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ELECTRONICS AND RADIO ENGINEERING

A Generator of Aperiodic Current Pulses of Artificial Lightning of a Rationed Temporal Form of 10/350 μs with an Amplitude of ±(100–200) kA

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Abstract—A high-power high-voltage generator that forms aperiodic current pulses of artificial lightning of a temporal form of 10 μs/350 μs and an amplitude of ±(100–200) kA with tolerances, which are normalized according to the IEC 62305-1–2010 International Standard, is described. The circuit and design solutions are described that make it possible, using a generator that is developed on the basis of capacitive energy storages, to provide the generation of aperiodic positive (negative) current pulses of a simulated lightning across an electric load with an ohmic resistance of 0.1 Ω and an inductance of 1.5 μH. The time in which the magnitude of the pulse amplitude I_m reaches 106 kA is $t_m \approx 24$ μs, the pulse duration at a level of $0.5I_m$ is $\tau_p \approx 340$ μs, and the pulse-front duration is $\tau_f \approx 15$ μs. The action integral of a current pulse of the first short stroke of artificial lightning with an amplitude of $I_m \approx 106$ kA, which was obtained according to the IEC 62305-1–2010 standard, was $J_a \approx 3.03 \times 10^6$ A^2 s, and the electric charge that passed through the aforementioned load was $q_l \approx$ 52.2 C.

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INTRODUCTION

Direct strokes of linear lightning (LL) to technological buildings (constructions) or LL strokes near them are serious sources of hazards for these structures themselves and for people and various engineering and electric networks inside them. In connection with this, the questions of the development and practical application of technological protection measures against the action of LLs on energy-saturated objects and primarily objects of industrial electrical-power engineering (nuclear and thermal electric-power plants, electricity transmission lines, substations, etc.)

At present, the general principles of protecting buildings, constructions, and their parts, including people and engineering utility lines, are determined by a number of existing international and national standards [1–5]. In accordance with these standards, when electrical devices and networks of the aforementioned objects are tested for lightning resistance to the first short LL stroke, an aperiodic lightning-current pulse must be used with a normalized time shape of τ_f/τ_p = 10 μs/350 μs, where τ_f and τ_p are, respectively, the current-pulse-front duration (with a tolerance of ±20%) and the current-pulse duration (±10%). The amplitude of this pulse must be I_m = ± (100–200) kA (±10%) [1–5].

In [1–5], four lightning-protection levels or four degrees of severity of testing objects for lightning resistance were established. In this case, for each lightning-protection level, the following parameters of a current pulse of a single-component LL were determined [1–5]: I level: I_m = ±200 kA (with a tolerance of ±10%), the specific energy (the lightning-current action integral) $J_a = 10 \times 10^6$ A^2 s (±35%), the passed charge q_l = ±100 C (±20%); II level: I_m = ±150 kA (±10%), $J_a = 5.6 \times 10^6$ A^2 s (±35%), q_l = ±75 C (±20%); III–IV levels: I_m = ±100 kA ±10%), $J_a = 2.5 \infty 10^6$ A^2 s (±35%), q_l = ±50 C (±20%). Note that the action integral of a lightning-current pulse $i_L(t)$ is determined by the expression $J_a = \int_0^{\tau_p} i_L^2(t)dt$, and the passed charge is $q_l = \int_0^{\tau_p} i_L(t)dt$. According to [1–5], during physical modeling of a considered current pulse of artificial lightning, its time parameter τ_f is of minor character, thus permitting the use of a range of 10 μs ⩽ τ_f ⩽ 15 μs and substantially simplifying its practical obtainment.

