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A COAXIAL DISK SHUNT FOR MEASUREMENT IN THE HIGH-CURRENT CIRCUIT OF HIGH-VOLTAGE GENERATOR OF STORM DISCHARGES OF PULSES OF CURRENT OF ARTIFICIAL LIGHTNING WITH THE INTEGRAL OF ACTION UP TO 15·10^6 J/OHM

Purpose. Description of construction and basic technical descriptions developed and created in Research & Design Institute «Molniya» of the National Technical University «Kharkiv Polytechnic Institute» high-voltage high-current coaxial disk shunt of type of SC-300M2, allowing reliably to measure the peak-temporal parameters (PTP) of pulses of current of artificial lightning in wide peak and temporal ranges with the integral of their action to 15·10^6 J/Ohm. Methodology. Electrophysics bases of high-voltage impulsive technique, scientific and technical bases of development and creation of high-voltage high-current pulsive electrical equipment including the powerful generators of current of lightning (GCL), and also measuring methods in discharge circuit of the powerful high-voltage GCL AVP high pulse currents of micro- and millisecond temporal ranges. Results. Offered and described new construction of measuring high-voltage heavy-current shunt, containing a measuring round disk from stainless steel easily soiled 12X18H10T of thickness of 2 mm and external diameter 80 mm. Experimental a way pulse active resistance of R_S≈0,08 mOhm of the indicated measuring disk and on his basis a calculation coefficient transformation is found of S_S of coaxial disk shunt of type of SC-300M2, numeral equal in the concerted mode of operations of his coaxial cable line (CCL) S_S≈2/R_S≈25·10^3 A/V. It is shown that it is expedient to use this value S_S for measuring in the heavy-current discharge circuit of the GCL ATP impulsive A- and repeated impulsive D- component of current of artificial lightning, and also ATP of aperiodic pulse of current of artificial lightning of temporal form 10 μc/350 μc. It is set that taking into account application in the end GCL of shunt of a co-ordinate divizor of voltage with two output coaxial sockets 1:1 (for S_{SA}≈25·10^3 A/V) and 1:2 (S_{SC}≈12.5·10^3 A/V) at measuring of ATP intermediate B-, protracted C- and shortened protracted C*- component of current of artificial lightning in GCL it is expedient to utillize a numeral value S_S for the examined shunt, equal 12.5·10^3 A/V. Practical approbation and verification of capacity of the improved measuring coaxial disk shunt of type of SC-300M2 is executed in the high-voltage heavy-current discharge circuit of the powerful GCL, forming on the actively-inductive loading of A- and C*- the components of current of artificial lightning with rationed ATP. Originality. Developed and created new high-voltage heavy-current measuring shunt of type of SC-300M2, allowing reliably to register rationed ATP of attenuation sinewave and aperiodic pulses of current of artificial lightning in the circuits of powerful GCL with amplitude to ±220 кA and integral them action to 13.5·10^6 J/Ohm. On the measuring coaxial disk shunt of type of SC-300M2 from Government Metrology Service of Ukraine the certificate of accordance of the set form is got. Practical value. Application of the created shunt of type of SC-300M2 in composition the high-voltage high-current discharge circuits of powerful GCL will allow in a certain measure to improve the metrology providing of tests of aviation and space-rocket technique, and also objects of electrical power engineering on stability to lightning. References 11, figures 4.
Key words: **powerful high-voltage generator of current of lightning, measuring coaxial disk shunt, measuring disk of shunt from stainless steel, calculation estimation of parameters of shunt.**

