].

Fig. 16. Generator of type TI-CS115 (NCS08), which reproduces pulse currents of the form CS115 [9] and NCS08 [7] on the TO

The output characteristics of the generator TI-CS115 (NCS08) are given in Table 4. The generator of pulsed currents of the type CS115 [9] and NCS08 [7] does not have known foreign analogues according to ATPs of special shaped test current pulses (see Fig. 17-19).

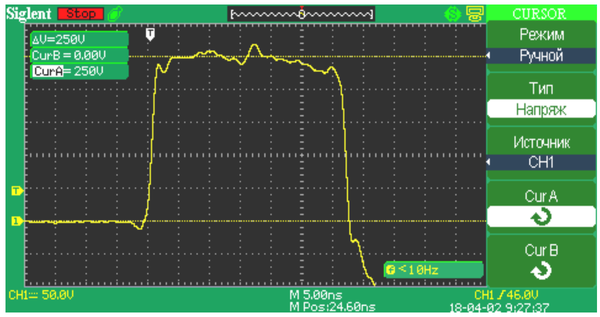


Fig. 17. Typical oscillogram of a test current pulse of the form CS115 with amplitude of 5 A of positive polarity generated by a generator of the type TI-CS115 (NCS08)

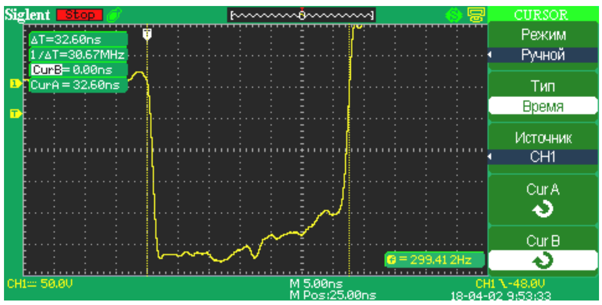


Fig. 18. Typical oscillogram of a test current pulse of the form CS115 with amplitude of 5 A of negative polarity generated by a generator of the type TI-CS115 (NCS08)

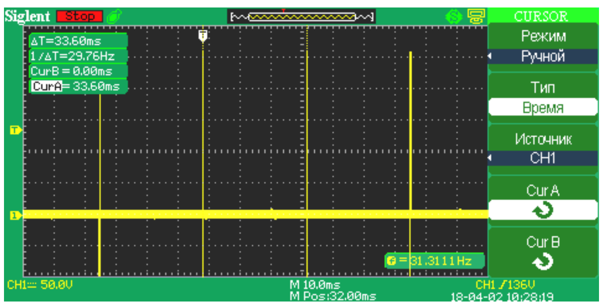


Fig. 19. Typical oscillogram of the repetition rate f_F =30 Hz of a test current pulse of the form CS115 generated by a generator of the type TI-CS115 (NCS08)

Table 4

Results of determining the characteristics of the generator TI-CS115 (NCS08) in the mode of measuring its current pulses

Technical characteristics of the output current pulse	Current I_p, A	T, ns	T_F, ns	T_D, ns	f_F, Hz	Pulse shape
Requirements of regulatory documents [7, 9]	5+1	not less than 30 ns	no more than 2 ns	no more than 2 ns	30 Hz ± 3 Hz	Trapezoid
Actual values for positive pulse	5±0.06	32.8	1.92	1.92	29.94±0.27	Trapezoid
Actual values for negative pulse	5±0.07	32.6	1.96	1.84	29.94±0.36	Trapezoid
Conclusion of compliance	meet	meet	meet	meet	meet	meet

Note: T is the duration of the horizontal part of the current pulse; T_F is the rise time of the front of the current pulse; T_D is the decay time of the current pulse; f_F is the repetition rate of current pulses.

5. A generator TI-CS116 (NCS09). This high-frequency generator is designed to test the components of the OAMT for conductive susceptibility to pulsed currents of the type CS116 [9] and NCS09 [7] also by the method of feeding test current pulses formed by it into the bundles of their cables through injectors. In this case, the current pulses have the shape of a damped sine wave, the frequency f_0 of which varies in the range from 10 kHz to 80 MHz. The current values are set depending on the frequency f_0 of the sinusoidal oscillations of the pulse current. The decrement of current oscillations is also regulated by the requirements of [7, 9]. The external view of the TI-CS116 (NCS09) type generator is shown in Fig. 20.

