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THE METROLOGY SUPPORT IN UKRAINE OF TESTS OF OBJECTS OF ENERGY, AVIATION AND SPACE-ROCKET ENGINEERING ON RESISTIBILITY TO ACTION OF PULSES OF CURRENT (VOLTAGE) OF ARTIFICIAL LIGHTNING AND COMMUTATION PULSES OF VOLTAGE

***Purpose.** Presentation and analysis of the modern state of the metrology support in Ukraine of model tests of equipment of objects of energy on resistibility to the action of pulsed current (voltage) of artificial lightning and commutation pulses of voltage, and also objects of aviation and space-rocket engineering on resistibility to lightning. **Methodology.** Electrophysics bases of engineering of high-voltage and large pulsed currents, theoretical bases of the electrical engineering, technique of the strong electric and magnetic fields, and also measuring technique. Scientific methods of analysis of scientific and technical information. **Results.** Information is resulted, touching the modern consisting of Ukraine of providing high-voltage measuring facilities conducted on requirements of the normative documents of the USA of SAE ARP 5412:2013, SAE ARP 5416:2013, International Standard of IEC 62305-1:2010 and Standard GOST 1516.2-97 model tests of equipment of objects of energy on resistibility to lightning and commutation resistibility, and also objects of aviation and space-rocket engineering on resistibility to lightning. It is marked that similar measuring facilities are not made by domestic industry. It is indicated that R&DPCI «Molniya» of the NTU «KhPI» disposes the proper measuring facilities of the own making, passing a state metrology check (calibration). Basic technical descriptions are described developed and created at this Institute: high-voltage high-current shunts of type of SC-300M1 and SC-300M2, intended for measuring of micro- and millisecond pulses of current amplitude to ±220 кA with the integral of their action to $15\cdot10^6$ J/Ohm; capacitive (type of CDV-100 and CDV-1,2) and ohmic (type of ODV-1,2 and ODV-2,5) dividers of pulsed voltage of micro- and millisecond duration, capable not only to measure but also form on the tested electric loading standard (non-standard) storm and commutation pulses of voltage amplitude to ±2 MV. **Originality.** First in the generalized kind possibilities are developed and created by the domestic scientific and technical workers of high-voltage high-current measuring facilities, intended for the aims of the metrology providing of model tests in obedience to the requirements of domestic and foreign normative documents of equipment of objects of energy on resistibility to lightning and commutation resistibility, and also objects of aviation and space-rocket engineering on resistibility to lightning. **Practical value.** Application in practice of model tests on powerful high-voltage pulsed current (voltage) of artificial lightning and commutation pulses of voltage of electrical equipment and component elements of objects of energy, aviation and space-rocket engineering on resistibility to lightning and commutation resistibility of the described special high-voltage measuring facilities will be instrumental in the decision of global in the world problem of protection from lightning of ground and air-based technical objects and to the increase of their strength security.* References 23, tables 4, figures 16.

Key words: **high-voltage generators of pulses of current (voltage) of artificial lightning and commutation pulses of voltage, objects of energy, aviation and space-rocket engineering, measuring facilities for the model tests of technical objects on resistibility to the action of pulses of current (voltage) of artificial lightning and commutation pulses of voltage**.

Изложено современное состояние метрологического обеспечения в Украине натурных испытаний объектов промышленной энергетики, авиационной и ракетно-космической техники на стойкость к прямому воздействию на них мощных импульсов тока (напряжения) искусственной молнии и апериодических коммутационных импульсов напряжения. Показано, что подобные испытания технических объектов на молниестойкость и коммутационную стойкость могут проводиться в соответствии с требованиями нормативных документов США SAE ARP 5412: 2013, SAE ARP 5416: 2013, международного стандарта IEC 62305-1: 2010 и стандарта ГОСТ 1516.2-97 в полевых условиях на уникальных отечественных высоковольтных сильноточных электроустановках, оснащенных современными измерительными средствами. Описаны основные технические характеристики разработанных и созданных в НИПКИ «Молния» НТУ «ХПИ» для метрологического обеспечения натурных испытаний указанных технических объектов на молниестойкость и коммутационную стойкость: измерительных коаксиальных сильноточных шунтов типа ШК-300М1 и ШК-300М2, емкостных и омических высоковольтных и сверхвысоковольтных делителей напряжения типа ЕДН-100, ЕДН-1,2, ОДН-1,2 и ОДН-2,5. Приведены примеры практического использования при натурных испытаниях на молниестойкость и коммутационную стойкость отмеченных технических объектов указанных нестандартизованных измерительных средств собственного изготовления. Библ. 23, табл. 4, рис. 16.

