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# POWERFUL HIGH-CURRENT GENERATOR OF MICROSECOND VOLTAGE PULSES WITH VOLTAGE AMPLITUDE UP TO ±2 MV AND CURRENT AMPLITUDE UP TO ±150 KA WITH ELECTRIC ENERGY STORED IN CAPACITORS UP TO 1 MJ

***Purpose. Development and evaluation, on the basis of existing ultra-high-voltage generator of pulsed voltages and currents of GINT-4 type, of the new scheme of design of its charging-discharging circuit (CDC), and creation of modernized powerful ultra-high-voltage high-current generator of GINT-2 type to form microsecond voltage pulses with amplitudes up to ±2 MV and current with amplitude up to ±150 kA in the electrical load, with electrical energy stored in its capacitive energy storage (CES) up to 1 MJ. Methodology. Fundamentals of theoretical and applied electrical engineering, electrical power engineering, electrophysical principles of high-voltage and high pulsed current engineering, fundamentals of electromagnetic compatibility (EMC), instrument engineering, high-voltage instrumentation and standardization. Results. The new scheme of design of CDC of the modernized powerful ultra-high-voltage, heavy-current generator of GINT-2 type of outdoor placement, that allows obtaining, with preservation of the main electrotechnical elemental base of existing powerful prototype generator GINT-4 (rated output voltage ±4 MV with rated electrical energy stored in CES of 1 MJ and maximal amplitude of output current pulse in electrical load up to ±75 kA) pulses of current of microsecond duration with doubled amplitude (up to ±150 kA) in the long (from 1 to 4 m length) air gap of standard two-electrode discharging «needle-plane» system, in comparison with parameters of current pulses with amplitudes up to ±75 kA that are formed in the discharging circuit of generator of GINT-4 type with the use of the analogous air discharging system, has been developed. Experimental evaluations of the developed new discharging circuit in CDC of the modernized generator of GINT-4 type has been performed in field conditions, and its advantages over the old discharging circuit in composition of CDC of generator of GINT-4 type have been shown. Calculated evaluations of rise rates of high pulsed current (HPC) in plasma channel of air spark discharge of CES with energy up to 1 MJ of generator of GINT-2 type, and strength of electric and magnetic field that are formed around this high-current channel of spark discharge and are powerful electromagnetic interference (PEMI) for objects of armaments and military equipment (OAME) were performed. It was shown that rise rates of HPC obtained for generator GINT-2 in the channel of long air spark discharge (of artificial lightning) and PEMI around this channel practically satisfy strict requirements of the NATO Standards AESTP-250: 2014 and USA MIL-STD-464C: 2010. Originality. The new scheme of design of CDC in composition of the modernized powerful ultra-high-voltage high-current generator of GINT-2 type (developer – Research and Design Institute «Molniya» of NTU «KhPI»), satisfying requirements of the mentioned standards for full-scale tests of OAME for EMC and immunity to action on them of PEMI from long atmospheric spark electric discharges (lightning) was developed for the first time. Practical value. Application of the created ultra-high-voltage high-current generator of GINT-2 type in tests of OAME for EMC and immunity to action on them of PEMI from artificial lightning will assist increase in reliability of OAME functioning in conditions of damaging (destabilizing) action on them HPC and PEMI of natural and artificial origin.*** References 19, figures 6.

*Key words*: **ultra-high-voltage high-current generator of voltage and current pulses, technical objects of military use, standards of tests for electromagnetic compatibility and lightning resistance.**

***Запропонована і апробована нова схема побудови потужного надвисоковольтного сильнострумного генератора імпульсних напруг та струмів ГІНС-2 зовнішньої установки, що формує на активно-індуктивному навантаженні мікросекундні імпульси напруги амплітудою до ±2 МВ і струму амплітудою до ±150 кА при електричній енергії, що запасається, до 1 МДж. Даний генератор побудований на основі розміщеного в польових умовах модернізованого стаціонарного генератора ГІНС-4 на номінальну напругу ±4 МВ і номінальний струм амплітудою ±75 кА з електричною енергією, що запасається в його високовольтних конденсаторах, номінальним значенням 1 МДж. Приведені описи схемних і конструктивних вирішень генератора ГІНС-2, що дозволяють забезпечити при збереженні основної електротехнічної елементної бази генератора ГІНС-4 отримання на довгому розрядному повітряному проміжку двоелектродної системи «голка-плоскість» імпульсів струму мікросекундної тривалості з подвоєною амплітудою в порівнянні з параметрами імпульсів струму, що формуються в розрядному колі генератора ГІНС-4 з використанням аналогічної двоелектродної системи. Переведення генератора ГІНС-4 в режим роботи генератора ГІНС-2 із зменшеним удвічі рівнем вихідної імпульсної напруги і збільшеним удвічі рівнем вихідного імпульсного струму обумовлено вимогами стандартів НАТО АЕСТР-250: 2014 і США MIL-STD-464C: 2010 при випробуваннях технічних об'єктів на електромагнітну сумісність і несприйнятність до дії на них потужніх електромагнітних завад від атмосферних грозових сильнострумних електричних розрядів (блискавок).*** Бібл. 19, рис. 6.