Описана конструкция разработанного и созданного измерительного коаксиального дискового шунта типа ШК-300М2, позволяющего с помощью коаксиальной кабельной линии связи и цифровых запоминающих осциллографов одновременно измерять амплитудно-временные параметры (АВП) основных компонент тока искусственной молнии, генерируемых высоковольтным генератором грозовых разрядов в соответствии с требованиями нормативных документов США SAE ARP 5412: 2013 и SAE ARP 5416: 2013. Приведены основные технические характеристики измерительного коаксиального дискового шунта типа ШК-300М2. Показано, что данный шунт позволяет измерять и АВП апериодического импульса тока временной формы 10 мкс/350 мкс, нормированный интеграл действия которого согласно требований международного стандарта IEC 62305-1: 2010 может численно составлять до 13,5·10^6 Дж/Ом. Библ. 11, рис. 4.
Ключевые слова: **мощный высоковольтный генератор тока молнии, измерительный коаксиальный дисковый шунт, измерительный диск шунта из нержавеющей стали, расчетная оценка параметров шунта.**

Introduction. US normative documents SAE ARP 5412: 2013 [1] and SAE ARP 5416: 2013 [2] define the requirements for amplitude-time parameters (ATP) of artificial lightning current pulses generated by the corresponding high-voltage lightning generators, commonly referred to as high-voltage generators of current of lightning (GCL), on electrical loads of aerospace equipment, tested for lightning. One of these types of powerful GCL reproducing the necessary ATP pulses of the simulated lightning current according to the requirements [1, 2] on the active-inductive load, was developed and created in 2007 by the staff of the Departments No. 3 of high-voltage pulse technology and No. 4 of electromagnetic tests of the Research & Design Institute «Molniya» of the National Technical University «Kharkiv Polytechnic Institute» [3]. According to [1, 2], in these tests of aeronautical and space-rocket devices, pulsed *A*- (or repetitive pulsed *D*-), an intermediate *B*- and prolonged *C*- (or shortened long *C**-) current component of artificial lightning can be used. Moreover, combinations of these current components which follow one after the other in time and differ greatly in their amplitudes (from hundreds of kA to tens of A) and flowing times (from hundreds of microseconds to one thousand milliseconds), can be different [1, 2]. Most often, in the practice of testing individual elements of such aircraft as civil and military aircraft for lightning, the following combinations of these lightning current components are used [1-4]: *A*-, *B*- and *C*- components, *A*-, *B*- and C^*- components and *D*-, *B*- and *C**- components.

For indicated lightning current components, such an important parameter for the electrothermal loading in the high-current discharge circuit of the powerful GCL of the test objects of aviation and rocket and space technology, in accordance with the requirements of [1, 2], as the integral of their action J_L, does not numerically exceed $2\cdot10^6$ J/Ω ± 20 %. We note that it is the value of this integral J_L that determines the value of the thermal energy released on the test element of an object. Therefore, the value of J_L often determines the electrothermal lightning capacity of such an object. In addition, when performing full-scale tests according to the requirements of the international standard IEC 62305-1: 2010 [5] of electric power facilities for the lightning strength of the value of the action integral JL of the aperiodic current pulse of 10 μs/350 μs of artificial lightning generated by the developed and created in 2012 at the Department No. 4 of electromagnetic tests of the Research & Design Institute «Molniya» of the NTU «KhPI» with powerful GCL [6], for the I level of their protection against lightning should be $10\cdot10^6$ J/Ω ± 35 %.

With the electrical current loading of the tested objects, it is necessary to register and monitor the ATP of the lightning current component used in the online mode. Typically, similar electrotechnological procedures are performed using measuring means, such as high-voltage high-current measuring shunts (HHMSs) with coaxial cable communication lines operating in a matched wave mode [3, 4], and digital storage oscilloscopes (DSO). As a rule, HHMSs are special non-standardized measuring tools, which are not produced by industry due to their insignificant quantitative need and absence from businessmen for such products of commercial interest. Therefore, domestic high-voltage electrical engineers, together with engineers-metrologists, have to solve their own engineering and technical problems for their development and production with subsequent state metrological certification.