Ключевые слова: **высоковольтные генераторы импульсов тока (напряжения) искусственной молнии и коммутационных импульсов напряжения, объекты энергетики, авиационной и ракетно-космической техники, измерительные средства для натурных испытаний технических объектов на стойкость к действию импульсов тока (напряжения) искусственной молнии и коммутационных импульсов напряжения.**

Introduction. In accordance with the requirements of the current US regulatory documents SAE ARP 5412:2013 [1], SAE ARP 5416:2013 [2] and International Standard IEC 62305-1:2010 [3] for field testing of aviation, rocket and space equipment and power objects to lightning resistibility to the latter pulses of artificial lightning current with different amplitude-time parameters (ATPs) from powerful high-voltage lightning current generators (LCG) are applied. In this case, the amplitudes I_{mL} of lightning current pulses flowing through the test objects can vary from tens of Amperes to hundreds of thousands of Amperes, and their duration τ_p is from hundreds of microseconds to one thousand milliseconds [1-3]. In the documents [1-3], the numerical values of the normalized ATPs used in the tests for the lightning resistibility of the considered technical objects of the current pulses of artificial lightning are described in more detail. In [4], the authors described the technical characteristics of unique domestic powerful high-voltage LCG, which realizes the requirements of documents [1-3]. The current Standard GOST 1516.2-97 [5] defines normalized ATPs of voltage pulses of lightning nature and commutation aperiodic voltage pulses used in testing the electrical strength of external (internal) insulation of industrial power engineering objects with capacitive characteristics (for example, switches, disconnectors, bushings, insulators, current transformers, capacitors, etc.). In this case, the thunderstorm aperiodic voltage pulse generated on the tested load by the pulsed voltage generator (PVG), constructed according to the classical Arkadiev-Marx scheme, is characterized by the time shape τ_f/τ_p=1.2 μs/50 μs (with tolerances on: front τ_f ± 30 %, voltage amplitude U_{mL} ± 3%, pulse duration τ_p at the level 0.5 U_{mL} ± 20%), the normalized maximum value of which U_{mL} usually does not exceed 1 MV [5]. We point out that the amplitude U_{mk} of commutation aperiodic voltage pulses, reproduced on electric load by the commutation voltage pulse generator (CVPG), reaches a level of several Megavolts. The time of rise T_{rise} of such voltage pulses to the level U_{mk} is several hundred microseconds, and their duration T_P at the level of 0.5 U_{mk} is up to several thousand microseconds [5]. For the prompt registration of the ATP of the specified current and voltage pulses, appropriate measuring means are required. It should be noted that the domestic industry does not produce such measuring aids. In this regard, the developers and creators of LCG, PVG and CVPG, as well as the operating engineering and technical personnel serving them, are required to independently solve the problems of metrology support of contractual works and applied scientific research carried out with the help of these high-voltage current and voltage generators in the considered relevant worldwide scientific and technical field of engineering and electrophysics of high currents and high (superhigh) voltages.

The goal of the paper is the presentation and analysis of the current state of metrology support in Ukraine of testing equipment of industrial power facilities for lightning resistibility and commutation stability, as well as for aviation and rocket and space equipment for lightning resistibility.

1. Metrology support of testing of technical objects for lightning resistibility. First, let us dwell on the issues of metrology support for the testing of aviation and rocket and space equipment and energy facilities for resistibility to the impact of artificial lightning current pulses on them. For aircraft and rocket and space equipment, such tests are regulated by the requirements of US regulations SAE ARP 5412:2013 [1] and SAE ARP 5416:2013 [2]. According to [1, 2], the following components of the artificial lightning current generated in high-voltage high-current LCG circuits can flow through the tested objects of the indicated technique: pulsed *A*- (or repetitive pulsed *D*-), intermediate *B*- and prolonged *C*- (or shortened long *C** -) components of artificial lightning current. The main ATPs of the component of the pulsed current of artificial lightning are given in Table 1. The following combinations of these lightning current components are most often used [1, 2, 6]: *A*-, *B*- and *C*-components; *A*-, *B*- and *C**- components; *D*-, *B*- and *C**-components.

Table 1

Normalized ATPs of the main components pulsed current of artificial lightning [1, 2, 4]

Artificial lightning component	I_{mL}, kA	I_c, kA	q_L, C	J_L, 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	–	–	$(0.25\div1)\cdot10^3$
C^*	–	0.4	6-18	–	–	15-45
D	100±10	–	–	0.25±0.05	≤25	≤0.5

Note. I_{mL} is the amplitude of the current pulse; I_c is the average value of the current; q_L is the amount of electric charge leaking through the object under test; J_L is the integral of the action of the current pulse; τ_f, τ_p are, respectively, the pulse front duration between the levels (0.1-0.9) I_{mL} and the current pulse at the level $\leq 0.1 I_{mL}$.

For industrial power facilities, the high-voltage high-current tests for lightning resistibility under consideration are governed by the requirements of the International Standard IEC 62305-1:2010 [3] and the national Standard GOST R IEC 62305-1:2010 [7] developed in Russia on this basis. An aperiodic pulsed current of artificial lightning of the time shape τ_f/τ_p=10 μs/350 μs of both polarities, characteristic of a direct short thunderstorm attack to terrestrial objects protected by a number of engineering services of power supply companies, is fed from the powerful LCG to the test object. Table 2 shows the main ATPs of this powerful test current pulse of artificial lightning.

Table 2

Normalized ATPs of the aperiodic current pulse of lightning of temporary shape 10 μs/350 μs [3, 4]

Name of the lightning current pulse parameter	Lightning protection level of the facility 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 at half-descend τ_p (at the level $0.5I_{mL}$), μs	350±35	350±35	350±35
Current amplitude I_{mL}, kA	200±20	150±15	100±10
Integral of action J_L, 10^6 J/Ω	10±3.5	5.6±1.96	2.5±0.875
Charge q_L, C	100±20	75±15	50±10

With regard to testing the electrical strength of external and internal insulation of power facilities to the effects of lightning discharges, according to [5], they are carried out using the above-mentioned thunderstorm voltage pulse of the time shape 1.2 μs/50 μs. In this case, for its measurement we can use measuring standard balls with a diameter from 125 mm to 1.5 m [8], as well as high-voltage capacitive (CDV) and ohmic (ODV) dividers of voltage for pulsed voltages of ±(0.1-2.5) MV, having in the composition of high-voltage and low-voltage arms [5, 9].