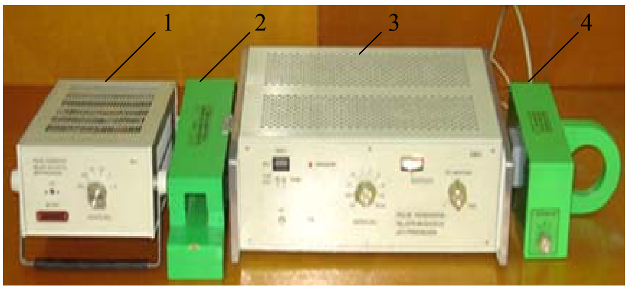


Fig. 20. General view of a high-frequency generator of the type TI-CS116 (NCS09) (1 – block F1; 2 – injector IG-3; 3 – power supply unit DP; 4 – block F2 with an inserted module M10)

The block diagram of the construction of this generator is shown in Fig. 21, and the main technical data on the parameters of the pulse current generated by it are given in Table 5, 6.

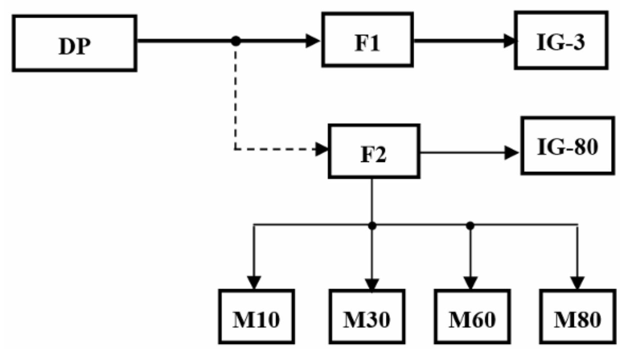


Fig. 21. Block diagram of the construction of a high-frequency generator of the TI-CS116 (NCS09) type (DP – power supply and switch control unit; F1 – frequency generation unit from 10 kHz to 3 MHz; F2 – frequency generation unit from 10 MHz to 80 MHz; M10 – replaceable module with frequency of 10 MHz; M30 – replaceable module with frequency of 30 MHz; M60 – replaceable module with frequency of 60 MHz; M80 – replaceable module with frequency of 80 MHz; IG-3 – injector for frequencies from 10 kHz to 3 MHz; IG-80 – injector for frequencies from 10 MHz to 80 MHz)

Table 5

Dependence of the peak value of the pulse current I_P on its frequency f_0

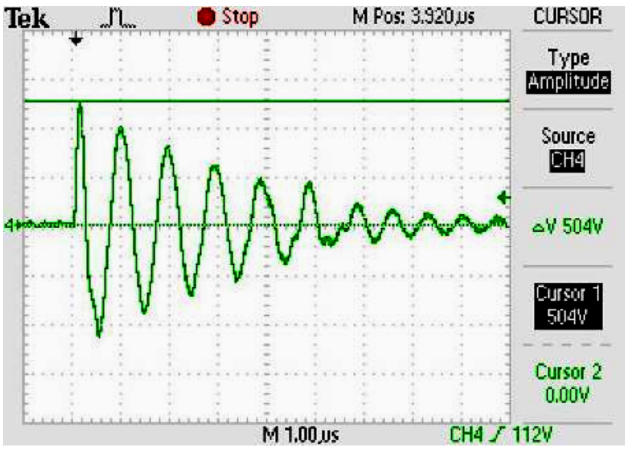
Frequency f_0, MHz	0.01	0.03	0.1	0.3	1	3	10	30	60	80
Current I_P in accordance with RD [7, 9], A	0.1+0.02	0.3+0.06	1+0.2	3+0.6	10+2	10+2	10+2	10+2	5+1	3.8+0.8
Current I_P according to the results of verification, A	positive polarity of pulse current									
	0.101±0.002	0.3±0.001	1.01±0.013	3±0.08	10.08±0.05	10.08±0.009	10.08±0.05	10.08±0.11	5.04±0.04	3.84±0.02
	negative polarity of pulse current									
	0.101±0.002	0.3±0.003	1.01±0.007	3±0.08	10.08±0.04	10.08±0.009	10.08±0.05	10.08±0.008	5.04±0.04	3.84±0.03

Table 6

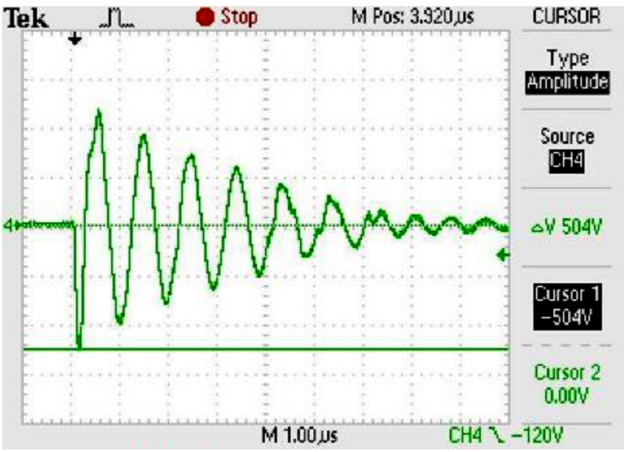
Dependence of the pulse current I_P by cycles on frequency f_0