1. The state of the engineering task. In [7], the design and technical characteristics of a measuring coaxial shunt of the ШК-300 type were described to determine the ATP pulses of artificial lightning current generated in high-current discharge circuits of the geological and technical measures in accordance with the requirements of normative documents [1, 2]. The structure of this shunt includes a manganin measuring disk with a thickness h_s≈0.3 mm with an external diameter D_{se}≈80 mm, which determines the impulse resistance of the shunt, which is approximately R_S ≈0.185 mΩ ± 1% [3, 7]. The practice of operating the ШК-300 shunt in laboratory conditions showed its insufficient electrothermal and electrodynamic stability in the high-current discharge circuit of the GCL which reproduces the pulsed current $i_L(t)$ of artificial lightning on the active-inductive load (R_l≈0.1 Ω, L_l≈1 μH) with an action integral equal to about J_L≈$2\cdot10^6$ J/Ω ± 20% [1, 2]. After approximately 100 specified high-current discharges of GCL for the test load and a measuring shunt of the ШК-300 type, the latter loses its metrological characteristics and becomes unsuitable for its further use. According to [5], according to [5], for the aperiodic current pulse of 15 μs/315 μs of an artificial lightning with an amplitude I_{mL}≈184 kA (J_L≈$7.88\cdot10^6$ J/Ω) according to [5], the shunt was destroyed by an internal impulse gas-dynamic pressure in a few hundred atmospheres due to the electric explosion (sublimation) of a part of the material of its thin measuring manganin disk [8]. As we see, when using high-voltage pulse technology with discharge currents of capacitor batteries GCL in hundreds of kA to the choice of the design of the corresponding measuring shunt, higher requirements for its electrothermal lightning resistance should be presented.

In [9], the design of a shunt shunt for the measurement of pulsed currents of microsecond duration with amplitude of up to 75 kA was presented. As a high-resistance measuring element in this shunt structure, parallel-connected straight-line segments of nichrome wire were placed along the circumference between two massive coaxial cylindrical electrodes of the shunt - internal brass and outer duralumin [9]. The ends of each piece of nichrome wire placed parallel to the longitudinal axis of the shunt were soldered to two parallel massive brass disks, between which was a cylindrical ceramic insulator. With a shunt sensitivity of about 350 mV/kA, it allowed reliably to measure only large microsecond pulses the currents of a high-voltage electrophysical installation (amplitude not exceeding 75 kA) and transmit without distortion the current pulse front up to 0.6 μs [9].

The goal of the paper is the development and creation at the Research & Design Institute «Molniya» of the NTU «KhPI» of a coaxial disk shunt of the ШК-300M2 type which makes it possible to reliably measure the ATP of current pulses of artificial lightning in wide amplitude and time ranges with an action integral up to $15\cdot10^6$ J/Ω.

2. Problem definition. The operational experience of the high-voltage high-current ШК-300 type high-current measuring shunt accumulated in the Department No. 4 of electromagnetic testing of the Research & Design Institute «Molniya» of the NTU «KhPI» demonstrates that, taking into account the state of the high-voltage impulse technique of the actual task of metrological support of tests on [1, 2, 5] of domestic aviation and rocket and space technology, as well as electric power facilities for lightning in this shunt construction improvement must be subject to: first, a thin measuring manganin disk; secondly, the insulation between the massive internal brass and massive outer brass cylindrical electrodes. These two positions are the «weak links» in the design of the ШК-300 measuring shunt with its intended application as part of measuring instruments designed to implement technical tasks in accordance with the stringent requirements of [1, 2, 5].

It is required to rationally select the geometry and material of the measuring disk, as well as the insulation between the main brass electrodes in the measuring coaxial shunt, which, after the improvement, has acquired the name ШК-300М2, is required within the applied engineering and technical approach. In addition, after the modernization of the measuring coaxial disk shunt, it is necessary to perform its practical testing and testing of the operability in the high-current discharge circuit of the current high-power high-voltage GCL according to [3].