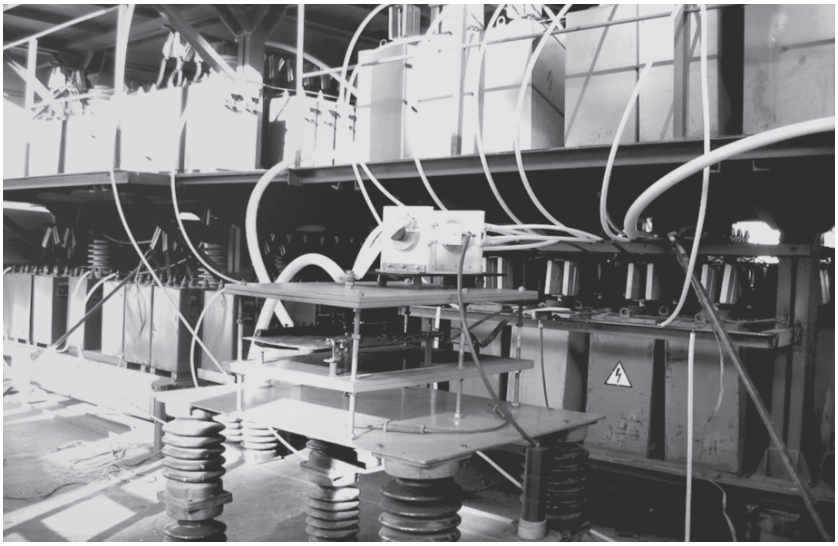

Fig. 1. An external view of a high-power high-voltage GITM-10/350: the working table of the artificial-LL current generator with KVGU-50 (a high-voltage three-electrode air-filled triggered switch with graphite electrodes), which is rated for a voltage of ±50 kV and a pulse lightning current with an amplitude of up to ±300 kA and is placed on the table, is at the foreground. The elements of the charging–discharging circuits of its separate PCGs are at the background.

Among high-voltage high-current electric facilities that currently exist at the leading scientific and technical centers and reproduce a required aperiodic current pulse of artificial lightning with a time shape of 10 μ s/350 μs, a Russian simulator of a pulse LL current should be mentioned [6]. This simulator forms appropriate current pulses with amplitudes I_m of up to ±100 kA across a low-resistance low-inductance electric load of a tested object.

In addition, a German generator of aperiodic artificial-lightning current pulses with a time shape of 8 μs/20 μs is known, which has a modular design; at a voltage of ±100 kV and a stored energy of 250 kJ, it can generate aforementioned pulses of a short LL stroke with an amplitude I_m of up to ± 200 kA [7].

A Ukrainian artificial-lightning current generator, which was described in [8], was developed in 2007 at the NIPKI Molniya, National Technical University, Kharkiv Polytechnical Institute in accordance with several International normative documents [9–12]. This generator forms the required amplitude and time parameters (ATPs) of the pulse (*A*), repeated pulse (*D*), intermediate (*B*), and long-duration (*C*) components of an LL pulse current in onboard devices of aircraft, rocket, and space engineering.

In connection with this, the development of a high-power generator of aperiodic artificial-LL current pulses with a time shape of 10 μs/350 μs with a normalized pulse-current amplitude I_m of ±100–±200 kA, which is formed across the electric load of a tested object, remains an urgent applied problem in the field of high-voltage high-current impulse technology. The high-current discharge circuit of such a generator must not contain a high-voltage shunting switch, which is complex in design, expensive, unreliable in operation, and closes the load at the moment when the current reaches its amplitude I_m [1, 5].

PERFORMANCE CHARACTERISTICS OF THE GENERATOR OF ARTIFICIAL-LIGHTNING CURRENT PULSES

In 2014, in accordance with the requirements of the IEC 62305-1–2010 International Standard in force [1], we developed and put into trial operation a generator of lightning-current pulses (hereinafter, GITM-10/350) that allows one to perform natural tests of electric devices of various objects of electrical-power engineering and other technological constructions, which are affected by aperiodic current pulses of the first short artificial LL stroke with a time shape of 10 μs/350 μs at a pulse amplitude I_m of ±100–±200 kA with the normalized tolerances for the ATPs of such pulses in accordance with the above standard.

This GITM-10/350 (its general view is shown in Fig. 1) contains four pulse-current generators (PCGs) that make it possible, when operating in parallel into a common active–inductive load of a device that is tested for lightning resistance, to obtain the required (according to the IEC 62305-1–2010 International Standard [1]) ATPs of an aperiodic current pulse of a short simulated LL stroke.