N (cycle number)	I_N/I_P in accordance with RD [7, 9]	Frequency f_0, MHz									
		0.01	0.03	0.1	0,3	1	3	10	30	60	80
		I_N/I_P according to the results of verification (I_N – current of the N-th cycle; I_P – rated current)									
1	from 0.73 to 0.85	positive polarity of pulse current									
		0.85	0.80	0.81	0.83	0.73	0.73	0.73	0.73	0.75	0.74
		negative polarity of pulse current									
		0.85	0.80	0.81	0.83	0.73	0.73	0.73	0.73	0.75	0.74
2	from 0.53 to 0.73	positive polarity of pulse current									
		0.59	0.60	0.58	0.65	0.59	0.54	0.59	0.55	0.54	0.54
		negative polarity of pulse current									
		0.59	0.60	0.58	0.65	0.59	0.54	0.59	0.55	0.54	0.54
3	from 0.39 to 0.62	positive polarity of pulse current									
		0.40	0.43	0.43	0.49	0.48	0.44	0.44	0.39	0.39	0.40
		negative polarity of pulse current									
		0.40	0.43	0.43	0.49	0.48	0.44	0.44	0.39	0.39	0.40
4	from 0.28 to 0.53	positive polarity of pulse current									
		0.30	0.28	0.29	0.37	0.37	0.37	0.35	0.29	0.29	0.28
		negative polarity of pulse current									
		0.30	0.28	0.29	0.37	0.37	0.37	0.35	0.29	0.29	0.28

Oscillograms of the current I_P for several frequencies f_0 from their above range are presented in Fig. 22-24.

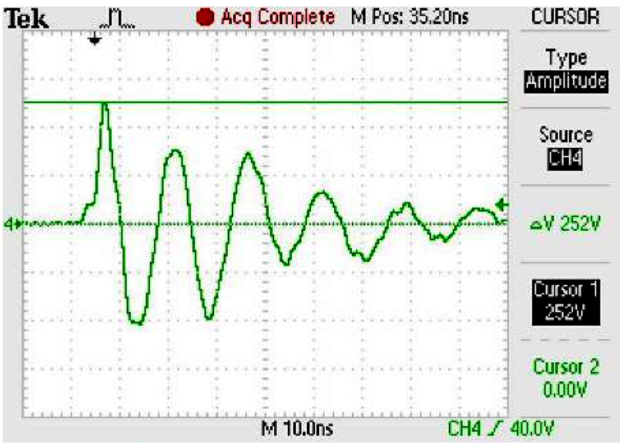


a

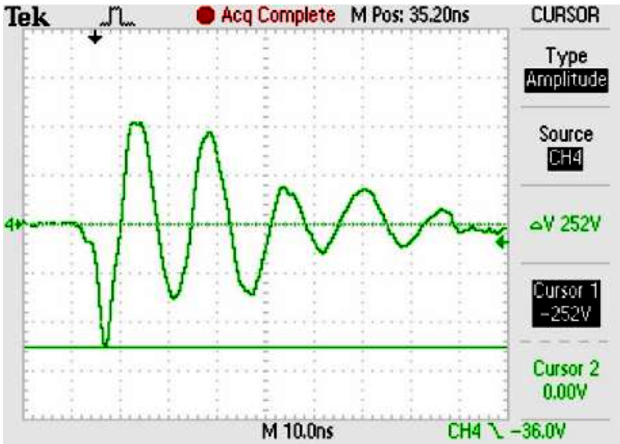


b

Fig. 22. Typical oscillograms of a test pulse current of the form CS116 with frequency f_0=1 MHz and amplitude of 10 A
(*a* – positive, *b* – negative polarity)



