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A Pseudospark Gap in the Inductive-Energy-Storage Circuit

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Abstract—A pseudospark gap is described that is capable of interrupting a current of up to 1 kA and shaping voltage pulses with an amplitude of up to 110 kV and rise time of ~100 ns. Analytical expressions for calculating the energy released in the device at the switching-off stage and the efficiency of the generator with an inductive energy storage system are obtained. The characteristics of the pseudospark gap and of a similar-design thyratron connected in the same circuit are compared. It is found that the turn-off time of the pseudospark gap is shorter than that of the thyratron by a factor of 2.5.

INTRODUCTION

Arc quenching in a pulse hydrogen thyratron makes it possible to use the thyratron as a current interrupter in high-voltage pulse generators with an inductive energy storage system [1]. In recent years, great interest has been shown in new high-current hollow-cathode field-emission devices based on a pulsed low-pressure discharge. These are the so-called pseudospark gaps (PSGs), which are considered as an alternative to conventional high-voltage hydrogen thyratrons. As with conventional hydrogen thyratrons, the condition for the discharge development in the PSG corresponds to the left branch of the Paschen curve, where the free path of electrons required for ionization exceeds the main spark-gap dimension [2, 3].

The principle of the operation of a PSG is, in many respects, similar to that of a conventional thyratron. The difference is in the absence of a hot cathode in the PSG, and the pulsed discharge is either a superdense glow discharge or an arc discharge. To provide a high-stability pulsed-discharge firing in the PSG, systems based on auxiliary stationary low-pressure glow discharge [4, 5] are widely used.

The high-current cold-cathode discharge is characterized by a greater discharge-maintaining voltage. This disadvantage can be avoided by the use of materials with a low cathode work function [6]. Since the PSGs have no hot cathode, the lifetime of these devices is longer, which is particularly important at a low hydrogen pressure in the device.

Therefore, it is of interest to analyze the operation of the PSG as a component of an inductive energy-storage system.

DESIGN OF THE PSEUDOSPARK GAP

The design of the PSG under investigation, which is described in [7–9] and shown in Fig. 1, allows the thyratron to be used in a grounded-cathode circuit, which is typical of the thyratron applications. Since the main emitting electrode is removed from the high-voltage gap of such a device, the lifetime of the device is increased by several orders of magnitude. In addition, the emitting area of the main emitting electrode is enlarged, which allows the current to be distributed over a larger area [10].

The screen prevents the erosion materials from depositing on the housing and prevents the bremsstrahlung X rays from leaving the anode–grid path and penetrating the device housing. The auxiliary anode serves as a trigger-spark electrode and can also be used to control the main discharge.

EXPERIMENTAL SETUP AND RESULTS OF THE INVESTIGATION

The experimental setup is a high-voltage pulse generator with an inductive energy-storage system (Fig. 2). The voltage U_1 = 1.5 kV, which is required to fire the auxiliary glow discharge in the cathode cavity, is applied to the auxiliary anode of the PSG *T* through the resistor R_4. The PSG is turned on by a positive pulse with an amplitude of 3–10 kV, which is applied to the control grid and to the auxiliary anode through a transformer *Tr* and resistors R_2 and R_3. The *Tr* transformation ratio is six. The amplitude of the control current is 1–5 A.

Once the PSG is turned on, the voltage from the capacitor C_1 is applied to the inductance *L* and the inductance current starts building up. When the current through the device-grid openings achieves the critical value (compare to [1]), the electric discharge in the device is quenched. At the moment of the current interruption, the energy accumulated in the inductance is sent to the load and a high-voltage pulse is thus shaped across it. The anode current was measured by a Rogowski coil with R_{sh1}. The grid and anode voltages were measured by an C1-75 oscilloscope via the divid-

