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HIGH-VOLTAGE PULSE GENERATOR ON THE BASE OF PLASMA TUBE WITH COLD CATHODE IN CROSSED FIELDS

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A new scheme of the high-voltage pulse generator with a partial discharge of a capacitive energy storage on the base of the magnetically-controlled opening plasma switch tube is presented and investigated. The high-current magnetron discharge with the secondary-emission cold cathode in crossed-fields is used in the tube. The particularity of the generator scheme is the application of the anode voltage to the tube through a voltage divider to decrease the magnetic control power. The other special feature is the usage of an additional closing switch device (*e.g.*, an ignitron) which is connected in series with the tube. The latter device is being triggered with some delay relatively the activation of the plasma switch tube. This technical approach creates conditions for a generation of the load current pulses with a minimal jitter due to ignition of a primary (pre-ionization) discharge in the tube before triggering the closing device. Therefore, the start of the load current pulses is determined by triggering the closing device however the finish of the same thing is depended on the magnetron discharge switching-off through magnetic field turning-off in the tube. The new generator provided a stable generation of pulses at the amplitude of up to 200 A, duration in the range of 15…70 μs, the anode voltage of up to 20 kV and the average power of up to 100 kW. The pulse generator is designed for use in radio electronic and electro physical systems as well as in a plasma technology.

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INTRODUCTION

In techniques of generating high-voltage rectangular pulses with a duration of tens to hundreds microseconds at current amplitudes up to several kiloamperes and the average power of up to 100 kW, gas-discharge (plasma) closing-type tubes are ordinarily used as switch devices together with artificial pulse forming lines as an energy storage [1]. Such technical approach is rather complex, material-consuming, and requires large cost input. Other schemes having a partial discharge of a capacitive energy storage are simpler, however they require the usage of high-voltage high-current opening devices (tubes-interrupters) which are able to repetitively switch-off the current with a frequency up to hundreds hertz [1, 2].

Among the known opening switches, the attractive one is the magnetically controlled gas discharge tube on the base of the magnetron discharge in crossed fields (**E**×**H**) which is able to work in pulse generators with the said above parameters [2, 3]. This tube has a secondary ion-electron emission cold cathode and a simple diode electrode structure having the low-voltage drop (~500 V) during the conductive phase of operation. The tube does not contain control grids between the cathode and the anode. The product of pd (p is the gas pressure, d is the length of the cathode-anode gap in the tube) corresponds to values which are less than this product matching the left branch of the Paschen curve. The mean free path of electrons for ionization collisions at the given p in the free space is much larger than d, but the real electron path within the tube equals d. Therefore, the gas ionization practically does not occur and the voltage hold-off of the cathode-anode gap without the magnetron discharge can reach 100 kV. This one is the so-called opening state of the tube. However, when the magnetic field crossing with the electric field at the induction $B > B_{cr}$ (B_{cr} is the critical induction, see (1) below) is created in the cathode-anode gap, electrons are trapped to their long cycloid trajectories by the magnetic field and are able to effectively ionize the gas. Then the magnetron discharge and the so-called closing or conductive state of the **E**×**H** tube are being established, the current goes through a load of the pulse generator. The turning-off the magnetic field leads to shutting down the magnetron discharge and the opening state of the tube is established with the interruption of the load current. The switch-on and switch-off processes may be repeated for generation of pulse series.

Also, the magnetron discharge based opening device, called as “Crossatron”, is well known [1, 2]. It contains control grids between main electrodes and performs similarly to vacuum electronic tubes having grids between the cathode and the anode that control the passing of the electrical current through tubes. However, the presence of the grids in the “Crossatron” leads to complications relevant to the grids cooling, their thermo-mechanic shape stability, and arising arc cascades between electrodes being at high operation power, especially, at long current pulses of tens to hundreds microseconds. Diode switch tubes are deprived of said complications. It is also worth to note the low-cost of diode tubes, too.