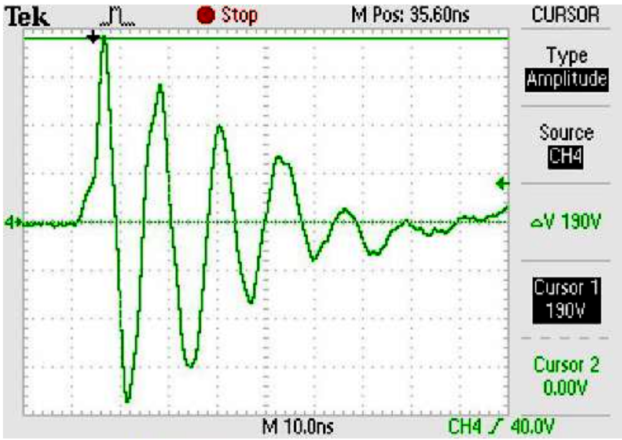
a



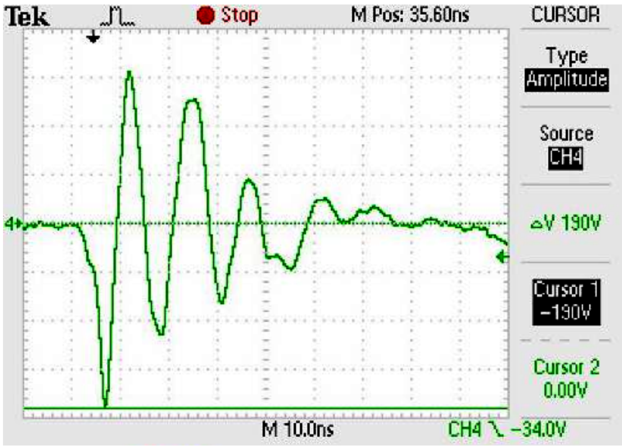
b

Fig. 23. Typical oscillograms of a test pulse current of the form CS116 with frequency f_0=60 MHz and amplitude of 5 A
(*a* – positive, *b* – negative polarity)

A comparison of the technical requirements of regulatory documents (RD) according to [7, 9] for the generated current pulses, with the ATPs generated by this electrical installation of current pulses, obtained by us in the process of verification of test electrical equipment, clearly indicates their full compliance. We point out that today the TI-CS116 (NCS09) high-frequency generator according to ATPs of generated test current pulses also has no foreign analogues.



a



b

Fig. 24. Typical oscillograms of a test pulse current of the form CS116 with frequency f_0=80 MHz and amplitude of 3.8 A (*a* – positive, *b* – negative polarity)

6. A generator G-NCS10. This current pulse generator is designed to test the components of the OAMT for lightning resistance in the form of NCS10 according to section 3.25 of the NATO Standard AESTR-500: 2016 [7]. A general view of the high-voltage generator G-NCS10 is shown in Fig. 25. This generator allows to generate a powerful aperiodic current pulse of a temporary shape of 50 μs/500 μs at current of up to 10 kA with charge voltage of its capacitor bank up to 2 kV. The G-NCS10 generator differs from the schemes of foreign electrical appliances of a similar class [7] by the original design of its charge-discharge circuits and high specific technical characteristics at the output. Today, this generator has no analogues in foreign countries according to the schemes for constructing its forming electric circuits and has a relatively low cost.

At the Institute, a mathematical model was developed to assess the distribution of the probability of lightning striking the surface of an aircraft. An experimental testing of a computer code for this scientific direction was carried out on the model of an A320 airplane. The frames of the process of such high-voltage tests of aircraft using the G-NCS10 generator and other generators are presented in Fig. 26.

Fig. 25. General view of a high-voltage current pulse generator of the G-NCS10 type, which implements the requirements of the NATO AESTR-500: 2016 Standard when testing OAMT in the form of NCS10 (Scientific-&-Research Planning-&-Design Institute «Molniya» of NTU «KhPI», Kharkiv, 2018)

Fig. 26. Frames from the process of experimental determination of the likely places of a lightning strike in an airplane model

In the course of these tests, it was found that the recommendations of US documents SAE ARP 5414 [30] and SAE ARP 5416 [14] require clarification due to the difference between streamer-leader processes on real and large-scale TOs. The solution to this problem is important not only for aircrafts, but also for other samples of OAMT.

Table 7 presents a list of the main types of tests that are regulated by the NATO Standard according to [7], and the possibility of their implementation at our Institute, taking into account promising developments, the completion of which is scheduled for the end of 2020.

