A 800-kV AND 32-kJ PULSE GENERATOR

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The characteristics of oil-insulated 8-stage Marx generator aimed at charging water-insulated line of STRAUS-R electron beam accelerator are presented. Two IEPM-100-0.4 capacitors are installed in each stage. Switches in the first three stage are 100-kV gas-filled trigatrons while in other stages – two-electrode trigatrons. Operation delay time is 108±5 ns at electric strength reserve of each switch being equal to ~ 80%. The circuit inductance is ~1.4 µH.

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For a high-power accelerator of electrons STRAUS-R (3.5 MeV, 60 kA, 60 ns) [1] functioning as a bremsstrahlung source in the mode beam focusing to a spot with diameter ≤ 4mm (0.27 Gy (Si) dose per pulse at a 1 m distance from the output flange), a modified Marx generator (GIN) is designed to charge a water-insulating double forming line of accelerator with a step-by-step variation of characteristic impedance (DSFL). For this purpose there was used the widely applied in VNIIEF high-voltage technological base, for example, [2-5].

In each of eight multiplying stages of GIN (Fig.1) two capacitors IEPM-100-0.4 UKhL4 (100 kV, 0.4 µF; ≤100 kA, 50±20 nH; 2 kJ) produced by Joint Stock Company SKZ "KVAR", Serpukhov, are connected in parallel. They have lavsan insulation impregnated with ecologically pure phenylxyleneethanol (PXE); its breakdown voltage ≥ 70 kV/(2.5 mm) and relative permittivity equal to 2.53 at 20°C, energy density is 0.17 J/cm^3, test constant voltage – 125 kV, average resource (service life) – 10^3 cycles at oscillatory discharge with a damping constant no more than 1.5.

Switches represent another important component of GIN. In terms of high requirements to reliability of all accelerator assemblies operation the Δt jitter of GIN switching delay should not exceed ±10 ns as related to the beginning of the start pulse supplied to the input of GIN at electric strength reserve of switches K ≥60%. The reduction of Δt and simultaneous increase of K is a complicated task because these are counteracting factors. However, there was available in VNIIEF the experience of a long-term application of 100-kV switches with nanosecond operation accuracy at K ≥ 60%. Thus, a reliable trigatron of [2] was taken as a base and somewhat elaborated. The operating components of basic electrodes and the control one are produced of powder alloy VNZh-2-3 (W, Ni 2%, Fe 3%). The size diameter of trigatron is 175 mm while its height is 117 mm. The leak test gas pressure is 2 MPa. The operation voltage range U_0 is 60…100 kV. The single trigatron testing at U_0=80…100 kV, pressure p =0.7…1 MPa of SF_6: N_2 = 4: 6 and, correspondingly, K=70...90%, and 150 kA current demonstrated that Δt <±3 ns in a series of $2 \cdot 10^3$ switchings at the start voltage amplitude 65 kV with the front of ~ 10 ns. Taking into account these results, into the first three stages there are installed such (the above-described) trigatrons P_1-P_3, while in other cascades – similar switches P_4-P_6 but with no control assemblies. The filled with electronegative mixture trigatrons should possess the specified polarities of potentials on electrodes to operate with nanosecond spread [5]. To their control electrodes a start pulse of positive polarity U_c is supplied through tight high-voltage electric resistors R_1, R_2 [6]. If the polarities of electrode potentials and start voltage are opposite to those specified, then, at other things being equal the delay and Δt increase almost by an order. At direct and reverse circuits of cascade capacitors charging there are applied one-layer coils L wound with steel wire (instead of more often used high-voltage resistors) what also increases reliability of GIN operation.

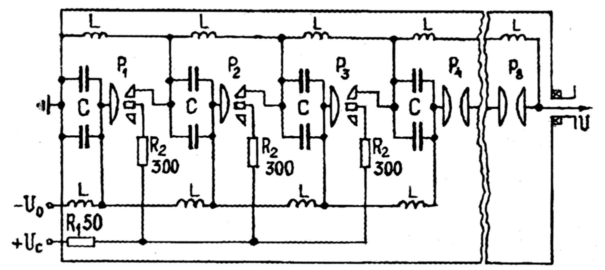

Fig.1. Electric circuit of GIN

At nominal voltage of capacitors charging U_0 = 100 kV the accumulated energy in them is 32 kJ and the output voltage amplitude when running idle is U ≈ 800 kV. However, for the specified application of GIN the operation voltage U_0 = 90 kV is accepted, what increases the resource of capacitors by a factor of 2.2 [7]. The charging of DSFL capacitor C_l =93 nF proceeds according to a well-known law 1 – cos ωt. At GIN capacitor "in a shock" 100 nF at the account of energy losses during the transition process C_l will be charged up to ~ 700 kV in a half of T period of circuit electric oscillations.

Particular attention was paid at design to assembling of each stage and GIN as a whole in order to provide its electric strength and minimize inductance L_g to shorten time of charging C_l and increase electric strength of water gaps in DSFL. Fig.2 demonstrates the separated in space assembled elements of one cascade. Two capacitors 1 form its base. At their terminals all components and elements available in the figure are fastened and connected to each other. Their structure and purpose is clear from the figure and caption in terms of circuit description in Fig.1. The consequent arrangement of such single-type cascades in a common metal tight tank 1 and their electrical connection according to the circuit (Fig.1) form a charge-discharge circuit of GIN with the use of tank as a back current guide.