At the same time there are some disadvantages that existing for the magnetically controlled diode tubes. The first issue is dealing with the power-consuming generation of the control induction $B > B_{cr}$ [1, 2]. Indeed, one can see from the well-known formula for the magnetron effect

$$B_{cr} = \frac{1}{d}\sqrt{\frac{2m}{e}U}, \qquad (1)$$

where e is the charge and m is the mass of electrons; U is the anode voltage. The value of the critical induction B_{cr} is bigger when U is higher. This issue is of great importance because the magnetic control needs high-current/high-power supply for control coils (B_{cr} ~ 0.1 T). Also, the higher is the switching voltage, the greater starting losses in the tube are. The only way to solve the said problems is a forced decrease of the anode voltage during the stage of the magnetic initiation of the magnetron discharge.

The next issue is a relatively large jitter in the beginning of the conductive state in the diode tube and instability of the anode current pulse duration at the purely magnetic control. This one is due to the absence of the initial gas ionization in the gap before the magnetron discharge ignition. The said problem is stronger when the pulse generator is used at the average power rating of tens kilowatt while the complex behavior of gas medium occurs in the tube.

In the present work, a new approach is realized to solve the above mentioned technical problems in the high-voltage pulse generator on the base of the diode tube-interrupter with crossed fields due to the usage of a modified electrical scheme of the pulse generator and an additional closing device connected in series with the tube-interrupter.

1. DESIGN AND TESTING OF THE NEW SCHEME OF PULSE GENERATOR

Fig. 1 shows the simplified drawing of the **E**×**H** tube and its general view. The electrode system of the tube is similar to one described in [3].

The gap d between the cylindrical anode (1) and the cathode (2) is 1 cm. The cathode diameter is 12 cm, the axis length of the cathode working surface is 19 cm, so the working cathode surface area is about 716 cm^2. Material of the electrodes is non-magnetic stainless steel. Hydrogen filling in the tube is maintained by the hot Ti-H reservoir (hydrogen generator) (6) at the pressure p in the range 3…10 Pa. As it is mentioned earlier the product pd corresponds to values which are less than this product matching the left branch of the Paschen curve for hydrogen. The hot Ti getter (7) stabilizes the composition of gas medium within the tube. The control coil (3) consists from four sections, each section has 4 turns. The coil is supplied by the pulse current from a thyristor generator. The cathode (2) has the longitudinal slit (8) for providing fast penetration of the pulse magnetic field generated by the coil (3) into the gap between the electrodes. The radioactive isotope tablet (5) is used to generate some primary ionization in the gap and to somewhat decrease the jitter of the primary **E**×**H** discharge arising in the tube. This discharge is one of glow types and is maintained due to secondary ion-electron emission of the cold cathode (2).

As it is well known the cold cathode current density in the **E**×**H** discharge may reach tens of A/cm^2 without the glow-to-arc transition [2, 3]. This fact is essential because in case of arcing the discharge can not be shut down and the tube cannot be opened by switching-off the control coil.

Fig. 2 shows the simplified electrical scheme of the pulse generator with the additional closing device connected in series with the **E**×**H** tube-interrupter. Fig. 3 shows the simplified operation diagrams illustrating the work of the pulse generator.

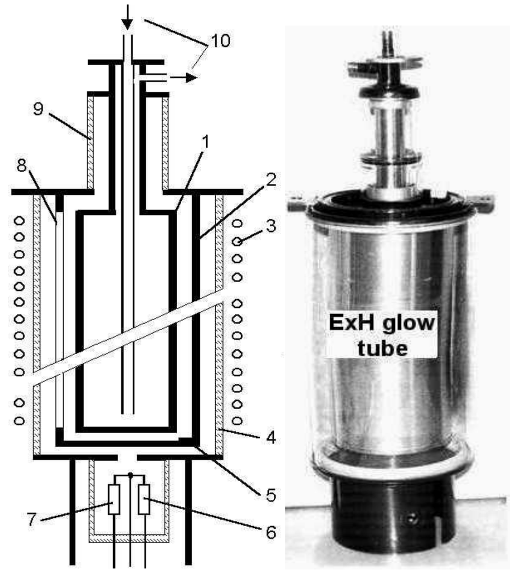

*Fig. 1. Simplified drawing of the **E×H** tube (a) and its general view without control coil (b): 1 – anode; 2 – cathode; 3 – control coil; 4 – glass envelope; 5 – radioactive isotope; 6 – Ti-H hydrogen reservoir (source of H_2); 7 – Ti-getter; 8 – slit in the cathode; 9 – anode isolator; 10 – water flow for cooling of the anode, the upper cathode flange was also provided with water cooling*