Table 7

Nomenclature of tests and measurements (sample from Table 501-6, 501-7 of AECTP-500: 2016 Standard [7])

Type of test	Name	Platform type	Degree of implementation
1	2	3	4
NCE01	Conducted Emissions, Power Leads, 30 Hz to 10 kHz	Submarine and Air Force only	Full
NCE02	Conducted Emissions, Power Leads, 10 kHz to 10 MHz	All types	Full
NCE04	Conducted Emissions, Exported Transients on Power Leads	Excluding space	Full
NCE05	Conducted Emissions, Power, Control & Signal Leads, 30 Hz to 150 MHz	Excluding space	Full
NCS01	Conducted Susceptibility, Power Leads, 30 Hz to 150 kHz	All types	Full
NCS02	Conducted Susceptibility, Control & Signal Leads, 20 Hz to 50 kHz	Excluding space	Full
NCS07	Conducted Susceptibility, Bulk Cable Injection, 10 kHz to 200 MHz	All types	Full
NCS08	Conducted Susceptibility, Bulk Cable Injection, Impulse Excitation	Excluding ships and submarines	Full
NCS09	Conducted Susceptibility, Damped Sinusoidal Transients, Cables and Power Leads, 10 kHz to 100 MHz	All types	Full
NCS10	Conducted Susceptibility, Imported Lighting Transients	Air Force only	Full
NCS12	Conducted Susceptibility, Electrostatic Discharge	Ground and Air Force only	Full
NRE01	Radiated Emissions, Magnetic Field, 30 Hz to 100 kHz	Excluding space	Full
NRE02	Radiated Emissions, Electric Field, 10 kHz to 18 GHz	All types	Up to 6 GHz
NRS01	Radiated Susceptibility, Magnetic Field, 30 Hz to 100 kHz	Excluding space	Full
NRS02	Radiated Susceptibility, Electric Field, 50 kHz to 40 GHz	All types	Up to 6 GHz; up to 50 V/m

Note: All types – including surface ships, submarines; ground forces, air force; space systems and launch complexes.

7. An installation for monitoring the state of electrical safety and grounding systems of electric power facilities. When performing this control, the electrical and technological parameters of the GDs of the required energy objects are determined. These parameters include: GD resistance; voltage on the GD; touch voltage and GD design. The analysis by the Institute staff on the results of diagnostics of the GDs of more than 1200 power facilities in Ukraine (including four NPPs, 15 TPPs, 4 HPPs, 100 substations with voltage class of 220-750 kV, 900 substations with voltage class of 35-150 kV, etc.) showed that during SC in the power system, exceeding the permissible value of touch voltage at power facilities is fixed at more than 75 % of substations with voltage class of 110-750 kV. The most widespread in the world practice of monitoring the safe operation of electrical installations and during experimental measurement of touch voltage at power facilities is a method based on the use of the «low current method» followed by reduction of the measured touch voltage in direct proportion to the ratio of the actual SC current to the measuring current at the facility [31, 32]. A method based on the application of direct SC current for these purposes is extremely dangerous both for electrical equipment and for technical personnel serving it.

Today, at the Scientific-&-Research Planning-&-Design Institute «Molniya» of NTU «KhPI», electrical engineering works are successfully carried out aimed at improving the reliability of operation of industrial enterprises, energy facilities and transport infrastructure by developing optimal recommendations for the modernization of their GDs based on electromagnetic diagnostics at power facilities operating in Ukraine. For this purpose, at our Institute in the 1990s, a measuring complex was developed and created for diagnosing the state of GDs of power facilities of the KDZ-1 type, the main technical characteristics of which are given in [33]. In 2019, we created a new MV 1000 device, the characteristics of which (Table 8) correspond to the world level in terms of completeness of covering the requirements of IEC standards in terms of ensuring the safe operation of electrical installations [34]. It allows to determine the resistance of contact joints and GDs; voltage on the GD; step voltage; touch voltage and topology of the location of the GDs in the ground.

Table 8

Instrument specifications of the device type MV 1000

Parameter name	Value
Frequency of generated alternating voltage and current, Hz	57 ± 1; 263 ± 2; 523 ± 3; 993 ± 3
Measuring range of generated alternating voltage, V	from 0.5 to 45
Measuring range of generated alternating current, A	from 0.05 to 8.0
Relative error of voltage (current) measurement, %, no more	± 4

Figure 27 shows a scheme for measuring touch voltage using this installation. According to this scheme, the potential electrode *P* must simulate two human feet.

To do this, they use a special electrode-plate with contact surface of size (25 × 25) cm^2. To create reliable contact of this electrode with the ground, a load weighing at least 25 kg is installed on it. The voltmeter is shunted by a resistor with resistance R_B, which should be equal to the resistance of the human body (as a rule, it is taken equal to about 1000 Ω). The horizontal distance from the place of contact of the human feet to the plate to the metal structure of the object is assumed to be from 0.8 m to 1 m [32].