*Ключові слова*: **надвисоковольтний сильнострумний генератор імпульсів напруги і струму, технічні об'єкти військового призначення, стандарти випробувань на електромагнітну сумісність і блискавкостійкість.**

***Предложена и апробирована новая схема построения мощного сверхвысоковольтного сильноточного генератора импульсных напряжений и токов ГИНТ-2 наружной установки, формирующего на активно-индуктивной нагрузке микросекундные импульсы напряжения амплитудой до ±2 МВ и тока амплитудой до ±150 кА при запасаемой электрической энергии до 1 МДж. Данный генератор построен на основе размещенного в полевых условиях***

***модернизированного стационарного генератора ГИНТ-4 на номинальное напряжение ±4 МВ и номинальный ток амплитудой ±75 кА с запасаемой в его высоковольтных конденсаторах электрической энергией номинальным значением 1 МДж. Приведены описания схемных и конструктивных решений генератора ГИНТ-2, позволяющих обеспечить при сохранении основной электротехнической элементной базы генератора ГИНТ-4 получение на длинном разрядном воздушном промежутке двухэлектродной системы «игла-плоскость» импульсов тока микросекундной длительности с удвоенной амплитудой по сравнению с параметрами импульсов тока, формируемых в разрядной цепи генератора ГИНТ-4 с использованием аналогичной двухэлектродной системы. Перевод генератора ГИНТ-4 в режим работы генератора ГИНТ-2 с уменьшенным вдвое уровнем выходного импульсного напряжения и увеличенным вдвое уровнем выходного импульсного тока обусловлен требованиями стандартов НАТО АЕСТР-250: 2014 и США MIL-STD-464C: 2010 при испытаниях технических объектов на электромагнитную совместимость и невосприимчивость к воздействию на них мощных электромагнитных помех от атмосферных грозовых сильноточных электрических разрядов (молний).*** Библ. 19, рис. 6.
*Ключевые слова*: **сверхвысоковольтный сильноточный генератор импульсов напряжения и тока, технические объекты военного назначения, стандарты испытаний на электромагнитную совместимость и молниестойкость.**

**Problem definition.** In accordance with the requirements of the current Standards of the NATO AECTP-250: 2014 [1] and the USA MIL-STD-464C: 2010 [2] when testing various objects of armaments and military equipment (OAME) for electromagnetic compatibility (EMC) and resistance to direct (indirect) the action on them of powerful electromagnetic interference (PEMI) caused by atmospheric thunderstorm high-current spark electric discharges (lightning) [3-5], it is required in the area of placement on the test site of the mentioned OAME to form such high electric and magnetic fields in the surrounding airspace due to the flow of a spark channel of artificial lightning with high pulses current (HPC) which should be characterized by the rate of lightning HPC rise of the order of $10^{11}$ A/s with its amplitude up to (100-200) kA. The rate of increase in the strengths of the electric and magnetic fields in the near circular zone with radius $r_c$ up to (3-10) m from the spark channel of artificial lightning should be, respectively, about $10^{11}$ V/(m·s) and $10^9$ A/(m·s) [1, 2]. To ensure the fulfillment of such stringent requirements for the amplitude-temporal parameters (ATP) of the HPC of artificial lightning and the PEMI, appropriate powerful ultra-high-voltage high-current test electrical installations are required that can simulate in the open air near or far from the tested OAME long (1 m and more length) spark electric discharges (lightning) with HPC of the specified ATPs. The development and creation of such an ultra-high-voltage (for output pulse voltage with amplitude of 1 MV or more) high-current (for output pulse current with amplitude of 100 kA or more) test electrical equipment is associated with large financial and material and labor costs. It is known that the cost of constructing such a special test electrical equipment operating in the microsecond time range of generated on an electrical load pulses of voltage and current, is about USD 1000 per 1 kJ of electrical energy stored in its capacitive energy storage (CES) [6]. Therefore, with the energy intensity required by [1, 2] of ultra-high-voltage high-current test electrical equipment of the order of 1 MJ for its construction in Ukraine, funds are required of at least USD 1 million. In this regard, an appropriate technical solution for its developers is the appropriate modernization of the existing generators of pulse voltages and currents (GINT), which ensures compliance with the requirements of regulatory documents [1, 2].