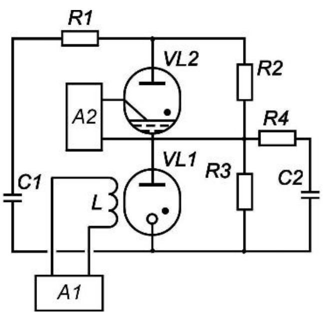

*Fig. 2. Electrical scheme of the pulse generator with the **E×H** tube-interrupter (VL1) and the additional closing device (VL2): A1, A2 – control pulse generators; C1 – energy storage; R1 – load; R2, R3 – voltage Divider; L – control coil; R4, C2 – circuit to form starting pulses for forming the stable primary low-current discharge in the tube VL1*

The capacitor C1 is charged from an external DC power supplier up to voltage U_{C1} (see Fig. 3). It serves as an energy storage/supplier for the load R1 during the load pulse current generation when both switch devices VL1 and VL2 are in the closed state. The generator A1 supplies the coil L with current pulses for generation of the control magnetic field within the tube VL1 and initiation of the **E**×**H** discharge as in the modulator tube, described in [3]. The additional switch VL2 is a high voltage device of a closing type. It may be either an ignitron with liquid Hg cathode (as it is shown in Fig. 2) or a thyratron with a thermionic or cold cathode, or a high-voltage thyristor module. In our case, the high-voltage ignitron IRT-6 is used [4]. The semiconductor pulse generator A2 is used to start the VL2 device. The circuit of the pulse generator A2 is similar to that described in [5].

The voltage divider *R2-R3* applies the voltage $U_{a.0}$ to the tube *VL1*, which is less than the voltage U_{C1} of the capacitor *C1* before initiation of the primary **E**×**H** discharge in the tube *VL1* ($t < t_1$) when the device *VL2* is in the non-triggering state. Since $U_{a.0} < U_{C1}$, this allows to 4initiate the **E**×**H** discharge at lower values of the coil current, see formula (1). Note the resistance of the load *R1* is much less than the input resistance of the voltage divider *R2-R3*. The role of the circuit *R4-C2* will be explained later.

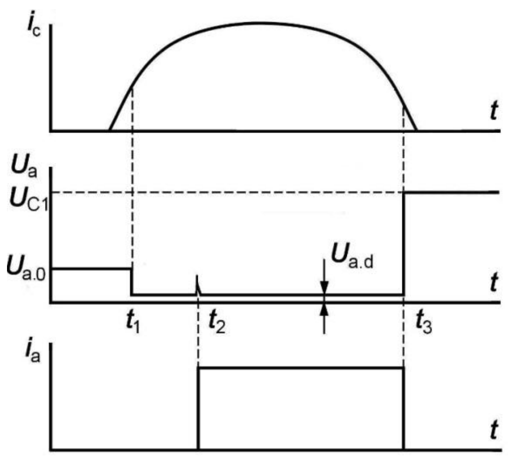

Fig. 3. Operation diagrams of the pulse generator: i_c – coil current; U_a – anode voltage of the tube VL1; U_{C1} – voltage on C1; $U_{a.0}$ – initial anode voltage of the tube VL1 (on the resistor R3); $U_{a.d}$ – voltage on the ***E***×***H*** *discharge (on the tube VL1 in the closed state); i_a – load current (current through VL1, VL2, and R1)*

2. OPERATION OF THE GENERATOR AND ITS OPTIMAL WORK CONDITIONS

In the initial state, capacitors *C1* and *C2* are charged to voltages U_{C1} and $U_{a.0}$, respectively. The U_{C1} value is set by the voltage of an external DC power supplier. The $U_{a.0}$ value is set by the voltage divider *R2-R3* or a voltage drop on *R3.* The dividing factor is chosen from the following conditions on $U_{a.0}$ values.