1.1. Measuring coaxial disk shunts type SC-300M1 and SC-300M2. To record the current pulses of artificial lightning with the ATPs according to the data of Table 1, 2, generated at the objects under test with powerful LCG [4], satisfying the requirements [1-3], special measuring high-voltage high-current disk shunts of SC-300M1 (Fig. 1) and SC-300M2 (Fig. 2) type of the coaxial design were developed and created at the R&DPCI «Molniya» of the NTU «KhPI». Similar shunt designs are characterized by their small inductance values (not more than 10 nH) and active resistance (no more than 0.2 mΩ), which provides insignificant influence of the own electrical parameters of the measuring shunt on the electromagnetic processes occurring in the load. A significant difference between the designs of these high-current shunts from known (for example, described in [6]) is the use in them instead of a thin-walled (with a thickness of not more than 0.3 mm) high-resistance manganin disk from which the drop in the pulsed voltage from the passage of a measured current pulse is taken, a disk of thickness of 1 to 2 mm from stainless steel 12X18H10T [10, 11].

Fig. 1. External view of the improved coaxial disk shunt type SC-300M1, intended for measurement in the micro- and millisecond ranges of damped sinusoidal and aperiodic current pulses of artificial lightning with amplitude up to ±220 kA in the high-current discharge circuit of a powerful high-voltage LCG with their integral of action up to $3\cdot10^6$ J/Ω [10]

Fig. 2. External view of the improved coaxial shunt type SC-300M2 designed to measure in the coordinated mode of operation of its cable signal transmission line in the micro- and millisecond ranges of current pulses of artificial lightning with amplitude up to ±220 kA in the high-current discharge circuit of high-voltage LCG with their integral of action up to $15\cdot10^6$ J/Ω [11]

Such a technical improvement of the design of the high-resistance measuring disk in the high-voltage high-current shunt (see Fig. 1, 2) has made it possible to significantly increase its electrothermal resistivity to high impulse currents (HICs) flowing along it and to avoid the development of the phenomenon of electric explosion (EE) of its metal dangerous for the mechanical stability of the shunt.

As is known [12, 13], the EE of the metal measuring disk of the shunt at registration of the HIC is accompanied by a sharp increase in the gas-dynamic pressure inside the shunt (up to hundreds of atmospheres [14]), usually leading to its destruction and failure. Fig. 3 is a schematic view of a shunt of the SC-300M2 type in the longitudinal section.

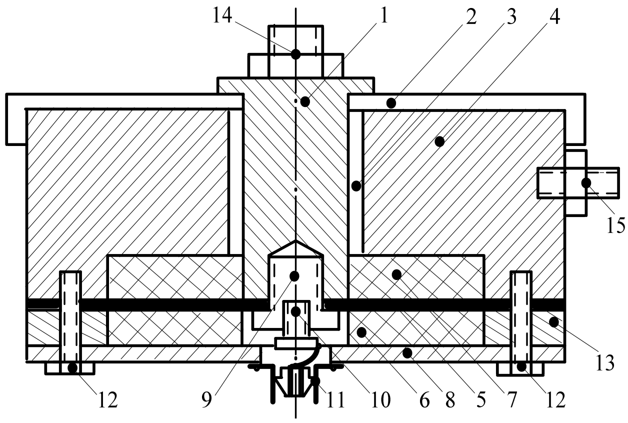

Fig. 3. Schematic view of the design of a coaxial disk shunt of the SC-300M2 type in its longitudinal axial section
(1 – a massive inner cylindrical brass electrode, 2, 3 – an insulating sleeves made of fluoroplastic, 4 – a massive outer cylindrical brass electrode, 5 – a measuring high-resistance steel disk, 6, 7 – massive clamping insulating disks, 8 – banded brass disk, 9, 10, 12 – steel fastening screws, 11 – CP-75 output coaxial connector, 13 – massive clamping brass ring, 14, 15 – respectively input (potential) and output (grounded) elements of the brass bolt connection of the shunt to the high-voltage high-current discharge circuit of the LCG) [11]

For the simultaneous measurement of several components of the total current of artificial lightning generated in a high-voltage high-current discharge circuit of the LCG, it was required to develop and create a special measuring matching voltage divider (MVD), which is connected to the output of an additional shielded coaxial communication line (Fig. 4). In the shown in Fig. 4 divider of the type SDN-300 there are two coaxial connectors 1:1 and 1:2, intended for the coordinated connection of their outputs to the inputs of the measuring channels of digital storage oscilloscopes (DSO) [6, 10].

Fig. 5 is a general view of the placement of three DSO type Tektronix TDS 1012 in a buried screened measuring hopper for field testing of aircraft equipment for direct impact in them according to [1, 2] of lightning current.