In the developed GITM-10/350, owing to a change in the level of the charging voltage U_C of high-voltage pulse capacitors of its separate PCGs, the aforementioned test LL current pulses of both polarities can also be obtained at their common electric load not with

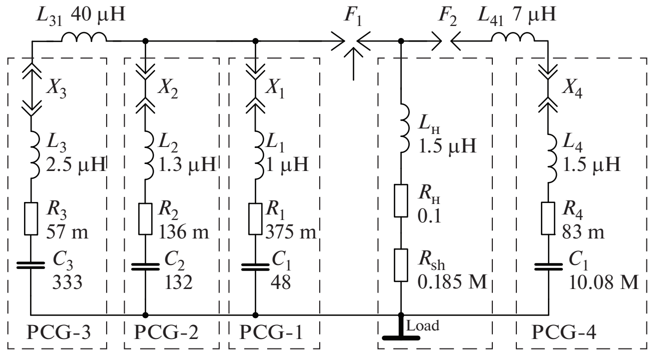

Fig. 2. An equivalent electric circuit of the high-current discharge circuits of four separate high-voltage PCG-1–PCG-4 and the complete electric circuit of GITM-10/350 (X_1–X_4 are massive conducting jumpers of the discharge circuits of PCG-1–PCG-4).

normalized (according to [1–5]) values of their amplitudes I_m, but in a wider current range of ± (10–200) kA.

Figure 2 shows an equivalent circuit for the GITM-10/350 generator, which includes high-current discharge circuits of its individual PCG-1—PCG-4. The data in Fig. 2 show that the high-voltage PCG-1–PCG-4, which are incorporated in GITM-10/350, are manufactured on the basis of capacitive energy storages. The PCG-1–PCG-3 electric-energy storages are equipped with IK-50-3 high-voltage pulse capacitors with a nominal voltage of ±50 kV and a nominal capacitance of 3 μF, and the PCG-4 is equipped with IM2-5-140 high-voltage capacitors (the voltage is ±5 kV, and the capacitance is 140 μF) [13]. The capacitors in the PCG-1–PCG-3 charging–discharging circuits are connected in parallel, while the capacitors in the PCG-4 are connected in series–parallel.

All capacitors in GITM-10/350 that have metallic cases are placed on two floors that are formed by its carrying metallic and insulating structures, which are insulated at their base from the ground using KO-400S supporting porcelain insulators [8]. Metallic cases of the IK-50-3 capacitors are installed on both the metal floor of the carrying structures of PCG-1 and PCG-2 and the insulating floor of the carrying structures of PCG-3. The metal cases of the IM2-5-140 capacitors are insulated from the metal structures of the floor of the PCG-4 stories using rectangular insulating beams of DSPB-E woody layered plastic with a cross section of 70 × 70 mm^2.

In this case, the PCG-1 contains 16 capacitors connected in parallel for a charging voltage of ±50 kV with a total nominal stored energy of 60 kJ (Fig. 1), the PCG-2 has 44 capacitors connected in parallel for a charging voltage of ±50 kV with a total nominal stored energy of 165 kJ (Fig. 1), the PCG-3 has 111 capacitors connected in parallel for a charging voltage of ±50 kV with a total nominal stored energy of 416 kJ (Fig. 3), and the PCG-4 has 288 capacitors for a charging voltage of ±10 kV that are connected in series–parallel in 144 parallel sections (two IM2-5-140 capacitors are connected in series in each section) with a total nominal stored energy of 504 kJ (Fig. 4).

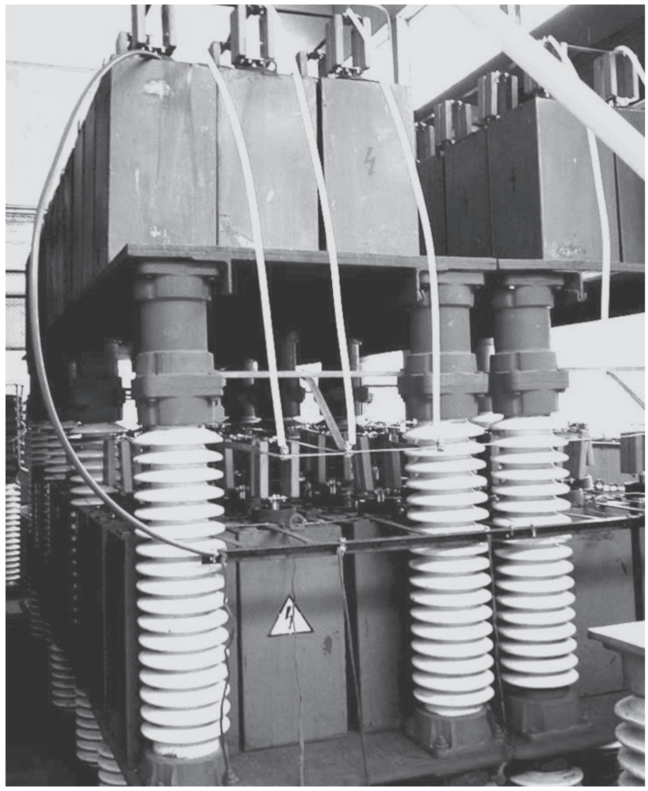

Рис. 3. The external view of the high-voltage PCG-3 (111 ±50-kV IK-50-3 capacitors that are connected in parallel).