3. Calculation evaluation of some parameters of the measuring coaxial disk shunt of the ШК-300М2 type. As the material of the measuring disk of a coaxial shunt of the type ШК-300М2, we chose the stainless steel 12Х18Н10Т of domestic production widely used in engineering and everyday life [10]. The average thickness h_{sm} of the measuring disk wall of the investigated high-current high-voltage coaxial shunt of the ШК-300М2 type in the adiabatic mode of its operation on the basis of the known laws of electrical and thermal physics can be estimated from the following relationship:

$$h_{sm} \approx (\pi D_{sm})^{-1}\left[(J_L \rho_s)/(c_s \Delta T_s d_s)\right]^{1/2}, \qquad (1)$$

where D_{sm}≈D_{se}/2; ρ_s, c_s, d_s are the specific electrical resistance, specific heat and density of the disk material at ambient temperature T_0 equal to room temperature 20 °C, respectively; ΔT_s=(T_s−T_0) is the ermissible short-term overheating of the material of the shunt disk with its current temperature T_s caused by the current flowing through it.

For design reasons, we assume that the outer diameter of the measuring steel disk in a ШК-300М2 shunt is D_{se}≈80 mm, and its internal diameter is D_{si}≈10 mm. Then, from (1) with D_{sm}≈40 mm, J_L≈15·10^6 J/Ω, ΔT_s≈100 °C and the initial data known for [10] for 12Х18Н10Т stainless steel (ρ_s≈72,5·10^{-8} Ω·m; c_s≈462 J/(kg·°C); d_s≈7900 kg/m^3), we obtain that the radial averaged wall thickness of the measuring steel disk will be numerically equal to h_{sm}≈1.4 mm. Taking into account a certain reserve in thickness h_{sm} and taking into account our very limited technological possibilities in the selection of materials, we choose the thickness of the wall of the measuring disk of stainless steel 12Х18Н10Т equal to h_{sm}≈2 mm.

Note that in (1) for a shunt of the ШК-300М2 type studied, the value of the short-term superheating ΔT_s of the material of the measuring disk, occurring during the time of the current $i_L(t)$ no more than 1000 ms in practically adiabatic mode, is limited by the type of solid insulation used to separate it from main brass electrode shunt. When using fluoroplastic insulation, the value of overheating ΔTs for reliable operation of ШК-300М2 shunt in the GCL composition should not be more than 100 °C [3, 4]. At ΔT_s≈50 °C and the initial data taken above for the integral of the action J_L of the pulsed lightning current, the geometric, electrical, and thermophysical characteristics of the steel shunt disk from (1), it follows that the h_{sm} thickness of the disk is exactly about 2 mm.

The active resistance R_{S0} of the measuring steel disk of the coaxial shunt ШК-300М2 in the quasi-stationary mode, which practically corresponds to the regime of DC current flowing through it, can be approximated by the following formula [11]:

$$R_{S0} \approx 0.5\,(\pi h_{sm})^{-1} \rho_s \ln(D_{se} / D_{si})\,. \qquad (2)$$

From (2) at h_{sm}≈2 mm, ρ_s≈72.5·10^{-8} Ω·m, D_{se}≈80 mm and D_{si}≈10 mm it follows that the sought value of RS0 is approximately equal to 0.12 mΩ. Measurement of the shunt of the ШК-300М2 shunt type, almost equal to the R_{S0} value, carried out by metrologists in a highly stable scheme of 19 A a DC generator showed that in this experimental case R_{S0}≈0.094 mΩ. It can be seen that the difference between the calculated and experimental data for R_{S0} in our case does not exceed 22 %.

4. Practical implementation of the measuring coaxial disk shunt type ШК-300М2. Fig. 1, 2, respectively, are a general view and a schematic arrangement of a measuring coaxial disk shunt of the type ШК-300М2. The weight of this measuring shunt is about 3.2 kg, and its overall dimensions do not exceed 90×95 mm.

Fig. 1. General view of a coaxial shunt type ШК-300М2 designed to measure on the screens of the DSO in an agreed mode of operation of its coaxial cable communication line of powerful current pulses of artificial lightning in a high-current discharge circuit of a high-voltage GCL with an integral of their action up to 15·10^6 J/Ω

From the data in Fig. 2, it can be seen that a measuring steel disk 5 of thickness h_{sm}≈2 mm is tightly clamped between its massive disks 6 and 7 with a thickness of 10 mm, made of a sheet of fluoroplastic insulation. Between the massive brass cylindrical electrodes 1 and 4 of the shunt through which the measured current pulse $i_L(t)$ of artificial lightning flows from the GCL capacitors, insulating sleeves 2 and 3 with a thickness of 3 mm are installed, also made of fluoroplastic insulation.