In the 1970s, for testing the electrical strength of the external (internal) insulation of electric power and OAME facilities for EMC and lightning resistance at the experimental testing ground of the Research and Design Institute «Molniya» of NTU «KhPI» (urban-type settlement Andreevka, Kharkiv region) a powerful generator of the GINT-4 type of stacked type was created, characterized by rated output voltage $U_{ex}$=±4 MV with rated electrical energy stored in its high-voltage capacitors equal to 1 MJ [7]. The insulating support structure (INS) of this generator was made on the basis of 576 porcelain support insulators of the KO-400S type, beams and braces made of wood laminated plastic of the DSPB-E-40 type, and its insulating protective (enclosing) structure is based on fiberglass pipes of the TSPO type and fiberglass roll electrical material of the REM-0,8 type [6, 7]. The scheme for constructing its charge-discharge circuit (CDC) adopted in the design of GINT-4, shown and described in [8, Fig. 12], provided a damped sinusoidal current pulse with amplitude of its first half-wave with duration of up to 11 μs no more $I_{m1}$≈±75 kA in a two-electrode system «needle-plane» [7, 9]. It should be noted that the CDC of the GINT-4 generator was made according to the classic bipolar Arkadiev-Marx circuit, containing 16 electrical cascades and, accordingly, 32 oppositely charged stages of it up to constant rated voltage $U_C$=±125 kV, separated by 16 two-electrode uncontrolled air switches made in the form of standard ball arresters (BA) with diameter of 125 mm [7]. Each stage of electrical cascades consisted of 4 high-voltage capacitors in a metal case of the type KBMG-125/1 (rated charging voltage $U_C$=±125 kV; electric capacitance $C$=1 μF) developed by the Research and Design Institute «Molniya» of NTU «KhPI». As a result, the CDC of the GINT-4 generator had 128 capacitors of the KBMG-125/1 type. In this regard, the capacity «in the discharge» $C_d$ of this generator was about 0.125 μF, and the rated value of the electric energy stored in its capacitors $W_g$=0,5$C_dU_{ex}^2$ was equal to 1 MJ. In bipolar charging circuits (two for each electric polarity of the capacitors $C$ of its CDC) of the indicated capacitors of the GINT-4 generator, single-section high-voltage charging resistors $R_C$ with nominal value of 500 Ω were installed in an amount of 32 (8 for each of the four charging legs of the stages of its cascades), made on the basis of nichrome wire wound on a long fiberglass pipe and filled with epoxy compound [7, 9] were installed.

The CDC of the GINT-4 generator contained 16 discharging single-section resistors $R_d$ (8 for each of the two oppositely charged branches of the stages of its cascades) with nominal value of 110 kΩ, each of which was made on the basis of a series fixed on a rectangular getinax plate of zigzag-shaped 50 constant ceramic volume resistors of the TVO-10-2,2 kΩ type and is designed for voltage of ±500 kV [7, 9]. All stages of the GINT-4 generator in the area of their BAs were equipped with damping resistors $R_{Ca}$ with nominal value of 0.5 Ω, made by winding nichrome wire on short fiberglass pipes and filling it with epoxy compound [7, 9]. In the discharge mode of the CDC capacitors of the GINT-4 generator to the electrical load due to nine damping resistors $R_{Ca}$, a total active resistance equal to $R_{C\Sigma}$≈4.5 Ω is connected to its discharge circuit. ATPs of voltage (current) pulses formed on an electrical load were determined by the choice in the CDC of this generator of the level and polarity of the charging voltage $U_C$ of the steps of its electrical cascades, as well as the circuits used at its output for generating the required electrical signals. The CDC design circuit adopted in the construction of the GINT-4 generator led to the obtaining of a sufficiently high level of the specific self-inductance of this type of generator at the output of its ultra-high-voltage discharge circuit, amounting to 20 μH/MV [7, 9]. In this regard, the own inductance $L_g$ of the discharge circuit of the generator of the GINT-4 type at $U_{ex}$=±4 MV was about 80 μH [7-10]. The relatively small value of the capacitance «in the discharge» $C_d$ =0.125 μF and the relatively large value of its own inductance $L_g$≈80 μH of the generator of the GINT-4 type, in principle, do not allow it to fulfill the considered requirements of the NATO AECTP-250: 2014 [1] and the USA MIL-STD-464C: 2010 Standards [2] when testing OAME for EMC, the effect of PEMI on them as wells lightning resistance. From the given technical characteristics of the GINT-4 type generator, it can be seen that in relation to the requirements presented in [1, 2], its main disadvantage is the relatively low level of artificial lightning HPC (no more than $I_{m1}$≈±75 kA) formed by it on an electrical load (for example, on a long air discharge gap). In this regard, an urgent applied problem is one that is aimed at modernizing the CDC of the ultra-high-voltage generator of the GINT-4 type with the goal of real approximation with its help to the fulfillment of the basic requirements of regulatory documents [1, 2] at the Research and Design Institute «Molniya» of NTU «KhPI» when testing OAME on EMC, the impact on them of the corresponding HPC, PEMI as well as lightning resistance.