Fig. 4. External view of the SC-300M1 measuring shunt connected to the input of an additionally shielded coaxial RF cable of the RK 75-7-11 type with a length of 70 m, the output of which is connected to a shielded matching voltage divider of the type SDN-300 with two output coaxial connectors 1:1 and 1:2 for the coordinated connection of the measuring channels of the three DSO (for example, Tektronix TDS 1012 series) to them, while simultaneously registering of three components of the total current pulse of the artificial lightning in the high-current discharge circuit of the LCG with different ATPs [6, 10]

Fig. 5. External view of the placement of three Tektronix TDS 1012 digital storage oscilloscopes that register in parallel useful electrical signals from one SC-300M1 measuring shunt in a buried screened measuring hopper designed for metrology support of field testing of various technical objects for lightning resistibility [9]

It should be noted that the DSO used by us in testing technical facilities for lightning resistibility have the corresponding certificates of metrological verification and calibration of the State Enterprise «Kharkivstandartmetrologiya» (for example, No. 08/2128K dated May 16, 2017).

Table 3 shows the main technical characteristics of the described shunts of the type SC-300M1 and SC-300M2 that passed the state metrological certification at the State Enterprise «Kharkivstandartmetrologiya» (inspection certificate No. 06/184 of June 27, 2017 and certificate of conformity No. 06/0206 of July 19, 2017) [11].

Using the data of Table 3 and the readings (in fractions or units of volts) recorded on the screen of the DSO from the measuring shunt of the drop of the U_S pulsed voltage, the required value of the measured lightning current pulse I_{mL} is determined as: $I_{mL} = K_S \cdot U_S$.

Table 3

The main technical characteristics of high-voltage high-current shunts SC-300M1 and SC-300M2

Shunt name	Characteristic value		
	R_S, mΩ	K_S, A/V	Mass, kg
SC-300M1	0.158±1 %	K_{SA}=12625	3.1
		K_{SC}=6312	
SC-300M2	0.080±1 %	K_{SA}=25000	3.2
		K_{SC}=12500	

Note. R_S is the active resistance of the shunt disk, mΩ; K_S=2/R_S is the shunt transform coefficient, A/V; K_{SA} is the shunt conversion factor for measuring in the discharge circuit of the LCG of the ATPs of *A*- and *D*- components of the lightning current and lightning pulse of the shape 10 μs/350 μs, A/V (from the 1:1 coaxial connector of the SDN-300 divider); K_{SC} is the shunt conversion factor when measuring in the discharge circuit of the GTM of the ATPs of *B*-, *C*- and *C**- artificial lightning current component, A/V (from the coaxial connector 1:2 of the SDN-300 divider).

1.2. Capacitive and ohmic voltage dividers type CDV-100, CDV-1,2, ODV-1,2 and ODV-2,5. In 2011, when studying the behavior of high-voltage insulation samples (in particular, wood) of test electrical installations of Department No. 4 of the Institute under the influence of large pulsed currents and high voltages on them, we found it necessary to have a small mobile capacitive voltage divider of amplitude up to ±100 kV (CDV-100) operating in the microsecond time range. Fig. 6 shows the connection diagram of the CDV-100 to the measuring circuit of the installation.

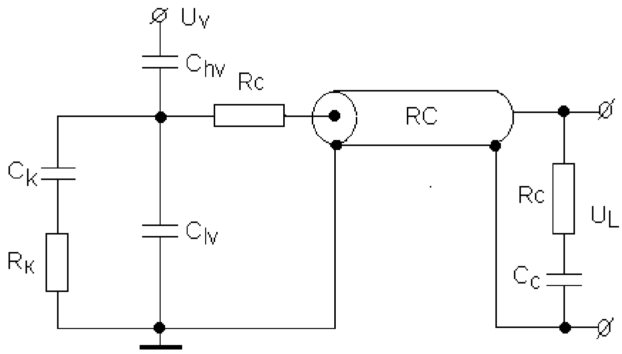

Fig. 6. Connection diagram of CDV-100 to the input of the DSO [15]

The measurement circuit in Fig. 6 of the high voltage U_V applied to the high-voltage divider arm with capacitance C_{hv}, connected in series with the low-voltage divider arm of with capacitance C_{lv}>>C_{hv}, is based on the agreed operating mode of the CDV-100 measuring circuit. To implement this mode, the coaxial RF cable (PC) with the impedance Z_B of the transmission line of the useful electrical signal from the low-voltage arm of the R_C=Z_B matching impedance divider and the connection on the low-voltage side of the circuit with the voltage U_L of the matching R_CC_C chain are used in the circuit of the wire (see Fig. 6). We indicate that the connection of the resistance R_C in accordance with the circuit in Fig. 6 reduces twice the useful signal with the level of voltage U_L applied to the measuring channel of the DSO. To improve the transmission characteristics of the divider under consideration, its low-voltage arm contains a corrective R_kC_k chain. In accordance with the circuit of Fig. 6 the following numerical values of the main electrical parameters of the CDV-100 divider were used (Fig. 7): C_{hv}=0.47 nF; C_{lv}=C_C=0.54 μF; R_C=Z_B=75 Ω; R_k=27 Ω; C_k=2.8 nF.