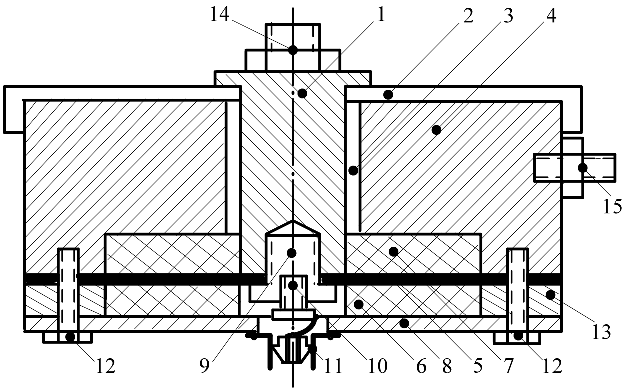

Fig. 2. Elements of the structure of a coaxial disk shunt of the ШК-300M2 type in its longitudinal axial section (1 – massive internal cylindrical electrode, 2,3 – insulating sleeves, 4 – massive outer cylindrical electrode, 5 – high-resistance steel measuring disk, 6,7 – massive insulation disks, 8 – a shroud disk, 9,10,12 – fastening screws, 11 – CP-75 output coaxial connector, 13 – massive clamping ring, 14, 15 – respectively input (potential) and output (earthed) bolted shunt connecting elements to high-current discharge circuit of the GCL)

These bushings significantly increase the electrical strength of the insulating gaps between the live parts of the high-voltage high-current shunt of the ШК-300M2 type, which positively affects the reliability of its functioning as part of a powerful GCL. The increased electrodynamic resistance of the shunt under investigation is provided by a massive pressure brass ring 13 with a thickness of 7 mm, a brass shroud disk 8 with a thickness of 5 mm and steel screws of fixation 12 in quantity of 8 pieces evenly distributed along the outer circular perimeter of the massive brass electrode 4 of the shunt.

A measuring coaxial disk shunt of the type ШК-300M2 is connected in the rupture of a high-current high-voltage discharge circuit of a powerful GCL of one or another version [3, 5]. Moreover, the inner cylindrical brass electrode 1 with diameter of 29 mm of the shunt is connected by means of the bolted joint elements 14 to the potential part of the high-current discharge circuit of the GCL, and its outer cylindrical brass electrode 4 with a diameter 80 mm with the help of the 15 bolt connection elements - to the grounded part of the discharge circuit of the GCL (usually to the metal grounded collector of the high-power capacitor bank of the generator).

5. Results of experimental approbation of a measuring coaxial disk shunt of ШК-300M2 type in a high-current circuit of high-voltage GCL. Fig. 3 shows an oscillogram of the pulsed *A*- component of artificial lightning current obtained by means of a measuring coaxial disk shunt of the type ШК-300M2, included in the discharge circuit of a powerful GCL [3] reproducing according to the requirements of normative documents [1, 2] on the active-inductive load (R_l ≈0.1 Ω, L_l ≈1.5 μH) pulses of artificial lightning current.