**The goal of the paper** is the development and testing on the basis of the existing super-high-voltage generator of the GINT-4 type of a new scheme for constructing its CDC and the creation of a modernized powerful ultra-high-voltage high-current generator of the GINT-2 type for the formation on an electrical load of microsecond voltage pulses with amplitude of up to ±2 MV and current with amplitude of up to ±150 kA with stored electrical energy in its CES up to 1 MJ.

**1. Results of the development of a new CDC scheme of the modernized powerful ultra-high-voltage high-current generator GINT-2.** When modernizing the CDC of the powerful ultra-high-voltage high-current generator of the GINT-4 type, our main attention was directed to increasing the capacity «in the discharge» $C_d$ and decreasing own inductance $L_g$ of this generator. Due to such measures, it becomes real for us to achieve the goal defined for the tested OAME by regulatory documents [1, 2]. In this case, an indispensable condition was the preservation in its CDC of the main electrical element base of the generator of the GINT-4 type.

Figure 1 shows a circuit diagram of a modernized powerful ultra-high-voltage high-current generator of the GINT-2 type, containing in its CDC, with its capacity «in the discharge» $C_d$=0.5 μF, eight electrical stages, eight uncontrolled air BAs with diameter 125 mm, one controlled BA of the trigatron type and 128 high-voltage capacitors of the KBMG-125/1 type.

In the CDC of the generator of the GINT-2 type, single-section discharge resistors $R_d$ with nominal value of 110 kΩ (4 for each polarity of its two branches of the charge of high-voltage capacitors $C$ of the sections of all cascades) remained the same from the CDC of the generator type GINT-4.

Figure 2 shows a general view of the GINT-2 generator.

In Fig. 1, the test object (TO) is a two-electrode discharge system «needle-plane», the length $l_a$ of the air gap in which can vary from 1 to 4 m. It can be seen that, in contrast to the scheme for constructing the generator of the GINT-4 type, the new CDC o the generator of the GINT-2 type in each stage of its electrical cascades contains eight capacitors of the KBMG-125/1 type. With parallel charging up to voltage $U_C$ of the corresponding polarity of these capacitors through charging resistors $R_C$ with nominal value of 30 kΩ, the stages of all stages are galvanically interconnected by means of charging-separating resistors $R_{CO}$ with nominal value of 180 Ω borrowed from the CDC of the GINT-4, which do not participate in the high-current discharge circuit of the generator of the GINT-2 type (see Fig. 1) [11]. In the discharge mode through air BAs $F_1$−$F_8$ with damping resistors $R_{Ca}$ with nominal value of 0.5 Ω, the steps of all stages are connected in series with each other, which determines the capacity «in the discharge» of each stage, equal to $C_C$ =4 μF. Taking into account the fact that when the generator of the GINT-2 type is discharged on the TO, all of its eight electrical cascades are connected in a series circuit ascending to the steel shield-roof (see Fig. 1), then