The forming electric elements of the discharge circuits of the PCG-3 (a seven-turn inductive element L_{31} ≈ 40 μH, Fig. 2) and the PCG-4 (a single-turn inductive element L_{41} ≈ 7 μH) are manufactured in the form of coils that are wound using an RK 75-44-17 large-size RF cable [14] with the stripped protective polyethylene shell and copper braid. These coils that contain a 6.6-mm-diameter circular continuous copper conductor, have virtually no effect on the intrinsic ohmic resistances R_3 and R_4 of the low-resistance discharge circuits of PCG-3 and PCG-4.

In order to avoid destructive consequences in GITM-10/350 in the emergency operating mode, which is initiated by an electric breakdown at the charging (discharging) stage of one of its high-voltage capacitors, in each of the generators (PCG-1–PCG-4) that are used in it, protective resistors are connected to all high-voltage terminals of their capacitors. These resistors are assembled in the form of compact structures consisting of high-voltage graphite–ceramic TBO-60-24 Ω constant resistors, which are connected in parallel [8].

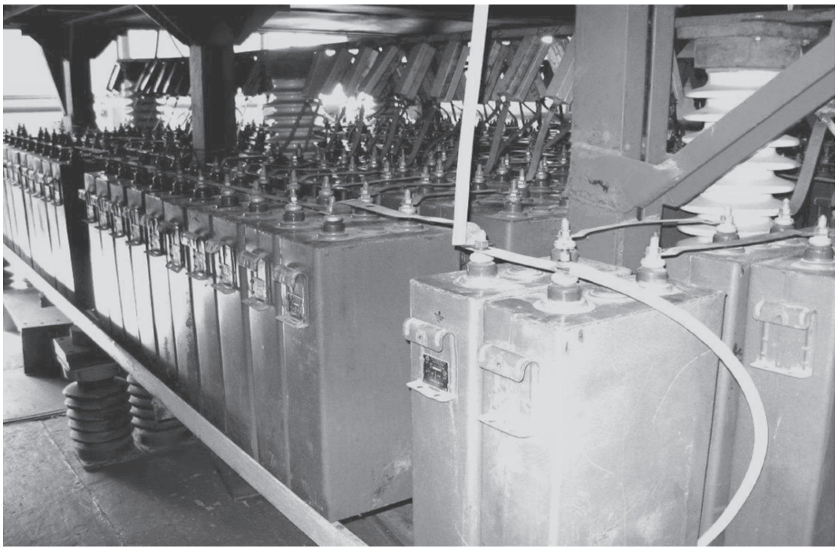

Fig. 4. The external view of the high-voltage PCG-4 (288 IM-50-3 capacitors that are connected in series–parallel for a total voltage of ±10 kV).

Switching in the high-current PCG-1–PCG-3 discharge circuits is performed with a high-voltage three-electrode air-filled triggered switch with graphite electrodes (KVGU-50 in Fig. 2, F_1) for a nominal voltage of ±50 kV and a pulse LL current with an amplitude of up to I_m = ±300 kA (Fig. 5). The KVGU-50 switch is controlled via feeding of a microsecond voltage pulse with an amplitude of ±100 kV from a GVPI-100 triggering generator to the middle graphite electrode of the switch [8]. The design of the KVGU-50 switch provides the adjustment of its two working air gaps within a range of 1–20 mm.

The high-voltage KVGN-10 two-electrode uncontrolled air-filled switch (Fig. 2, F_2) for a nominal voltage of ±10 kV and a pulse-current amplitude I_m of up to ±100 kA, which is intended for switching a high-current discharge circuit of the PCG-4, consists of two graphite erosion-resistant electrodes with flat working surfaces, the gap between which is adjusted from 1 to 10 mm. KVGN-10 is triggered with a pulse voltage that arises at the elements R_1 and L_1 of the electric load upon operation of KVGU-50 and the onset of a flow of a pulse discharge current from PCG-1–PCG-3 through this load.