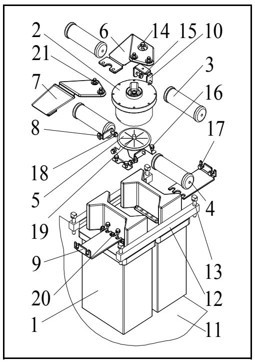

Fig.2. Typical assembling elements of one cascade. 1 - capacitor (2 units), 2 – trigatron, 3,4 – charging circuit coils, 5-10 – buses, 11 – tank, 12 – temple, 13 - caprolon bolt, 14 – 21 mounting bolts

The assembly of output voltage outlet from GIN to DSFL is equipped with an assembly of high-voltage electrode connection to the GIN body and modified Rogowski coils (RC) [8]. The rod output conductor is displaced manually for short-circuit what is convenient in a set of test modes of GIN operation.

The characteristics and stability of R_1 and R_2 resistors affect the delay and velocity of breakdown development in trigatrons. Through a compromise of a set of conflicting requirements there was experimentally found the following values: $R_1 \approx 50\ \Omega$ and $R_2 \approx 300\ \Omega$. The resistors are operable in any position. Their diameter is 50 mm while the length – 180 mm.

The depth δ of skin layer in R1 resistor solution on $f = 5 \cdot 10^7$ Hz frequency equivalent to duration of the 10 ns front of U_c pulse equals to 50 mm. It is 2.3 times longer than the radius of the 22-mm column of solution, thus, the current density by resistor cross-section becomes almost regular by the end of front duration. In R2 resistors the δ depth is 2.5 times longer than the specified one what is caused by a 6 times higher value of ρ specific resistance of solution.

A tank of carbonic steel is a basic power element of GIN. The tightness between the cover and the tank is provided by a backing of polyurethane of "Vitur" make. The internal surface of the tank and its cover is coated with UR-231 lacker to reduce the contact of steel with transformer oil. The hooks are welded to the tank for the sake of convenient displacement of GIN. The tank dimensions are as follows: 2400×800×800 mm (without output assembly), the GIN mass is 1700 kg.

After the assembling of GIN stages was settled, there were estimated its total inductance $Lg \approx 1.5\ \mu H$ using a method of summing up inductance values of discharge contour segments and total active resistance $Rg \approx 0.5\ \Omega$ defined by the loss angle tangent in dielectric of capacitors, active resistance of discharge channels in switches [9], resistance of contact connections and all current guiding buses.

The initial tests of GIN were performed at short-circuited output and U_c = 65 kV with a 10-ns front. The measured by parameters of the discharge current damped oscillations the inductance $L_g = 1.4\ \mu H$ and $R_g \approx 0.7\ \Omega$ are close to rated values. To determine electric strength and time characteristics, a high-power liquid resistor with 3.5 Ω resistance was connected to the GIN output. A capacitive voltage divider is arranged on the start cable at its input to the GIN.

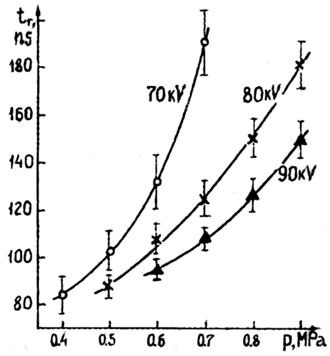

Fig.3. Dependence of GIN operation delay time t_r

Rogowski coils served as a current sensor (detector) through resistor. The measured average time t_r of GIN switching delay depending on voltage U0 = 70, 80 and 90 kV and on gas mixture pressure p (40% SF6+60%N2) in the switches is available in Fig.3. At optimal pressure p = 0.7 MPa and U0 = 90 kV (reserve K = 80%), the delay time t_r = 108 ± 5 ns. Single switching of GIN were realized at voltages U_0 =95 and 100 kV with no negative aftereffects for GIN.

Then, GIN functioned as a component of STRAUS-R accelerator when there were chiefly tested and mastered the required modes of generating and focusing of a beam of accelerated electrons, bremsstrahlung generation. At U0 variation from 75 to 90 kV there took place within a year and a half about 160 switchings of GIN with no disturbance of its operability. The results of experimental researches of accelerator and its characteristics are presented in [1].

The gained experience made it possible to quickly test and elaborate the functioning modes of the second version of the similar accelerator with the analogous GIN after about 80 joint switchings and put this STRAUS-R into operation.

Both GINs demonstrated reliable operation and presented prototypes of a GIN with 1-MV output voltage as applied to the charging of forming lines in inductors of a multi-module installation GAMMA [10] and 600 kV – in inductors of STRAUS-2 [11] and LIU-R accelerators [12].

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ИМПУЛЬСНЫЙ ГЕНЕРАТОР НА 800 кВ И ЭНЕРГИЮ 32 кДж

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Приведены характеристики маслоизолированного восьмикаскадного генератора (ГИН) Аркадьева-Маркса для зарядки до 700 кВ за <1 мкс водоизолированной линии ускорителя пучка электронов СТРАУС-Р. В каждом каскаде установлено по два конденсатора ИЭПМ-100-0.4. Коммутаторы в первых трех каскадах – газонаполненные тригатроны на 100 кВ, в остальных – двухэлектродные. Время задержки срабатывания 108±5 нс при запасе электропрочности каждого разрядника ~80%. Индуктивность контура ГИН ~ 1,4 мкГн.

ІМПУЛЬСНИЙ ГЕНЕРАТОР НА 800 кВ І ЕНЕРГІЮ 32 кДж

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Наведено характеристики маслоізольованого восьмикаскадного генератора (ГІН) Аркадьєва-Маркса для зарядки до 700 кВ за <1 мкс водоізольованої лінії прискорювача пучка електронів СТРАУС-Р. У кожному каскаді встановлено по два конденсатора ІЕПМ-100-0.4. Комутатори в перших трьох каскадах – газозаповнені тригатроны на 100 кВ, в інших – двухелектродні. Час затримки спрацьовування 108±5 нс при запасі електроміцності кожного розрядника ~ 80%. Індуктивність контуру ГІН ~ 1,4 мкГн.