We point out that high-voltage ceramic capacitors of the K-15-10 type (with a capacitance of 4700 pF for a rated voltage of ±50 kV) were used to create a high-voltage arm of the CDV-100 pulsed voltage divider. In this connection, the capacitance C_{hv} consisted of 10 series-connected capacitors of the indicated type, placed in air in an insulating pipe made of glass textolite of STEF brand (length of 915 mm and inner diameter of 151 mm with wall thickness 12 mm). The low-voltage arm of the divider under consideration with capacitance of C_{lv}=0.54 μF was realized on the basis of two parallel capacitors of the K-73-11 type with capacitance of 0.27 μF at a voltage of 250 V [15]. The matching active resistance R_C was assembled from two parallel-connected resistors of the MLT-2 type with a rating resistance of 150 Ω. The electrical part of the low-voltage arm of the described divider was placed in a rectangular aluminum casing with a CR-75 coaxial connector rigidly fixed to the isolator base of the divider and connected to the grounding bus of the test setup. The calculated value of the division factor for CDV-100 in the circuit according to Fig. 6 was numerically K_{D1}=$2C_{lv}/C_{hv}$=2298. The performed high-voltage experiments showed that the experimental value of the CDV-100 division factor is K_{D2}≈2515 [15].

Fig. 7. General view of the mobile high-voltage pulsed voltage divider CDV-100 for a rated voltage of ±100 kV, placed on the test field of a superhigh voltage pulsed voltage generator of the GIN-1,2 type of our own flooring design (the GIN-1,2 generator is located behind the CDV-100 divider; to the right of the CDV-100 divider there are movable standard measuring balls with a diameter of 125 mm) [15]

In Fig. 8 shows the electrical circuit with the use of a high-voltage capacitive voltage divider of the type CDV-1,2, designed to form a non-standard commutation aperiodic pulse of a time shape of 250 μs/5000 μs of amplitude up to ±1 MV in the long air gap between the electrodes E_1 (disk) and E_2 (rod) [16]. In this circuit, the CDV-1,2 divider at a nominal voltage of ±1.2 MV performs not only the role of the measuring mean, but also the role of the superhigh voltage forming capacitance.

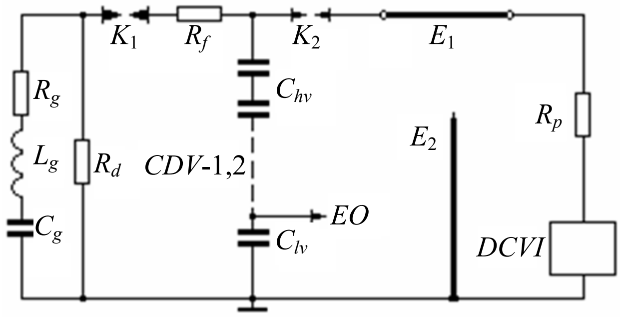

Fig. 8. A schematic electrical circuit for the forming in the GIN-1,2 type generator discharge circuit in a long air gap of a commutation aperiodic voltage pulse of a time shape of 250 μs/5000 μs with an amplitude up to ±1 MV based on the use of a capacitive voltage divider of the CDV-1,2 type [16]

In the circuit according to Fig. 8 to the potential electrode E_1 of the air gap from the DC voltage installation (DCVI) through a protective resistance R_p of 1.4 GΩ (14 resistors of the KEV-5-100 MΩ type with a total length of 2.05 m), a DC voltage of up to ±50 kV can be applied. The generator of pulsed voltages of type GIN-1,2 had following own electric parameters [16]: R_g=48 Ω; L_g=6 μH; C_g=20.8 nF; discharge resistance R_d=340 kΩ. The front active resistance R_f, connected to the circuit in Fig. 8 between the cut-off K_1 and the isolating K_2 switches was 360 kΩ. The capacitance C_{hv} of the high-voltage arm of the divider CDV-1,2 was chosen equal to 130 pF, and the capacitance C_{lv} of its low-voltage arm, connected to the oscilloscope or DSO, was 2.6 μF. At the same time, the calculated division factor for CDV-1,2 had a numerical value equal to K_{DC} = $C_{lv}C_{hv}$=$20\cdot10^3$ [16].

Fig. 9 shows a general view of a high-voltage test stand, which uses as a base of its design the electrical circuit in accordance with Fig. 8 with a capacitive voltage divider of the type CDV-1,2.

Fig. 10 shows a general view of the ultrahigh-voltage ohmic voltage divider ODV-1,2 developed and created at the Department No. 4 of the Institute.

The insulating supporting structure (ISS) of the divider ODV-1,2 is assembled from five rigid hollow fiberglass sections fixed in a single rack, inside which high-voltage ceramic resistors of the type TVO-5-250 Ω were placed on the getinax plates [17]. Each divider section contains 40 consistently and zigzag connected on both sides of the getinax plate of the indicated resistors with a total active resistance of 10 kΩ. In the case of using the four specified sections in the divider, the design of an ohmic divider of the ODV-1 type for a nominal voltage of ±1 MV (Fig. 11) can be realized [17].