The nonpotential (grounded) electric circuit of the GITM-10/350's high-current discharge circuit includes a measuring ShK-300 coaxial low-inductance shunt, which is connected in series to the electric load. The shunt underwent State Metrological Certification, and its intrinsic ohmic resistance is $R_{sh} \approx 0.185$ mΩ (Fig. 2) [8]. This measuring shunt in the GITM-10/350 discharge circuit is used with a coaxial output having a conversion factor of 11.26×10^3 A/V. Owing to its electrodynamic and energy characteristics, the ShK-300 shunt can pass pulsed currents of both microsecond and millisecond durations with amplitudes of up to ±250 kA and charges of up to ±250 C at a dissipated energy in the shunt of up to 650 J [8].

The practical realization of the required (according to [1–5]) maximum normalized ATPs of aperiodic current pulses with a time shape of 10 μs/350 μs of an artificial lightning with an amplitude of I_m = ±200 kA in GITM-10/350 with a low-resistance active–inductive load ($R_1 \approx 0.1$ Ω and $L_1 \approx 1.5$ μH) is performed at a total charging voltage of the high-voltage capacitors of ±(30–31) kV for PCG-1–PCG-3 and ±(9.0–9.2) kV for PCG-4. In the latter case, the charging voltage U_{C_4} in PCG-4 for its separate capacitors IM2-5-140 does not exceed ±4.6 kV. To obtain the minimum normalized (according to [1–5]) ATPs of the considered aperiodic current pulses of a simulated LL with an amplitude of I_m = ±100 kA in GITM-10/350 with the aforementioned electric load, the charging voltage $U_{C_1} = U_{C_2} = U_{C_3}$ of separate IK-50-3 capacitors for PCG-1–PCG-3 changes in a range of ±(15–15.5) kV, and the charging voltage U_{C_4} of separate IM2-5-140 capacitors for PCG-4 is ±(2.25–2.3) kV.

Figure 6 shows an oscillogram of an aperiodic current pulse of an artificial lightning with normalized ATPs in accordance with the requirements of the IEC 62305-1–2010 International Standard [1], which was obtained in the GITM-10/350 discharge circuit with a low-resistance active–inductive load. At charging voltages of $U_{C_1} = U_{C_2} = U_{C_3} = -15$ kV and $U_{C_4} = -2.25$ kV, the magnitude of the negative current pulse amplitude of a short simulated LL stroke that passed through the above electric load was $I_m \approx 106$ kA.

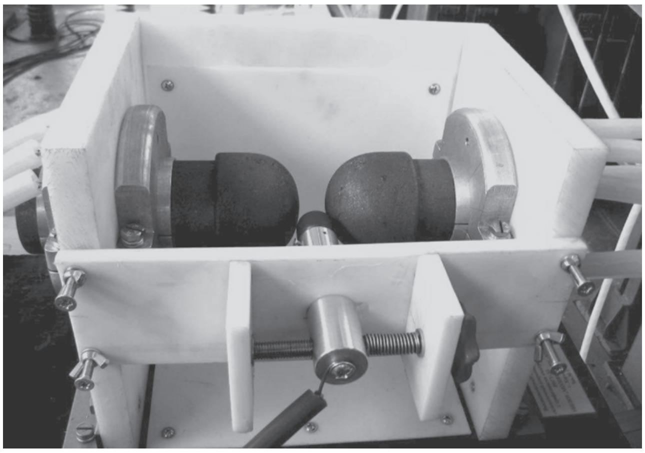

Fig. 5. The external view of the high-voltage KVGU-50 for a voltage of ±50 kV and a pulse current of an artificial lightning with an amplitude I_m of up to ±300 kA.