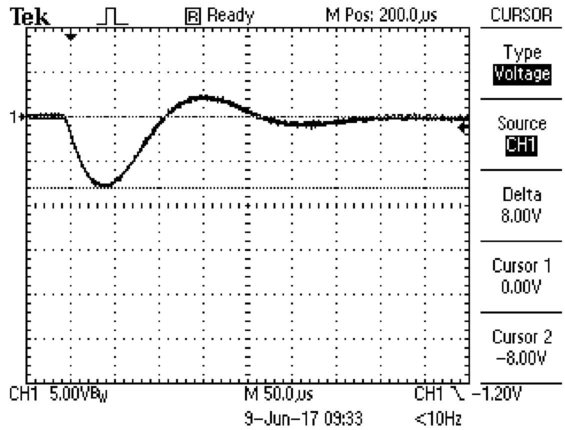

Fig. 3. The oscillogram of the pulsed *A*- component of the artificial lightning current with normalized ATPs in the high-current discharge circuit of the GCL [3] obtained with the help of a measuring coaxial disk shunt of the type ШК-300M2 (I_{mA1}≈–200 kA; t_{mA1}≈38 μs; J_A≈$2.39\cdot10^6$ J/Ω; U_{cA}≈–29.7 кV; S_{SA}≈$25\cdot10^3$ A/V; scale on the vertical – 125 kA/cell; scale on the horizontal – 50 μs/cell)

In the course of experimental studies of the behavior of the improved design and characteristics of a ШК-300M2 shunt in the discharge circuit GCL [3] whose capacitor bank, when forming the one shown in Fig. 3 components of the lightning current were charged to a constant voltage U_{cA}≈ –29.7 kV, it was found that its impulse resistance R_S takes a numerical value equal to about R_S≈0.08 mΩ ± 1%. This experimental R_S value under flow conditions along the measuring steel shunt disk shown in Fig. 3 pulsed current $i_L(t)$ of artificial lightning differs from the active resistance R_{S0}≈0.094 mΩ of the shunt in question by no more than 15% in direct current. It should be noted that the indicated values of the active resistances R_S and R_{S0} are in good agreement with the results of previous studies of transient electromagnetic processes and the penetration depths of the pulsed electromagnetic field in conducting non-magnetic media on the sections of the first three half-waves of the decaying sinusoidal current pulse acting on them [4]. Due to the peculiarities of the distribution in the metal of the measuring disk of the shunt of the pulsed electromagnetic field from the measured pulsed current $i_L(t)$ of the simulated lightning, its impulse resistance R_S will always be less than the active resistance of the R_{S0} disk measured at constant current [4].

It is known that the value of the impulse active resistance R_S of the shunt measuring disk in the coordinated mode of connecting its coaxial cable communication line to the DSO determines its conversion coefficient S_S having the dimension A/B and calculated by the ratio S_S,≈$2/R_S$. In this case, the value of the S_S parameter is numerically equal to the current flowing through the shunt disk when a voltage of 1 V is applied to its input. In this connection, the ATP, measured with a coaxial ШК-300М2 shunt of the pulse current $i_L(t)$ of artificial lightning in the discharge chains of a powerful GCL will be determined by the following relationship:

$$i_L(t) \approx S_S U_{LO}(t)\,, \qquad (3)$$

where $U_{LO}(t)$ is the pulse voltage recorded by means of a measuring shunt on the screen of the DSO.

Taking into account the presented results, we find that the conversion coefficient SS of the measuring shunt of the ШК-300М2 type for the recording mode according to them [1, 2] of the *A*- and *D*- components of the pulsed current of artificial lightning, and also according to [5] 10 μs/350 μs will be $S_{SA}≈2/R_S≈25·10^3$ A/B. When using a shunt made at the end of a coaxial cable line of a shunt made on the basis of an PK 75-7-11 radio frequency cable with a 75-Ω impedance matching voltage divider [3, 7], the S_S conversion coefficient of the investigated shunt-type shunt of the ШК-300М2 type in mode of registration of the intermediate *B*-, long *C*- and shortened long *C**- component of the artificial lightning current will be equal to $S_{SC}≈1/R_S≈12{,}5·10^3$ A/V. This MVD is implemented with two output coaxial connectors 1:1 (for S_{SA}) and 1:2 (for S_{SC}) based on three 110 Ω resistors and placed in a separate shielded housing [3, 7].

Fig. 4 shows the oscillogram of the shortened long-time *C**- component of the current of artificial lightning in a high-current discharge circuit of the GCL [3] which follows in time immediately after the pulsed *A*- current component of the lightning and simultaneously fixed on the DSO screen by means of a measuring coaxial disk shunt of type ШК-300М2. We will point out that in the conducted experiments the DSO Tektronix TDS 1012 series were used in a buried measuring bin and remote from the GCL discharge circuits at a distance of approximately 70 m.