Fig. 9. General view of the high-voltage test stand of the R&DPCI «Molniya» of the NTU «KhPI», intended for testing lightning protection equipment of technical objects with commutation aperiodic voltage pulse with amplitude up to ±1 MV of time shape 250 μs/5000 μs and containing in the scheme a mobile superhigh voltage capacitor voltage divider of the type CDV-1, 2 [16]

Fig. 10. General view of a mobile superhigh-voltage ohmic voltage divider of the type ODV-1,2 at a rated voltage ±1.2 MV, located at the factory test field of a high-voltage test stand SVI-1,2, designed to determine in the laboratory conditions the pulsed electrical strength of polymer insulation of its own production (enterprise ES «Polymer», Bakhmut city, Ukraine, 2006) [9, 17]

Fig. 11. General view of the high-voltage test stand of the R&DPCI «Molniya» of the NTU «KhPI», on the test field of which mobile generator of pulsed voltages of the type GIN-1,2, the divider of the type ODV-1 and standard measuring balls with a diameter of 250 mm are placed [17]

For the divider of the type ODV-1,2, the high-voltage arm is characterized by an active resistance R_{hv}=50 kΩ. Its low-voltage arm is made of two parallel-connected resistors of the MLT-2 type with a total active resistance R_{lv}=2.5 Ω. In this connection, the calculated division factor for the divider ODV-1,2 is $K_{DR}=R_{hv}/R_{lv}=20\cdot10^3$. In practical use in the measuring path, connected to the low-voltage arm of a divider of the type ODV-1,2, the matching circuit, which is similar to that shown in Fig. 6, the coefficient of its division K_{DR} is doubled and numerically is about $40\cdot10^3$. Experimental verification of the K_{DR} value using standard balls of diameter of 250 mm (see Fig. 11) according to the requirements of [8] showed that it takes a numerical value of about $39.8\cdot10^3$. From Fig. 10, 11 it can be seen that above the ISS of dividers of the type ODV-1,2 and ODV-1, anti-crown metal shields are installed, which simultaneously improve the distribution of a strong electric field along their upper sections [17].

The use in the discharge circuit of shown in Fig. 8, 11 the generator of pulsed voltages of the type GIN-1,2 at a rated voltage of ±1.2 MV with an own discharge resistance R_d=240 kΩ and an additional shaping resistance R_{f1}=1.98 kΩ (Fig. 12) of the ohmic voltage divider of the type ODV-1,2 (or ODV-1) makes it possible to form following requirements [5] a standard lightning aperiodic wave of a voltage of 1.2 μs/50 μs with the above tolerances and the required values of its amplitude $U_{mL}\leq\pm1$ MV [16, 18]. Here, the capacitive nature of the load ($C_L\approx10$ pF) and the parasitic capacitance of the ODV-1,2 divider, approximately 50 pF, should be taken into account in the calculation circuit for the formation of a standard lightning pulse of the shape 1.2 μs/50 μs.

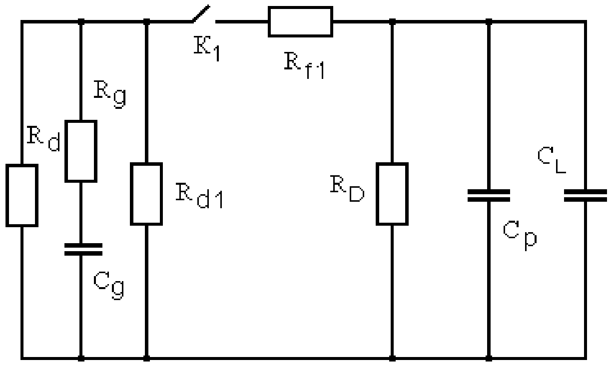

Fig. 12. Electric circuit for obtaining in the discharge circuit of the generator GIN-1,2 on the tested load with the capacitive characteristic of a standard lightning voltage pulse of the time shape of 1.2 μs/50 μs with the use of the ohmic voltage divider of the type ODV-1,2 with an active resistance R_D=50 kΩ (R_d=240 kΩ is the own discharge resistance of GIN-1,2, R_{d1}=3.91 kΩ is the additional discharge resistance of GIN-1,2; R_g=48 Ω; C_g=20.8 nF; R_{f1}=1.98 kΩ; C_L≈10 pF; C_p≈50 pF) [9, 18]

The utilization in the discharge circuit of the pulsed voltage generator of the GIN-1,2 type to a rated voltage of ±1.2 MV of a capacitive voltage divider of the CDV-1,2 type (Fig. 13) allows on the electrical load under test with the indicated capacitive characteristic (C_L≈10 pF) to form a standard commutation pulse of voltage of a time shape of 250 μs/2500 μs with an amplitude U_{mk}≤±700 kV with normalized tolerances (for a rise time ±20%, for a half-decay time ±30%, for the amplitude U_{mk} ±3 %) [5, 18]. It should be noted that the mobile capacitive voltage divider CDV-1,2 contains three *C*- sections connected in series, each of which is placed in a 900 mm diameter glass-fiber plastic pipe of TSEF brand with an outer diameter of 300 mm with a wall thickness of 35 mm. Each of its *C*- sections consists of 12 series-connected high-voltage ceramic capacitors of type K 15-10-4700 pF at ±50 kV. Each of these sections of the divider is filled with transformer oil of T-1500 grade, and its upper and lower terminals are connected to round metal flanges with a diameter of 350 mm [16, 18].