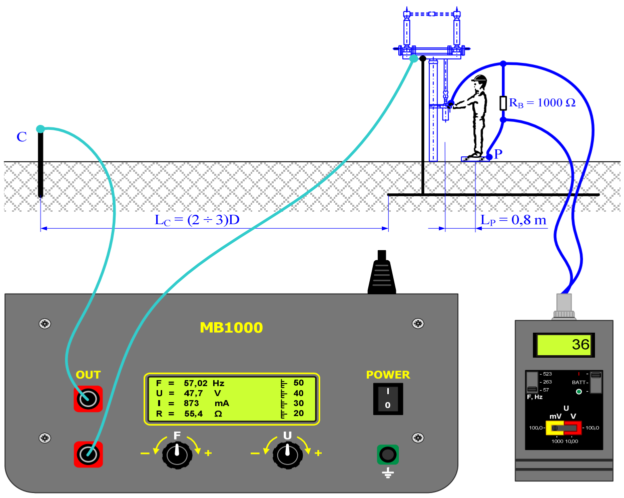


Fig. 27. Touch voltage measurement scheme

The current electrode *C* (see Fig. 27) is located from the place of measuring the touch voltage at a distance equal to (2-3)*D*, where *D* is the diagonal of the GD. Such a distance was accepted for equivalent homogeneous soil according to [31]. The generator is connected to the equipment and electrode *C*, and a voltmeter is connected between the potential electrode and the equipment. To simulate the most adverse seasonal conditions, the installation site of potential electrode *P* is wetted. They lead the measured values of the touch voltage to a real SC current and compare the result with a known acceptable normalized voltage value.

It should be noted that the specified MV 1000 type electrical appliance allows to determine the topology of the GD location without revealing the soil at the place of work on its (this GD) diagnosis (Fig. 28).

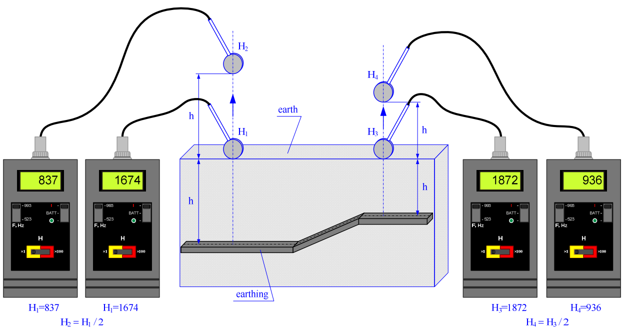


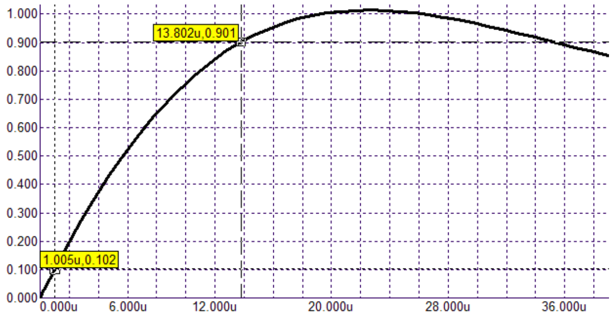
Fig. 28. Scheme for determining the topology of the location of the object's GD using an electrical installation of type MV 1000

Using a new electric device of type MV 1000 for diagnosing the state of the GDs allows:

- increase the accuracy of determining the parameters of the GDs (error – up to 4 %, for analogues – up to 10 %);
- finally move in Ukraine to the European model for determining the normalized parameters of the GDs of power facilities, where the main parameters are touch voltage and step voltage;
- increase the reliability and operation safety of existing domestic power plants (TPPs, NPPs, HPPs) and substations;
- increase the competitiveness of the Scientific-&-Research Planning-&-Design Institute «Molniya» of NTU «KhPI» in Ukraine and enter the European electrical engineering market regarding diagnostics of GDs (the first step to achieve such a commercial goal was the presentation of the MV 1000 device at the International technical exhibition ENERGETAB, Bielsko-Biala, Poland, September 17-19, 2019).

8. An installation for determining the pulse resistance of lightning rods and supports of power lines. In the domestic document [35] there is no concept of pulse resistance of a GD. However, in international requirements, in particular, according to [15, 36], the resistance of the GDs of lightning rods and the supports of overhead power transmission lines (PTLs) is determined at the action on them of a current pulse with specified ATPs as the ratio of the peak voltage value on the GD to the peak value of the current flowing through GD. In the world there are a number of devices that allow to determine the pulse resistance of the GD. A detailed analysis of existing portable devices for this purpose is presented in [37], among which there are Polish WG-407, WG-507 and MRU-200, Japanese PET-7, ZED-meter manufactured in the USA, Ukrainian IK-1U and Russian impedance meter. It should be noted that only three of these devices allow measurements to be made when simulating the impact on power objects of lightning voltage (current) pulses, namely: WG-507 with a voltage (current) pulse of 4/10 µs, MRU-200 with voltage pulses (current) 4/10 µs and 10/350 µs, and IK-1U with voltage pulses (current) of a temporary shape of 1.2/50 µs and 8/20 µs.