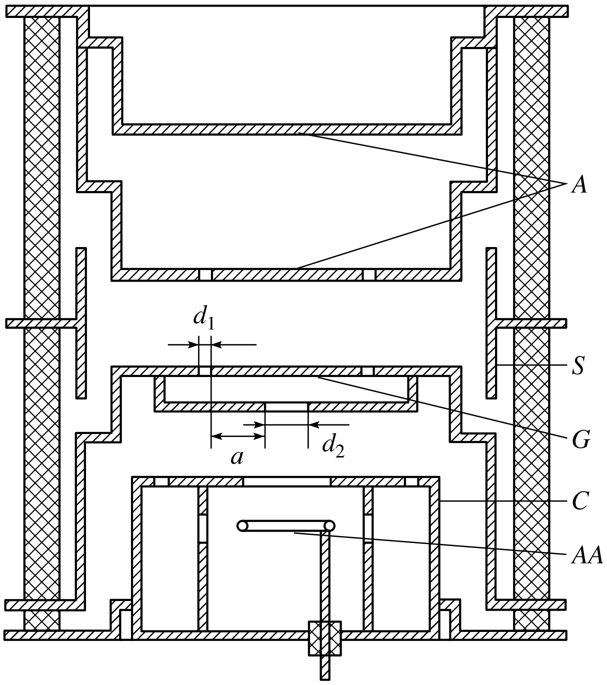

Fig. 1. Design of the pseudospark-gap under investigation: (A) anode; (S) protective screen; (G) control grid; (C) cathode; (AA) auxiliary anode; (d_1) diameter of the grid openings; (d_2) diameter of the grid-screen opening; and (a) overlap of the grid openings and the grid-screen opening.

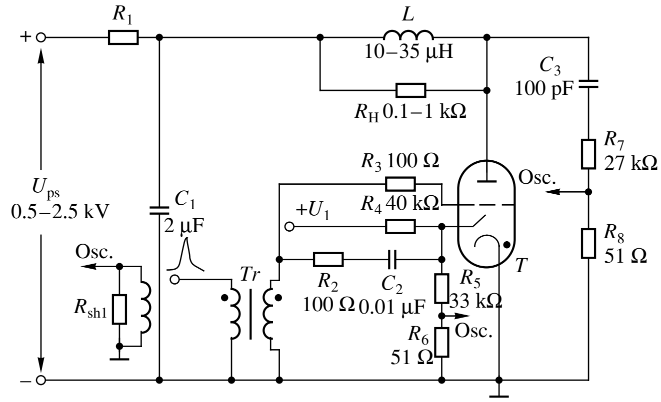

Fig. 2. Experimental-setup circuit diagram.

ers R_5, R_6 and R_7, R_8, respectively. The capacitor C_3 is a dc blocking capacitor that isolates the voltage divider from the constant component of the anode voltage.

It was found that the critical charge at which the current interruption occurs in the PSG, as well as in the thyratron, depends on the hydrogen pressure and on the design of the grid assembly (Fig. 3, curve *2*). The charge that passes through the device is defined by the parameters of the electric circuit

$$Q = U_{ps}C_1(1 - \cos\omega t_{int}), \qquad (1)$$

where U_{ps} is the power-supply voltage, C_1 is the capacitance of the capacitor, $\omega = 1/\sqrt{LC_1}$ is the circuit natural frequency, and t_{int} is the time of the current passage through the spark gap.

A comparison of the plot obtained for the PSG to the plot of the charge required the interruption of the current in the ТГИ2-500/20 thyratron (Fig. 3, curve *1*) shows that the charge passed through the grid opening at the moment of interruption is nearly the same in both devices over the same pressure range though we observe an arc discharge in the thyratron and a glow discharge in the PSG. The designs and the geometries of the grid assemblies in the PSG under investigation and in the ТГИ2-500/20 thyratron are similar, and the hydrogen generators used in both devices are of the same type. This observation supports the view that, for a given grid-assembly design and a fixed gas pressure, the charge required for current interruption is a constant.

In the mode investigated, the PSG interrupted a current ~1 kA and shaped a voltage pulse across the load with an amplitude of 110 kV, the power-supply voltage being 2.5 kV. As in the case of the thyratron, the maximum voltage amplitude was limited by the anode-to-grid breakdown over the outer surface of the device ceramic housing. According to the theoretical estimates [11], a 3-mm vacuum gap (a typical grid–anode spacing in the devices of this kind) with a perfect electrode finish is to be broken down by a 400–500-kV nanosecond voltage pulse applied to it. Our installation could not provide such an operating mode.