The minimum permissible voltage drop $U_{a.0}$ on the resistor *R3* has to be higher than 1 kV at which the discharge in the tube *VL1* is reliably ignited. The maximal voltage $U_{a.0}$ should be lower than 5 kV for a notable reduction of B_{cr} as well as the reduction of the control coil current relatively the values that could be in the schemer having no additional closing device and working with purely magnetic control of the tube at our U_{C1} = 20 kV. By the way, the purely magnetic control was used for E×H tube in [3].

Then a current pulse i_c is applied to the coil *L*, a magnetic field is created in the cathode-anode gap of the tube *VL1* initiating the primary low-current E×H discharge in the gap along with transition of the tube to the conducting state at the time t_1 (see Fig. 3). After that the resistor *R2* of the voltage divider *R2-R3* begins to perform the function of the limiting resistor for the primary E×H discharge in the tube.

Our experiments have demonstrated that the excitation of the stable primary low-current E×H discharge on the large cathode surface takes place only when a starting short-time pulse is generated with the amplitude I_{st} in the range of $(10\ldots40)I_{min}$ and the duration of at least 5…20 μs. Herein, I_{min} is the minimum stable glow discharge current in crossed E×H fields. The value of I_{min} is 10…50 mA in our case. The "stable discharge" means the relaxation oscillations free one having no misses in load current pulses. It is known low-pressure glow-type discharges often oscillate at low currents, especially when high ballast (current limiting) resistors are used. The large cathode surface of the *VL1* promotes arising oscillations due to a strong decrease of the mean cathode current density and a possible variation of secondary ion-electron emission along the cathode surface.

The starting pulse is formed by the *R4-C2* circuit. The resistance *R4* and the capacity *C2* are selected within the certain range (see later) to obtain the required parameters of the starting pulse. From a physical point of view, the starting pulse is required for a rapid accumulation of a sufficiently large concentration of charged particles in the cathode-anode gap and the formation of the stable low-current primary glow E×H discharge. Unfortunately, no-one exactly knows what is the structure of this discharge at the low average cathode current density (< 0.1 mA/cm^2). However, we can suggest that the primary discharge is formed by constricted glow spots analogously to the normal glow discharge.

After ending the starting pulse, the *R2* ballast resistor current is mainly going through the tube *VL1*. The magnitude of this current have been chosen at the level of $(1\ldots4)I_{min}$ in which the storage capacitor *C1* is discharged insignificantly. During this period, the tube anode voltage is equal to the voltage maintaining a low-current glow E×H discharge, i.e., to $U_{a.d}$ ~ 300 V (see Fig. 3). This discharge supports the pre-ionization in the tube and ensures that the tube is ready for a high-current switching with the minimal jitter in a wide range of operating parameters.

At the t_2 time (see Fig. 3) a triggering pulse from the generator *A2* is applied to the additional switch device of the closing type *VL2* which enters into the conducting state and shunts the ballast resistor *R2* (at the upper part of the voltage divider *R2-R3*). The current through the load *R1* and the tube i_a (see Fig. 3) rises sharply to the nominal value with the jitter of the order of 1 μs.

At the t_3 time, when the magnetic field of the coil is becoming less than it is necessary to maintain the E×H discharge in the tube *VL1*, the latter turns off and the current in the load is interrupted. Also, the current in the device *VL2* is terminating and the voltage at the tube is becoming equal to the residual voltage on the storage capacitor *C1* due to the post-discharge conductivity of the device *VL2*. The capacitor *C2* is being fastly charged up to the same voltage – to the voltage on the storage capacitor *C1.* Since the device *VL2* is deionized, the capacitor *C2* is being slowly discharged to the level determined by the *R2-R3* divider.