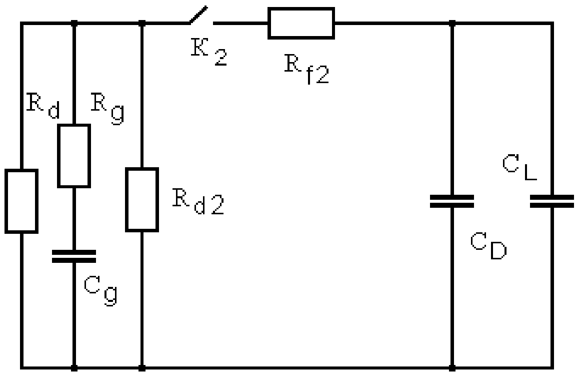

Fig. 13. Electric circuit for obtaining in the discharge circuit of the generator GIN-1,2 on the tested load with the capacitive characteristic of a standard commutation pulse of a time shape of 250 μs/2500 μs with the use of a capacitive voltage divider of the type CDV-1,2 with a total capacitance C_D=130 pF (R_d=240 kΩ is the own discharge resistance of the GIN-1,2; R_{d2}=840 kΩ is the additional discharge resistance of the GIN-1.2; R_g =48 Ω; C_g=20.8 nF; R_{f2}=395 kΩ ; C_L≈10 pF ; K_2 is the cut-off high-voltage switch of the generator GIN-1,2) [9, 18]

To measure with an error of no more than 5 % at industrial power facilities of aperiodic lightning and commutation voltage pulses up to ±2.5 MV, an ultrahigh-voltage ohmic voltage divider of the ODV-2,5 type was created in the Department No. 4 of the Institute [19, 20]. The main technical characteristics of this pulsed voltage divider are given in Table 4 [20].

Table 4

The main technical characteristics of a superhigh-voltage ohmic voltage divider ODV-2,5

No.	Characteristic name	Value
1	The maximum level of the measured voltage U_m, kV	±2500
2	The active resistance of the high-voltage divider's arm R_{hv}, kΩ	107.3
3	The active resistance of the low-voltage divider's arm R_{lv}, Ω	4
4	Division coefficient, K_{DR}	$26.82 \cdot 10^3$
5	Height (length), m	12.6
6	Mass, kg	350

General view of a superhigh-voltage ohmic voltage divider of the type ODV-2,5, functioning as a part of a unique CVPG at ±2.5 MV, is shown in Fig. 14. The high-voltage arm of the ODV-2,5 divider is made up of nine *R*- sections connected in series and placed outside and inside the glass-fiber pipe of the TSEF brand with an outer diameter of 120 mm and a wall thickness of 10 mm. Each *R*- section contains 20 series-parallel-connected high-voltage ceramic resistors of the TVO-10-2,4 kΩ type, assembled on two glass-fiber plates with a length of 1400 mm and a thickness of 5 mm. As a result, the resistance of each section of the high-voltage divider arm is about 12 kΩ, and its total resistance is R_{hv}≈107.3 kΩ [20].

Fig. 14. General view of a superhigh-voltage ohmic voltage divider of the ODV-2,5 type for a rated voltage of ±2.5 MV, connected in the CVPG discharge circuit to a two-electrode «needle-plane» system with an air gap length of 3 m (the upper steel rod-electrode of this electric discharge system is located at the center of its lower flat electrode made of thin galvanized steel with a plan size of 5 m × 5 m) [23]

The low-voltage arm of the ODV-2.5 divider is made of small-sized ceramic resistors of the TBO-2-2 Ω type with a total active resistance R_{lv}=4 Ω. In this connection, the calculated division coefficient K_{DR} for the considered voltage divider of the type ODV-2,5 is approximately equal to $K_{DR}=R_{hv}/R_{lv}=26{,}82\cdot10^3$. With the agreed mode of measuring the pulsed voltage on the load, the division coefficient for the divider of the type ODV-2,5 will be doubled and take a numerical value of about $53{,}65\cdot10^3$. An experimental estimate of the reaction time T_R of the ohmic divider of the type ODV-2,5 on the action of a rectangular voltage pulse [21] showed that for this type of divider T_R≈170 ns [19]. In this regard, the voltage divider of the type ODV-2,5 can be used to measure voltage pulses with an amplitude of U_m≤±2.5 MV, varying in micro- and millisecond time bands. A comparison of the metrological characteristics of a superhigh-voltage ohmic divider of the ODV-2,5 type with the characteristics of the known high and ultra high voltage meters [22] indicates that the domestic voltage divider of the ODV-2,5 type meets modern requirements and developments in the field of high-voltage measuring equipment.

Fig. 15 shows the oscillogram of a superhigh-voltage pulse of microsecond duration, obtained with the help of the ohmic voltage divider of the ODV-2,5 type on a long air gap of 3 m at its electrical breakdown in the «rod-rod» system [20]. From the oscillogram of Fig. 15 it can be seen that the cut-off voltage U_C in our case is approximately $U_C \approx 25$ V × $53.65\cdot10^3 \approx 1341.3$ kV. Here, the pre-discharge time T_C for this insulating air gap is about $T_C \approx 5 \times 2.5\cdot10^{-6}$ s≈12.5 µs, and the cut-off time T_{DC} of the microsecond voltage wave does not exceed the value 5.47 µs.