The voltage-pulse rise time measured at the load was 100 ns, which is less than the pulse-rise time for the thyratron by a factor of 2.5.

When operating with a resistive load, it is important to know the current passing through the load. From the load current, taking into account the circuit parameters, we can determine the energy characteristics of the generator and calculate the voltage across the load and the switch anode voltage. In order to calculate the current, let us consider the high-voltage part of the circuit for the moment of the interruption of the current through the switch (Fig. 4) and write the equations in accordance with the Kirchhoff laws:

$$\begin{cases} L\dfrac{di}{dt} + i_l(t)R_l = 0 \\ i_l(t) = i(t) - i_{sw}(t), \end{cases} \qquad (2)$$

where $i_l(t)$ is the load current at the moment of switching, $i(t)$ is the inductance current at the moment of switching, $i_{sw}(t)$ is the switch current at the moment of switching, R_l is the load resistance, and L is the storage-system inductance.

We can solve this system of equations by defining a function describing the variation of the switch current. To calculate the switch current, we can approximate it by a linear function

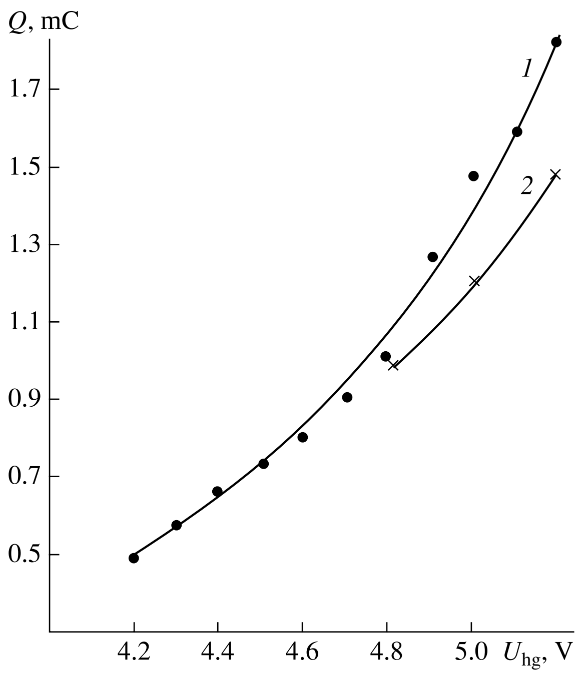

Fig. 3. Charge required for current interruption in (*1*) ТГИ2-500/20 thyratron and (*2*) PSG versus hydrogen-generator filament voltage U_{hg}.

$$i_{sw}(t) = I_m\left(1-\frac{t}{t_{sw}}\right) \text{ at } 0<t<t_{sw}, \quad (3)$$

where I_m is the inductance current at the moment of its interruption and t_{sw} is the current-switching time.

Such an approximation allows us to obtain the final formula for the load current that is simpler and yields virtually the same result as the more exact approximation of the actual process by the exponential function of the form

$$i_{sw}(t) = I_m(2-e^{t/\tau_1}) \text{ at } 0<t<t_{sw}, \quad (4)$$

where I_m is the inductance current at the moment of the interruption and $\tau_1 = t_{sw}/\ln 2$ is the current-decay time constant.

On solving the system of Eqs. (2) with Eq. (3) accounted for, we obtain the expression for the load current

$$i_l(t) = I_m\frac{\tau}{t_\kappa}(1-e^{-(t/\tau)}) \text{ at } 0<t<t_{sw}, \quad (5)$$

where $\tau = L/R_l$ is the circuit time constant.

The energy dissipated in the switch during the switching-off is defined as

$$W_{sw} = \int_0^{t_{sw}} u_a(t)i_{sw}(t)dt, \quad (6)$$

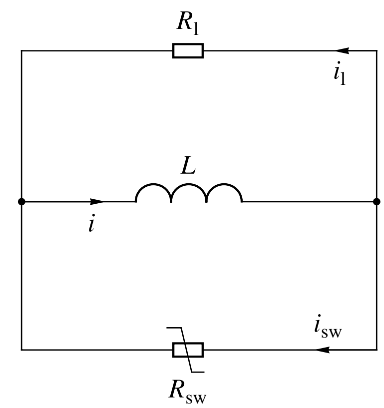

Fig. 4. Simplified circuit diagram of the high-voltage part of the generator for the moment of current interruption.