In this regard, the staff of the Scientific-&-Research Planning-&-Design Institute «Molniya» of NTU «KhPI» improved the existing measuring complex of the type IK-1U due to «stretching» the duration of the required current pulse 10/350 µs in the mode of generating a current pulse 8/20 µs with a decrease in its amplitude [37]. This was achieved by developing a new forming unit and expanding the measuring range of a pulse voltmeter. In addition, this made it possible to minimize costs by preserving the basic circuitry solutions of the IK-1U generator. The choice of elements for a new set-top box for the device was determined using the *MicroCap* computer code in the *Transient Analysis* mode taking into account the existing values of active and reactive elements. The simulation results of the operation of the IK-1U complex with the forming unit in the 10/350 µs mode (Fig. 29,*a*,*b*) show the compliance of the temporal parameters of the current pulse formed in it with a normative document [15].



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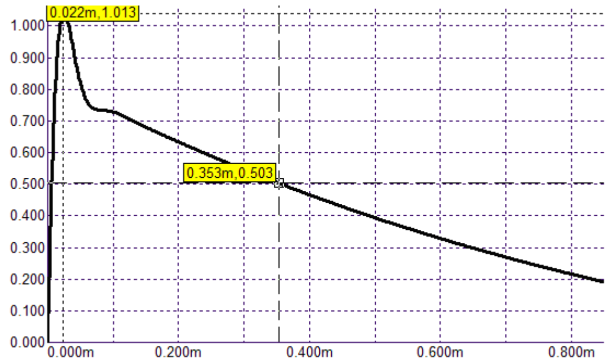
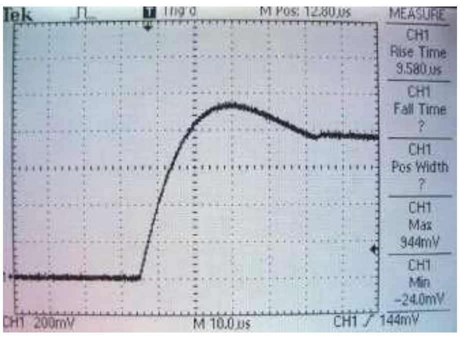


b

Fig. 29. Simulation results for the IK-1U generator of the front of an aperiodic current pulse (*a*) and its duration (*b*) in *MicroCap* code [37]

Based on the results of the simulation, a mock-up of the forming unit for the new device was created in the form of a set-top box to the existing IK-1U complex. Figure 30 shows oscillograms of the front and duration of a thundering aperiodic current pulse of 10/350 μs obtained in IK-1U [37].



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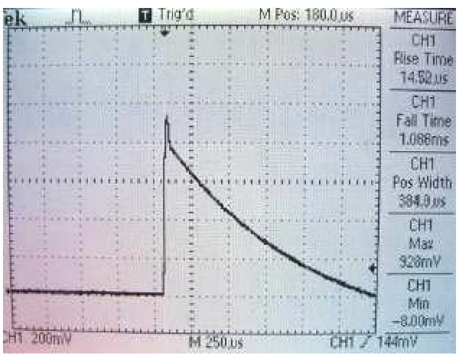

b

Fig. 30. Oscillograms of the front of the current pulse (*a*) and its duration (*b*) in the mode of formation of the temporary shape 10/350 μs by the modernized IK-1U complex [37]

Table 9 shows the main technical characteristics of the advanced measuring complex IK-1U with a new forming unit. After modernization, the IK-1U electrical installation allows the electrical diagnostics of the GD and PTL supports to be performed using three temporary shapes of voltage (current) pulses (1.2/50 μs, 8/20 μs and 10/350 μs), which significantly distinguishes it from foreign analogues [37] .

Table 9

Technical characteristics of the complex IK-1U [37]

Parameter name	Value
Fronts of voltage and current pulses (at levels of 0.1–0.9 from its amplitude), μs	1.2 ± 0.1; 8 ± 0.8; 10 ± 2.0
Duration of voltage and current pulses (at the level of 0.5 of their amplitude), μs	50 ± 5; 20 ± 4; 350 ± 35
Maximum amplitude of voltage pulses generated for the shapes 1.2/50 μs and 8/20 μs (in the 10/350 μs mode), V	1000 (600)
Range of measurements of the amplitude of voltage pulses, V	from 0.5 to 200
Maximum amplitude of current pulses generated for the shapes 1.2/50 μs and 8/20 μs (in the 10/350 μs mode), A	25 ± 5 (1 ± 0.05)
Range of measurements of the amplitude of current pulses, A	from 0.1 to 25
Relative error of voltage (current) measurement %, no more	10

The modernized complex IK-1U successfully passed testing when performing electromagnetic diagnostics of the state of the GDs at more than 100 operating electrical substations in Ukraine.