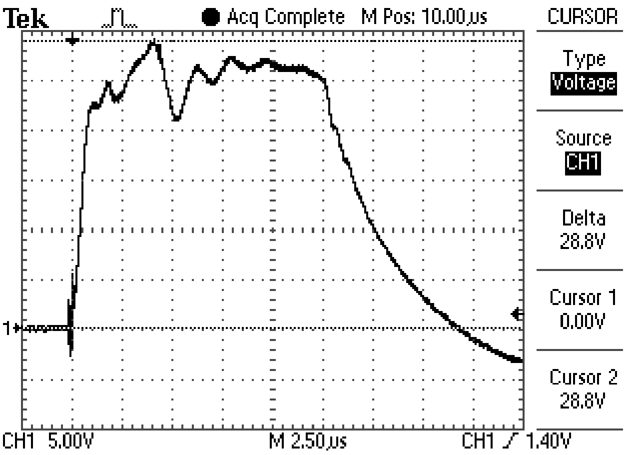

Fig. 15. Oscillogram of a superhigh voltage pulse of positive polarity on the air gap of 3 m long in a «rod-rod» system cut at its rising part and registered with the ohmic voltage divider ODV-2,5 (cut-off voltage U_C≈1341.3 kV, pre-discharge time T_C≈12.5 µs, the cut-off time T_{DC}≈5.47 µs, the vertical scale is 268 kV/cell; the horizontal scale is 2.5 µs/cell) [20]

2. Metrological support of testing of technical objects for commutation stability. In order to conduct full-scale testing of power engineering facilities for commuttaion stability, a unique CVPG was created at the R&DPCI «Molniya» of the NTU «KhPI» at the experimental range of the Institute (Andreevka, Kharkiv region) in 2012. The CVPG is rated for a voltage of ±2 MV [23]. This outdoor CVPG allows, in the field conditions, to reliably form, in accordance with the requirements of [5], a standard aperiodic commutation pulse of the time shape of 205 µs/1900 µs of both polarities in the field conditions on a large-sized electrical load under test.

To measure the ATPs of voltage pulses formed in the CVPG generator circuit, a superhigh-voltage ohmic voltage divider of the ODV-2,5 type described above can be used [20]. The data in Fig. 14 clearly illustrate the practical use of a superhigh-voltage ohmic voltage divider of the ODV-2,5 type at metrology support for testing the electrical strength of long air gaps in electric power devices for commutation stability. Fig. 16 shows the oscillogram of a full standard commutation pulse of time shape of 205 µs/1900 µs of positive polarity obtained in the discharge circuit of the CVPG generator in field conditions in the open air using an ohmic voltage divider of the ODV-2,5 type [23]. From the oscillogram of Fig. 16 it follows that the amplitude U_{mk} of the commutation voltage wave in this case is approximately $U_{mk} \approx 9$ V × × $53.65\cdot10^3 \approx 483$ kV. For the voltage commutation pulse formed on a long air gap, the rise duration T_{rise} reaches a numerical value of about T_{rise}≈205 µs. In this case, the duration of the commutation voltage pulse T_P at the level of $0.5U_{mk}$ equals approximately 1900 µs.

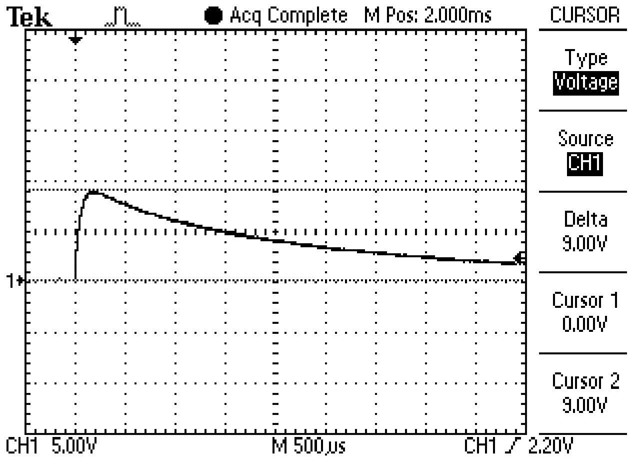

Fig. 16. Oscillogram of the full standard aperiodic commutation voltage pulse of positive polarity generated in the discharge circuit of the superhigh voltage generator of the CVPG on a two-electrode «needle-plane» system with an air gap length of 3 m and recorded with an ohmic voltage divider ODV-2,5 (U_{mk}≈483 kV; rise duration of the voltage pulse is T_{rise}≈205 µs, duration of the voltage pulse is T_P≈1900 µs, the vertical scale is 268 kV/cell, the horizontal scale is 500 µs/cell) [23]

Conclusions.

1. Analysis of the current state of metrologicy support of full-scale testing of industrial power engineering objects, aircraft and rocket and space equipment on lightning resistibility and commutation stability in Ukraine shows that the R&DPCI «Molniya» of the NTU «KhPI» currently has not only high-voltage pulsed technology reproducing in this area required by the

requirements of domestic and foreign regulatory documents test pulses of current and voltage by powerful high-voltage electrical installations, placed outdoor and in heated special laboratory premises, but also the corresponding measurement means, passed state metrological calibration.

2. The composition of these high-voltage measuring instruments used in the practice of full-scale tests at testing the durability of energy facilities, aircraft and rocket and space equipment to affect their electrical equipment, components and components of lightning current (voltage) pulses and commutation voltage pulses include the following non-standardized devices of own manufacture: high-voltage high-current shunts of type SC-300M1 and SC-300M2, intended for measurement of micro- and millisecond pulses of a current of amplitudes up to ±220 kA with an integral of their action up to $15\cdot10^6$ J/Ω; capacitive (CDV-100 and CDV-1,2 type) and ohmic (ODV-1,2 and ODV-2,5 type) dividers of pulsed voltage of micro- and millisecond duration, capable both of measuring with the help of metrologically attested DSO, and forming the standard (non-standard) lightning and commutation voltage pulses with amplitude up to ±2 MV on a tested certain electrical load with a capacitive characteristic.

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