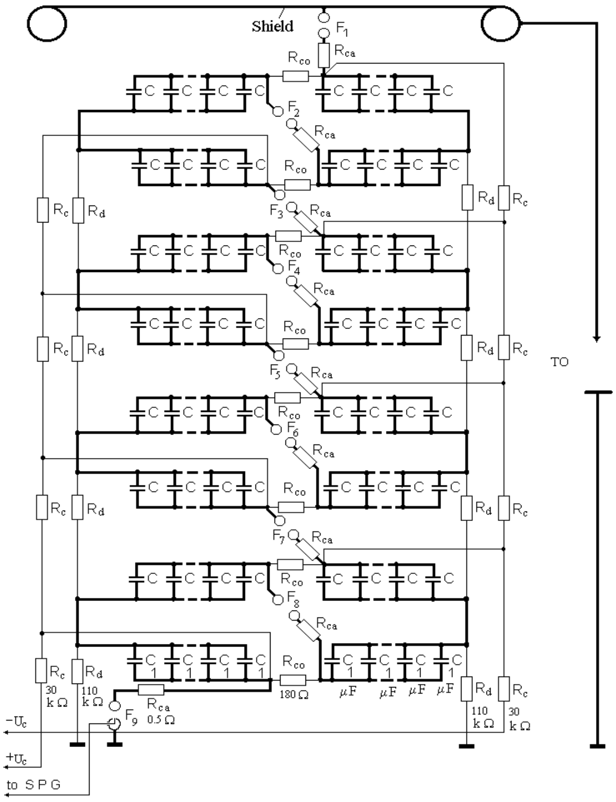


Fig. 1. Circuit diagram of the modernized powerful generator of pulse voltages and currents GINT-2 for rated voltage of ±2 MV, rated current of ±150 kA and rated electrical energy stored in its capacitors of 1 MJ, assembled on the basis of the generator of pulse voltages and currents GINT-4 for rated voltage of ±4 MV, rated current of ±75 kA and rated electrical energy stored in its CES of 1 MJ (the bold line shows a new discharge circuit of the ultra-high-voltage high-current generator)

Fig. 2. External view of the modernized powerful ultra-high-voltage high-current generator of the GINT-2 type, containing a flat steel shield-roof with slope of rectangular shape with area of 60 m$^2$ with round edges (in the foreground, to measure the ATPs of voltage pulses formed at the test object, an ohmic voltage divider is installed on ±2.5 MV of the ODN-2 type)

the value of the capacitance «in the discharge» $C_d$ of such a generator becomes equal to 0.5 μF. It can be seen that the value of this capacitance of the GINT-2 generator has become four times greater than the capacitance «in the discharge» $C_d$ of the generator of the GINT-4 type. It is important to point out that in the CDC of the generator of the GINT-4 type, the discharge circuit of its 16 electrical cascades occurred along a spiral of relatively large diameter (up to 6 m) ascending from the bottom up to the shield-roof [7, 9].

There were four electrical stages of this generator per one turn of this spiral. In the modernized CDC of the GINT-2 generator (Fig. 3), the discharge circuit of its eight electrical cascades is carried out along a linear-bifilar loop path of relatively small width (up to 3 m) ascending from the bottom up to the shield-roof. As a result of this proposed design of the new CDC, the specific own inductance of the ultra-high-voltage generator of the GINT-2 type began to be up to 10 μH/MV. At rated output voltage $U_{ex}$=±2 MV, the own inductance $L_g$ of this generator decreased four times compared to the own inductance $L_g$≈80 μH of the generator of the GINT-4 type and began to not exceed 20 μH (with the INS height of the considered powerful generators up to 12 m [7, 9]).

Fig. 3. External view of the main elements of the modernized CDC of the generator of the GINT-2 type, which were previously electrical element base of the GINT-4 generator

For technological and technical reasons (for the possibility of using the CDC of the GINT-4 and GINT-2 generators in the future when creating an ultra-high-voltage generator of aperiodic switching voltage pulses of the standard 250 μs/2500 μs [12]), $R_C$ charging resistors in the CDC of the GINT-2 generator were replaced with «new» two-section resistors with nominal value of 30 kΩ and length of about 1500 mm (Fig. 4).

Each section of the «new» charging resistors $R_C$ in the CDC of the GINT-2 generator was made of 50 connected in series and zigzag connected ceramic bulk resistors TVO-5-300 Ω, placed on a flat rectangular getinax plate and filled with epoxy compound [12].