9. Electric drive and field characteristics to solve the problems of ensuring its EMC. A new scientific and technical direction was developed at the Institute related to the development and research of electric drives based on linear motors (LMs) of electromagnetic and inductor types, as well as switched reluctance machines (SRMs) [38, 39]. In the practical application of such LDs and SRMs as part of electric drives of various devices and systems, one of the most important tasks is to ensure their EMC. In this regard, work on the study of transient electromagnetic processes and calculation of magnetic fields in LDs and SRMs has come to the fore. For mathematical modelling of these electromechanical systems, we have applied:

- modelling based on the solution of differential equations of electrical phase circuits;
- modelling based on the well-known circuit-field mathematical models of LDs and SRMs;
- modelling based on the approach of a generalized electromechanical energy converter.

When determining the field characteristics of LDs of electromagnetic and inductor types, the staff of the Institute used the well-known Finite Element Method – the basis of the FEMM computer code. The results of these field calculations became a guideline in assessing their EMC as part of a turnout drive for railway transport [39]. The practical application of the results of these studies will allow to develop measures to reduce the level of emission of radio interference generated by the LDs and bring them into line with the requirements of UN Regulation No. 10.

An inductor-type LD magnetic field was also calculated [39]. The developed mathematical models using the FEMM code became the basis for the calculated assessment of the EMC of this type of LD.

From the above review of domestic powerful high-voltage test electrical equipment designed to solve problems in the field of electrical safety, EMC and the resistance of power facilities, OAMT, AT and SRT to the damaging effects of standard aperiodic lightning current pulses, switching voltage pulses and other special shapes of current pulses (voltage), it follows that the considered individual electrical installations of the Scientific-&-Research Planning-&-Design Institute «Molniya» of NTU «KhPI», which implement the requirements of International and national regulatory documents [4-10, 13-16, 36], are characterized by a relatively low cost in general, a high unification of components and applied materials, the originality of the construction of high-current discharge circuits of their high-voltage current (voltage) generators and their synchronous parallel electrical start circuits.

Conclusions. Designed and created as part of a single electrical complex of the Scientific-&-Research Planning-&-Design Institute «Molniya» of NTU «KhPI» high-voltage test installations of the type UITOM-1, GTM-10/350, GKIN-2, TI-CS115 (NCS08), TI-CS116 (NCS09), G- NCS10, MV 1000 and IK-1U are capable in accordance with the requirements of US regulatory documents SAE ARP 5412: 2013, SAE ARP 5414: 2013, SAE ARP 5416: 2013, RTCA DO-160G: 2011, US military Standards MIL-STD-464C: 2010, MIL-STD-461G: 2015, NATO Standards AECTP-500: 2016, AECTP-250: 2014, International Standards IEC 62305-1: 2010, IEC 61024-1: 1990 and Interstate Standard GOST 1516.2-97 to conduct field tests of objects of industrial energy on electrical safety and resistance to standard aperiodic lightning and switching voltage (current) pulses in order to really determine the stability of their electrical components and the electrical strength of their insulation, as well as weapons and military equipment, aircraft and rocket and space technology to electromagnetic compatibility and resistance when exposed to them in accordance with current international requirements of normalized high-voltage current pulses of artificial lightning, as well as other special temporary shapes of current pulses (voltage).

Acknowledgment. Work on the development and creation of high-voltage test electrical equipment at the Scientific-&-Research Planning-&-Design Institute «Molniya» of NTU «KhPI» was carried out as part of a number of applied scientific and technical projects funded by the Ministry of Education and Science of Ukraine: «Development and research of prototypes of advanced technical means of lightning protection of aerospace equipment» (state registration number 0104U000447); «Development and research of the possibility of creating a powerful electrophysical installation for generating full lightning current and testing of electric power facilities for lightning resistance» (state registration number 0106U012302); «Ensuring energy security of Ukraine by increasing the operation reliability of strategic energy facilities in normal and emergency modes» (state registration number 0117U000534); «Ensuring compliance of armaments and military equipment of Ukraine with modern requirements of NATO Standards on electromagnetic compatibility» (state registration number 0117U000533); «Development of test systems for standard weapons and military equipment of Ukraine according to NATO Standards on electromagnetic compatibility» (state registration number 0119U002571).

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