In order to prevent the *VL2* device transition into continuous burning mode the discharge rate of the capacitor *C2* through resistors *R3* and *R4* is set lower than the rate of recovery of the device voltage hold-off.

Experimental testing of the new pulse scheme was carried out with the electrical scheme the simplified drawing of which is presented in Fig. 2. The generator has generated rectangular current pulses with an amplitude around 200 A on an active load of 100 Ω resistance and 20 kV voltage. The average power of the generator was up to 100 kW and the duration of the magnetic field pulse was 100 μs.

When the generator was built on the base of the single **E**×**H** tube-interrupter, the power loss for magnetic control was equal to 16 kW at 400 Hz. The periodic instability (jitter) of the onset of high-current switching had reached 17 μs and had been depending on the pulse rate. The current pulse duration in the load was fluctuating in the range of 30…55 μs. After the generator power has been increased above 100 kW the duration of normal operation was not exceeding 4…5 min and then the tube-interrupter was operating with instability and a pulse missing.

The two-device scheme (see Fig. 2) for testing of the new generator has been built with the described above **E**×**H** tube-interrupter (see Fig. 1) as *VL1* and the ignitron of IRT-6 type as *VL2*. The $I_{\min}$ value of the tube was set at 23 mA, the $U_{a.0}$ value was set at 5 kV, the resistances *R2* (600 kΩ) and *R3* (200 kΩ) were chosen in accordance with the above said criteria for the $U_{a.0}$ value selection.

The current i_a in the period [t_1, t_2], i.e., during the low-current primary discharge, was 33 mA. The resistance *R4* = 6.8 kΩ and the capacitance *C2* = 1800 pF have ensured the display of the discharge constant of 12.2 μs and the amplitude of the starting pulse of I_{st} = 730 mA.

As a result, the magnetic control power loss was decreased down to 4 kW at the pulse rate of 400 Hz. The duration of current pulses in the load was smoothly regulated in the range of 15…70 μs by changing the time moment t_2 of the ignitron *VL2* triggering. The maximum average power transferred to the load was 112 kW. The jitter of the start of switching did not exceed 1.5 μs when operating at 400 Hz up to a half an hour.

When the parameters of the starting pulse were decreased, the generator operation was deteriorated. Moreover, when the capacitor *C2* was disconnected the upper limit of the stable operation in terms of the pulse rate was only 100 Hz. Increasing the resistance *R2* to 1 MΩ and above led to an unstable low-current discharge in the **E**×**H** tube and also the high-current pulse misses have occurred. In this case, the upper limit of the stable operation in the pulse rate range was about 50 Hz. Decreasing the resistance *R3* below the selected value of 200 kΩ (in particular, down to 50 kΩ) led to the transition of the ignitron IRT-6 to the unstable recovery of its voltage hold-off.

There could be some modifications of the pulse generator on the base of two switching devices connected in series. Some of them address methods for creating a pre-ionization in the **E**×**H** tube. In the first modification having no voltage divider, the pre-ionization may be realized by a low-current primary magnetron discharge maintained by a DC power source (voltage ~ 1 kV) connected to the tube through a high-voltage isolating diode (e.g., kenotron). In the second modification, the starting pulse may be formed by a separate generator. The latter modification must include a high voltage isolating electronic element, too. Obviously, it is more convenient and simpler to introduce a stable preliminary ionization with the *R2-R3* voltage divider and the *R4-C2* circuit.

Decreasing the voltage on the **E**×**H** tube prior to the magnetron discharge initiation can be made not only using the voltage divider *R2-R3*. This also could be made using the second closing switching device (a hydrogen thyratron is better) connected in parallel to the tube *VL1* through the capacitor C_p instead of the device *VL2*, connected in series as it is shown in Fig. 2. Using the latter approach the ignition of the magnetron discharge in the tube was occurred when the capacitor C_p was charging from the zero voltage. Our experiments have confirmed the possibility of the realization of this technical approach, however the absence of the pre-ionization in the tube and the complexity of providing generator operation stability, since the increase of the jitter, made this approach less preferable than the one that was presented in Fig. 2.