Fig. 4. General view of round cylindrical «old» (bottom) and flat rectangular «new» (top) charging resistors $R_C$, respectively, with nominal value of 500 Ω and 30 kΩ, which are part of the CDC, respectively, of powerful ultra-high-voltage generators of the GINT-4 type and GINT-2 type

We point out that when the CDC capacitors $C$ of the GINT-2 type generator (see Fig. 1) reaches the specified level of charging voltage $\pm U_C$ from the starting pulse generator (SPG), a triggering microsecond voltage pulse with amplitude of ±10 kV (the polarity of this pulse is determined by the polarity of the charge of the first electrical section of the generator stage from the ground) is fed to the trigatron-type controlled air arrester $F_9$ [13]. After the actuation of the controlled BA $F_9$ with diameter of 125 mm due to the sequential occurrence of overvoltages in the discharge circuit of the CDC of the GINT-2 generator, the air BAs $F_1$–$F_8$ of all stages are triggered along its height, which leads to the formation of the required voltage and current pulses on the TO. The polarity of the output voltage pulse $U_{ex}$ of the GINT-2 generator will be of the opposite polarity of the charge of its first section of the electric cascade from the ground, connected directly to the BA $F_9$.

**2. Results of calculation and experimental testing of the new CDC circuit of the powerful ultra-high-voltage high-current generator GINT-2.**

According to the laws of theoretical electrical engineering, it is known that in the *RLC*-circuit as applied to the CDC of the modernized generator of the GINT-2 type, which is characterized by a halved level of the rated output voltage $U_{ex}$ (up to ± 2 MV) and a fourfold reduced own inductance $L_g$ (up to 20 μH) compared with the CDC of the generator of the GINT-4 type [7], provided $R_{C\Sigma}<2(L_g/C_d)^{1/2}$, the amplitude $I_{m1}$ of the sinusoidal discharge current at its output will be directly proportional to the value $(C_d)^{1/2}$ [14]. Since the capacity «in the discharge» $C_d$ of the generator of the GINT-2 type has become four times higher than the corresponding capacitance $C_d$ of the generator of the GINT-4 type, the considered amplitude $I_{m1}$ of the rated discharge current at the output of the CDC of the modernized generator of the GINT-2 type should double with the corresponding amplitude $I_{m1}\approx\pm 75$ kA of the current [7, 9] in the discharge circuit of the generator of the GINT-4 type and amount to approximately ±150 kA. A characteristic feature of the CDC of the modernized generator of the GINT-2 type is that the period $T_g$ of oscillations of the discharge current in it in accordance with Thomson formula $T_g\approx 2\pi(L_gC_d)^{1/2}\approx 21$ μs [14] remains practically unchanged in comparison with the value of $T_g$ in the CDC of the generator of the GINT-4 type.

The calculation estimate of the maximum value of the rate of rise of the discharge current $i_C$ in the CDC of the modernized generator of the GINT-2 type with TO in the form of an air «needle-plane» system can be performed according to the following approximate relation:

$$di_C/dt \approx 2\pi T_g^{-1} I_{m1} . \qquad (1)$$

At $T_g\approx 21$ μs and $I_{m1}\approx 150$ kA, according to (1), the sought-for calculation value of the maximum rate of rise of the sinusoidal discharge current $i_C$ in the CDC of the GINT-2 generator will be about $0.45\cdot 10^{11}$ A/s. It can be seen that the obtained numerical value of $di_C/dt$ approaches the requirements of regulatory documents [1, 2]. The calculation value of the maximum rate of rise in the air of the magnetic field strength $H_C$ around the zone of flow of the high-current discharge channel from the GINT-2 generator with TO in the form of a «needle-plane» discharge system, taking into account the law of total current, can be determined by the following approximate formula:

$$dH_C/dt \approx (2\pi r_c)^{-1} di_C/dt \approx r_c^{-1} T_g^{-1} I_{m1} . \qquad (2)$$

From (2) at $r_c\approx 4.46$ m, $T_g\approx 21$ μs and $I_{m1}\approx 150$ kA it follows that the numerical value of $dH_C/dt$ turns out to be approximately equal to $1{,}6\cdot 10^9$ A/(m·s). The obtained $dH_C/dt$ value fully meets the requirements from [1, 2].

As for the calculation estimate of the maximum rate of rise in the air of the electric field strength $E_C$ around the cylindrical zone of the long spark discharge channel from the GINT-2 ultra-high-voltage generator with TO in the form of a standard «needle-plane» air discharge system, on the one hand, it can be estimated by the following approximate expression:

$$dE_C/dt \approx U_{CU}/(T_C l_a) , \qquad (3)$$

where $U_{CU}$ is the cutoff voltage for the output pulse $U_{ex}$ in the discharge circuit of the GINT-2 generator with the specified TO in the form of a «needle-plane» system; $T_C$ is the pre-discharge time in the «needle-plane» system; $l_a$ is the length of the air gap in the «needle-plane» system.