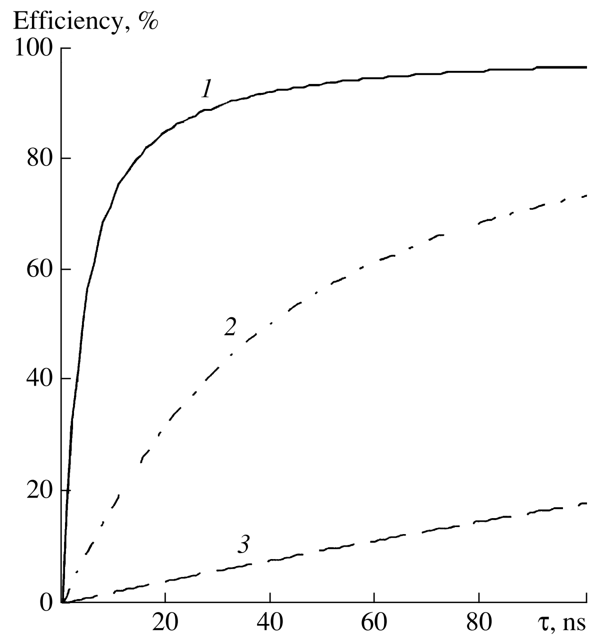

Fig. 5. Efficiency versus circuit time constant for t_{sw} = (*1*) 10 ns; (*2*) 100 ns; and (*3*) 1 μs.

where W_{sw} is the energy dissipated in the switch, $u_a(t) = i_l(t)R_l$ is the voltage at the switch anode, and $i_{sw}(t)$ is the switch current.

With Eqs. (3) and (5) accounted for, the loss in the PSG at the switching-off stage is

$$W_{sw} = \frac{I_m^2 L}{2}\left[1+\frac{2\tau^2}{t_{sw}^2}(1-e^{-(t_{sw}/\tau)})-\frac{2\tau}{t_{sw}}\right]. \quad (7)$$

The efficiency of the generator is defined as

$$\frac{W-W_{sw}}{W}100\% = \left[\frac{2\tau}{t_{sw}}-2\left(\frac{\tau}{t_{sw}}\right)^2(1-e^{-(t_{sw}/\tau)})\right], \quad (8)$$

where $W = LI_m^2/2$ is the total energy accumulated in the inductance.

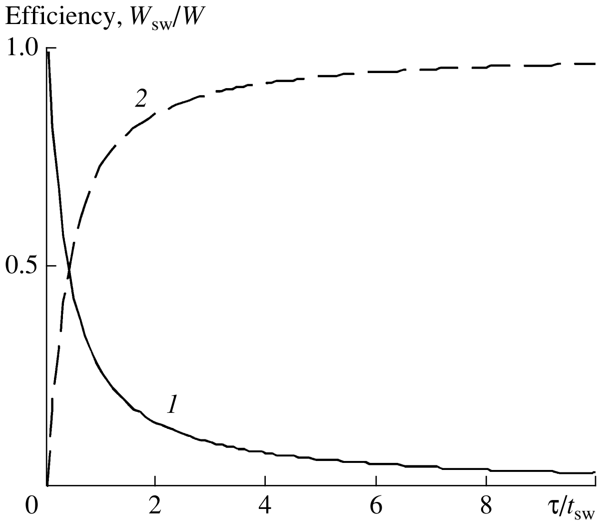

Fig. 6. (*1*) Switching-off loss and (*2*) efficiency versus τ/t_{sw}.

It follows from formula (8) that, when the inductive storage system operates into an active load, the circuit efficiency is independent of the amplitude of the interrupted current and depends only on the ratio of the circuit time constant to the switch turning-off time. Figure 5 shows the efficiency versus circuit time constant for various t_{sw}, and Fig. 6 shows the efficiency and switching-off loss versus ratio τ/t_{sw}. It can be seen that the efficiency increases as τ increases and as the switching time decreases.

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