Also, another experiment with two switching devices connected in series has been carried out. The low-current magnetron discharge in the **E**×**H** tube was continuously sustained in the magnetic field of a permanent magnet with applying the voltage of 1 kV to the tube from a DC power supply through the isolating electronic element. This discharge provided the continuous pre-ionization in the tube. The triggering of the second (*VL2*) device (ignitron IRT-6) has provided the start of the high-current pulse in the load with the jitter of ~μs's instability. The switching-off the magnetic field in the tube has led for finishing the current pulse in the load. In order to shutdown the magnetic field in the tube we used the compensation of the permanent magnetic field by a pulse magnetic field generated with the control coil. However, it was technically difficult to compensate ideally the magnetic fields in the large tube and we were not able to maintain the stable work of the tube-interrupter in the said above range of parameters. Therefore, the latter modification was also not preferable than the one which was presented in Fig. 2 and described earlier in the paper.

CONCLUSIONS

A new scheme of the high-voltage pulse generator with a partial discharge of a capacitive energy storage on the base of the magnetically-controlled opening plasma switch tube with the secondary-emission crossed-fields cold cathode in crossed-fields has been described. A high-current inverted magnetron discharge was used in the **E**×**H** tube. The particularity of the generator scheme is the application of the anode voltage to the **E**×**H** tube through a voltage divider to decrease the magnetic control power. The other special feature is the usage of an additional closing switch device (e.g., an ignitron) which is connected in series with the **E**×**H** tube working as a current interrupter. The closing device defines the starting moment of the load current pulse while the **E**×**H** tube-interrupter determines the finishing of the current pulse in the load.

Our experiments have confirmed the effectiveness of the new proposed two-device scheme for the pulse generator with a partial discharge of capacitive energy storage. As a result, the magnetic control power has been decreased by a few times. The proposed generator operation mode provides pre-ionization in the tube due to ignition of the primary discharge before triggering the closing device. That decreases the jitter and stabilizes the work of the generator in general. Some complexity of the generator electrical scheme due to imposition of the second switch device is paying off by enhancing its stable operation with the jitter about 1 μs at the anode voltage up to 20 kV, pulse current amplitude up to 200 A, pulse duration in the range of 15…70 μs, and average power up to 100 kW. The new pulse generatator is intended for use in radio electronics and electrophysics systems as well as in a plasma technology.

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ГЕНЕРАТОР ВИСОКОВОЛЬТНИХ ІМПУЛЬСІВ НА ОСНОВІ ПЛАЗМОВОЇ ЛАМПИ З ХОЛОДНИМ КАТОДОМ У ПЕРЕХРЕЩЕНИХ ПОЛЯХ

А.І. Кузьмичєв

Представлено та досліджено нову схему генератора високовольтних імпульсів з частковим розрядом ємнісного накопичувача енергії на основі магнітокерованої розмикаючої плазмової лампи. У лампі використовується сильнострумовий магнетронний розряд із вторинно-емісійним холодним катодом у перехрещених полях. Особливістю схеми генератора є подача анодної напруги на лампу через дільник напруги для зменшення потужності магнітного керування. Іншою особливістю є використання додаткового замикаючого приладу (наприклад, ігнітрону), який підключається послідовно до лампи. Останній прилад спрацьовує з деякою затримкою відносно активації плазмової лампи. Такий технічний прийом створює умови для генерації імпульсів струму навантаження з мінімальним джиттером за рахунок запалювання первинного (передіонізаційного) розряду в лампі до спрацьовування додаткового замикаючого приладу. Тому початок імпульсів струму навантаження визначається спрацьовуванням замикаючого приладу, але завершення імпульсів струму навантаження залежить від вимкнення магнетронного розряду через відключення магнітного поля в лампі. Новий генератор забезпечив стабільну генерацію імпульсів амплітудою до 200 А, тривалістю в діапазоні 15…70 мкс, анодною напругою до 20 кВ і середньою потужністю до 100 кВт. Генератор імпульсів призначений для використання в радіоелектронних та електрофізичних системах, а також у плазмовій техніці.