We point out that the parameters $U_{CU}$ and $T_C$ included in (3) must be determined in accordance with the requirements of the current interstate standard GOST 1516.2-97 [15]. With the experimental data obtained for the high-current circuit of the ultra-high-voltage generator of the GINT-2 type with the considered discharge system «needle-plane» having numerical values $U_{CU}\approx 1180$ kV, $T_C\approx 1.7$ μs and $l_a$=2 m, from (3) we obtain that in this case, the sought value of $dE_C/dt$ takes on a numerical value equal to about $3.47\cdot 10^{11}$ V/(m·s). It is seen that the obtained calculated value of $dE_C/dt$ approaches the value required by [1, 2].

Figure 5 shows a typical oscillogram of a microsecond voltage pulse $U_{ex}(t)$ obtained in the high-current discharge circuit of this generator ($U_C$ = ±100 kV) during an electric breakdown at the TO of a long air gap

($l_a$=2 m) in the «needle-plane» discharge system for the case of experimental testing of the new CDC of the modernized powerful generator of the GINT-2 type. It is seen that the spark breakdown of this air gap occurs on the growing part of the ultra-high voltage pulse formed and applied to it. In this case, the pulsed cutoff voltage $U_{CU}$ is ~1180 kV, and the pre-discharge time $T_C$ is about 1.7 μs.

On the other hand, taking into account the classical electrodynamic ratio in air between the strengths of the electric $E_C$ and magnetic $H_C$ fields in the electromagnetic wave formed for testing the OAME ($E_C/H_C$≈377 Ω in the far circular zone from the source of electromagnetic radiation [6]) for the $dE_C/dt$ value at the front of the first half-wave of the $E_C$-field strength in the near air circular zone with radius of $r_c$≤10 m from the spark discharge channel of artificial lightning in the considered high-current discharge circuit of the generator of the GINT-2 type, the following approximate expression can be written:

$$dE_C / dt \approx 377 dH_C / dt . \quad (4)$$

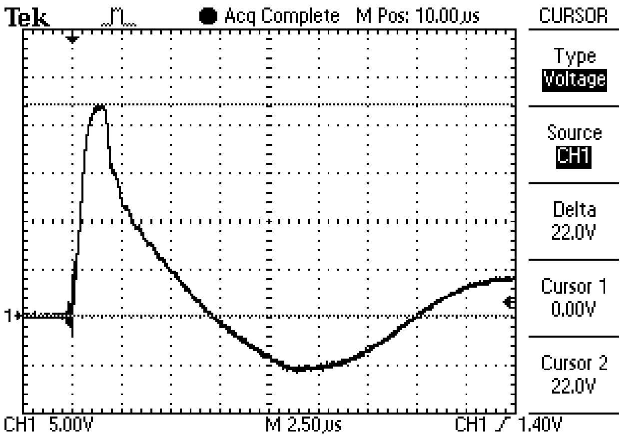


Fig. 5. Oscillogram of the voltage pulse cut off on the rising part applied to a long air gap ($l_a$=2 m) connected to the high-current circuit of the ultra-high-voltage generator GINT-2 of the two-electrode discharge system «needle-plane» ($U_C$=±100 kV; $U_{CU}$≈1180 kV; $T_C$≈1.7 μs; vertical scale – 268.2 kV/cell; horizontal scale – 2.5 μs/cell)

The possibility of using formula (4) in the carried out approximate calculation estimate of the value of $dE_C/dt$ is indicated by the fact that the distance from the center of the spark discharge channel of the simulated lightning, to which the first half-wave of the $E_C$-field strength propagates through the air with an electric breakdown of an air gap of length $l_a$≤(1-4) m in a two-electrode system «needle-plane» for $T_C$≤2 μs (see Fig. 5), numerically does not exceed 600 m. Such an approach in the calculation estimation of $dE_C/dt$ does not contradict the requirements of the above documents [1, 2]. In addition, a similar approach is used to assess the ATPs of formed in the near air zones of artificially generated high-power electromagnetic pulses (EMPs) simulators (for example, micro- and nanosecond EMPs of nuclear explosions) [16].

Then from (4) at $dH_C/dt$≈1.6·10$^9$ A/(m·s), obtained above from (2) at $r_c$≈4.46 m for the case under consideration ($T_g$≈21 μs; $I_{m1}$≈150 kA) , it follows that $dE_C/dt$ can take a numerical value equal to approximately 6.03·10$^{11}$ V/(m·s). This slew rate for $dE_C/dt$ practically meets the requirements set out in the normative documents [1, 2].