In this case, the time that corresponds to the amplitude I_m of the artificial-lightning current was $t_m \approx$ 24 μs. The front duration of the obtained normalized LL current pulse between levels of $(0.1–0.9)I_m$ was $\tau_f \approx$ 15 μs, and the duration of the aperiodic LL current pulse at a level of $0.5I_m$, which was formed at the chosen active–inductive load, was $\tau_p \approx$ 340 μs. The action integral of the aperiodic artificial-lightning current pulse with a magnitude of the normalized amplitude of $I_m \approx$ 106 kA that was obtained in this case was $J_a \approx 3.03 \times 10^6$ A^2 s, and the magnitude of the electric charge that passed through the used load is $q_l \approx$ 52.2 C. A numerical estimate of the action integral J_a and the charge q_l for the oscillogram of the discharge current in the used load, which is shown in Fig. 6, was performed using the following approximate calculation relationships [15]:

$$J_a \approx k_L^2 I_m^2 [0.14 t_m + 0.66\tau_p + t_m \tau_p (1.52 t_m + 7.4\tau_p)^{-1}]; \quad (1)$$

$$q_l \approx k_L I_m (1.32\tau_p + 0.27 t_m), \quad (2)$$

where $k_L = [(0.21 t_m \tau_p^{-1})^{\frac{0.76 t_m}{(3.7\tau_p - 0.76 t_m)}} - (0.21 t_m \tau_p^{-1})^{\frac{3.7\tau_p}{(3.7\tau_p - 0.76 t_m)}}]^{-1}$ is the normalizing coefficient for an aperiodic artificial-lightning current pulse (in our case, $k_L \approx 1.082$).

The presented simulation results that correspond to the data in Fig. 6 and formulas (1) and (2) were obtained under laboratory conditions at charging voltages of $U_{C_1} = U_{C_2} = U_{C_3} = -15$ kV and $U_{C_4} = -2.25$ kV of separate high-voltage pulse capacitors of the above four PCGs of the developed GITM-10/350 for producing an aperiodic current pulse of the first short artificial-LL stroke, which is normalized to a time shape of 10 μs/350 μs and the amplitude I_m. These data indicate that they correspond to the III–IV lightning-protection levels for protecting engineering objects that satisfy the requirements [1–5].

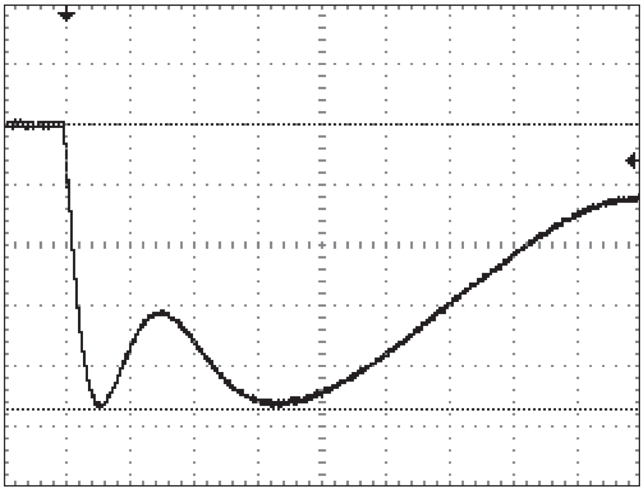

Fig. 6. An oscillogram of an aperiodic discharge-current pulse of the high-voltage GITM-10/350 in the circuit of a low-resistance active–inductive load ($R_l \approx 0.1$ Ω, $L_l \approx 1.5$ μH, $U_{C_1} = U_{C_2} = U_{C_3} = -15$ kV and $U_{C_4} = -2.25$ kV, $I_m \approx -106$ kA, $t_m \approx 24$ μs, $\tau_f \approx 15$ μs, and $\tau_p \approx 340$ μs). The vertical and horizontal scales are 22.52 kA/division and 50 μs/division, respectively.

CONCLUSIONS

A high-power high-voltage generator that is able to form aperiodic current pulses of the first short artificial-lightning stroke of positive (negative) polarity with a normalized time shape of 10 μs/350 μs and a normalized amplitude of $I_m = \pm(100–200)$ kA was developed and tested. When such testing current pulses of a simulated LL are obtained under the laboratory conditions, the operating voltage of IK-50-3 high-voltage pulse capacitors with a total number of 171 for its PCG-1–PCG-3 does not exceed ±31 kV, and the operating voltage of IM2-5-140 high-voltage pulse capacitors with a total number of 288 for PCG-4 does not exceed ±4.6 kV. The stored energy in four PCGs of this high-power high-voltage GITM-10/350, which operate at the aforementioned charging voltage into a common electric load, reaches 640 kJ. The designed generator can be used for testing the stability of various electric devices of objects of industrial electric-power engineering and technical constructions under the action of a current pulse of an artificial LL with a normalized shape and a normalized amplitude in accordance with international and national standards according to [1–5].

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