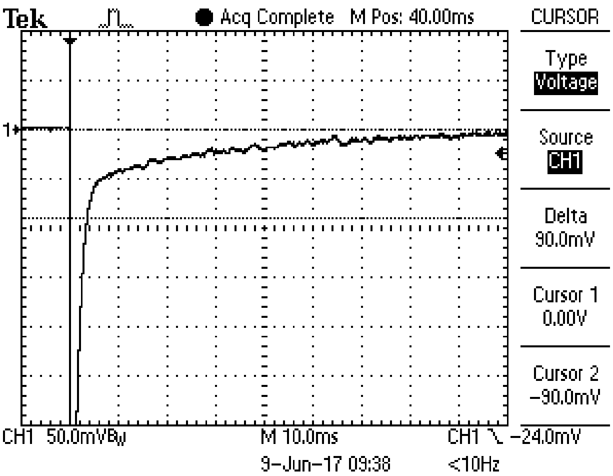

Fig. 4. The oscillogram of the shortened long *C**- component of the artificial lightning current with normalized ATPs in the discharge circuit of the GCL [3] obtained simultaneously with the current *A*- component flowing before it with the aid of a measuring coaxial disk shunt of the type ШК-300М2 ($I_{mC*}≈−750$ A; $t_{mC*}≈5$ ms; $τ_{pC*}≈15$ ms; $q_{C*}≈−18.1$ C; $S_{SC*}≈12.5·10^3$ A/B; $U_{cC*}≈−4$ kV; scale on the vertical – 625 A/cell; scale on the horizontal – 10 ms/cell)

The charging voltage of the negative polarity of the capacitor bank GCL [3] which forms on the active-inductive load ($R_l≈0.1$ Ω; $L_l≈1.5$ μH) the shortened *C** - current component of the simulated lightning applied to the data in Fig. 4 was $U_{cC*}≈-4$ kV. Note that the ones shown in Fig. 3 and 4 ATPs of the pulsed *A*- and shortened long-time *C**- current component of a lightning simulated in the laboratory conditions correspond to the current requirements of normative documents [1, 2].

Conclusions.

1. The developed and created at the Department No. 4 of electromagnetic tests of the Research & Design Institute «Molniya» of the NTU «KhPI» measuring coaxial disk shunt of type ШК-300М2 developed and created allows for its direct placement in a high-current high-voltage discharge circuit of a powerful GCL by means of one additional shielded coaxial cable communication line up to 70 m and a few located in remote from the GCL buried deep shielded bunker DSO in an agreed mode of their operation simultaneously and repeatedly measured on the active-inductive load of the tested object, the main components of artificial lightning current with normalized ATPs in accordance with the requirements of US regulations SAE ARP 5412: 2013 and SAE ARP 5416: 2013 with their amplitude up to ±220 kA and the action integral up to $2.4·10^6$ J/Ω.

2. The measuring coaxial disk shunt of the ШК 300М2 type is capable of repeatedly recording on the active-inductive load and transmitting in a coordinated mode along the coaxial cable communication line to the DSO the aperiodic pulses of a time current of 10 μs/350 μs of a short stroke of an artificial lightning generated in a high-current high-voltage discharge circuit of a powerful GCL with standardized ATPs according to the requirements of the International Standard IEC 62305-1: 2010 with their amplitude up to ±220 kA and the action integral up to $13.5·10^6$ J/Ω.

3. The high-current experiments on a high-power high-voltage GCL were carried out in June 2017 at the Experimental and Test Site of the Research & Design Institute «Molniya» of the NTU «KhPI» in accordance with the requirements of the US regulations SAE ARP 5412: 2013 and SAE ARP 5416: 2013 of the measuring coaxial disk shunt type ШК-300М2 which passed the state metrological certification at the state enterprise «Kharkivstandartmetrologiya» (certificate of conformity No. 06/0206 of 19.07.2017).

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