Figure 6 shows a typical oscillogram of the damped sinusoidal discharge current $i_C(t)$ ($T_g$≈21 μs) in the CDC of the generator of the GINT-2 type with an electrical breakdown of an air gap of length $l_a$=1 m in the «needle-plane» discharge system. From the data in Fig. 6 it follows that when the charging voltage $U_C$ of capacitors in the CDC of the GINT-2 generator increases to the rated level and equal to ±125 kV, it becomes possible to obtain current pulses in the air discharge system «needle-plane» with the amplitude of the first half-wave equal to $I_{m1}$≈± 150 kA.

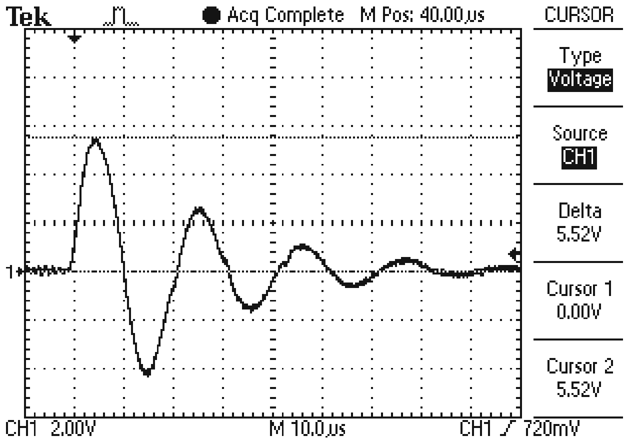


Fig. 6. Oscillogram of the pulsed current in the discharge high-current circuit of the ultra-high-voltage generator of the GINT-2 type with an electrical breakdown of an air gap of length $l_a$=1 m in the «needle-plane» discharge system ($U_C$=±50 kV; $I_{m1}$≈62.1 kA; $T_g$≈21 μs; vertical scale – 22.52 kA/cell; horizontal scale – 10 μs/cell)

When measuring the ATPs of voltage pulses formed in the discharge circuit of the GINT-2 generator (see Fig. 5), an ultra-high-voltage ohmic divider of pulsed voltage for ±2.5 MV type ODN-2 (see Fig. 2) with a division coefficient $K_d$≈53.65·10$^3$ [17] matched in the measuring circuit was used. From ODN-2 a shielded cable communication line with length of up to 60 m was coordinatedly connected to a Tektronix TDS 1012 digital storage oscilloscope, placed to reduce electromagnetic interference in its working channel and to increase the measurement accuracy of these ATPs far from the generator of the GINT-2 and the TO type in a buried shielded measuring bunker.

When registering the ATPs of the discharge current pulses $i_C$ in the CDC of the GINT-2 generator, a coaxial shunt of the ShK-300 type [18] verified by the State Metrological Service with a shielded cable communication line up to 70 m in length, having a conversion coefficient numerically equal to $K_S$≈$11.26 \cdot 10^3$ A/V and coordinatedly connected to the measuring path with a Tektronix TDS 1012 digital storage oscilloscope, placed to reduce the parasitic influence of external PEMI on it far from the test site in a buried shielded measuring bunker [19].

Taking into account the absence in the open literature of data on ultra-high-voltage test installations of NATO countries that implement the requirements of the above Standards [1, 2], we can conclude that, in terms of their technical characteristics (ATPs of voltage, current and PEMI pulses generated at the TO, the level of electric energy storage in its CES and a relatively low cost of development and construction), an ultra-high-voltage generator of the GINT-2 type meets the high world requirements in the field of high-voltage pulse technology.

**Conclusions.**

A powerful ultra-high-voltage high-current generator of pulsed voltages and currents of the GINT-2 type, developed and created at the Research and Design Institute «Molniya» of NTU «KhPI» which forms microsecond voltage pulses with amplitude of up to ±2 MV and current with amplitude of up to ±150 kA with electric energy stored in its high-voltage capacitors up to 1 MJ on an active-inductive electrical load made in the form of a standard two-electrode air discharge system «needle-plane» allows, in accordance with the requirements of the current Standards of the NATO AECTP-250: 2014 and the USA MIL-STD-464C: 2010 to carry out full-scale tests of weapons and military equipment for electromagnetic compatibility and resistance to direct (indirect) impact on them of HPC and powerful electromagnetic interference caused by atmospheric lightning spark discharges (lightning).

**Note.**

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