Method of nanosecond triggering for a sealed-off pseudospark switch

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Abstract. This paper describes a method of nanosecond triggering for the modified version of the commercially produced pseudospark switch TPI1-10k/50. The switch uses the trigger unit with the auxiliary glow discharge, and the proposed method is based on the principle of the current interception from the trigger unit to the grounded cathode cavity when the trigger pulse arrives. Different electric circuits for triggering have been investigated. In the circuit, where the so-called trigger resistor or the trigger inductance are available, in the whole range of hydrogen operating pressure, the range of the delay time of triggering corresponds to (80–100) ns with a jitter of (3–6) ns. In the electric circuit, where the trigger resistor is shortened, the delay time increases to about (110–140) ns. However, the jitter remains at approximately the same level.

1. Introduction

The pseudospark switch is a high-current device that depends on a low-pressure pulsed gas discharge with hollow cathode [1–5]. The switch design resembles the design of the classical hydrogen thyatron with a hot cathode. However, the essential difference lies in the fact that there is no hot cathode in the pseudospark switch. Then such type of the switch is also referred to as a cold-cathode thyatron or the grounded-grid thyatron [6, 7].

In the first and the further publications, the data on physic of gas discharge and on the designs of the pseudospark switches were obtained with a usage of the demountable chambers in which the operating pressure is maintained by means of external gas supply [4–6, 8–11]. The different methods for triggering the switch have been proposed and tested [3, 5–7]. By now, the sealed-off switches with a heated hydrogen reservoir, that are intended for a great variety of the applications in the pulsed power systems, are developed [2, 7, 12]. Similar cold-cathode thyatrons are currently commercially produced by the Pulsed Technology Ltd. (Ryazan, Russia) [7].

The widespread interest for such thyatrons associated, in particular, with the installations where the nanosecond stability in the device triggering is crucial. One of the illustrative applications is the parallel operation of a large number of the thyatrons to a common load in the linear inductive accelerators. For example, in the accelerator LIA-2, to obtain the pulsed output voltage at a vacuum diode of 2 MV, the parallel switching of 96 cold-cathode thyatrons TPI1-10k/50 with nanosecond triggering jitter is necessary [13–15].

The preceding experience in designing and testing the cold-cathode thyatrons [4, 7, 16] encouraged us to modify the trigger unit of the device TPI1-10k/50. The first prototypes of the modified ceramic-metal sealed-off versions are described in [17–19]. The distinctive feature of the
modified design is that the trigger unit uses a low-current auxiliary glow discharge which is sustained between the electrodes in a form of two hollow cavities. In general, this design offers a possibility to provide a lot of methods for triggering. This paper presents the method especially intended for the regimes of the device operation with a low delay time of triggering and low jitter in the delay time with respect to the instant of arrival of the trigger pulse to the trigger unit.

2. Design of the modified thyratron and the principle of operation

Schematic design of the modified thyratron TPII-10k/50 jointly with the electric circuit for triggering proposed in [15, 18] is shown in figure 1.

![Figure 1. Schematic design of the thyratron and the electric circuit for the novel method of triggering. V₀ = (10–40) kV, C₀ = 4 nF, R₀ = 18 Ω, R₁ = 30 kΩ, R₆ = 30 Ω, R₇ = 4.7 kΩ, C₇ = 3.3 nF.](image-url)

The high-voltage electrode system of the device consists of the main anode A, the grounded hollow cathode C, and the intermediate gradient electrode G placed in the ceramic casing with an external diameter of 95 mm. Similar to the classical thyrratrons, the operating pressure in the device is maintained by means of a heated hydrogen reservoir, which is powered by the voltage \( V_H \) thus providing a current of about 2 A. The voltage at the reservoir is changed in a range of \( V_H = (5.2–5.7) \) V. This is evident that increase in this voltage leads to increasing the hydrogen pressure that is to decreasing the static breakdown voltage of the main gap between the electrodes A and C. However, it should be noted that in the described conditions the static breakdown voltage is not less than 40 kV.

The trigger unit of the thyratron is comprised of the hollow electrodes \( A_1 \) and \( C_1 \) whose inner diameters are 36 mm and the distance between the bottoms of the hollow cavities is 92 mm. Before the triggering, a low-current steady-state auxiliary glow discharge is sustained in the trigger unit due to the power supply \( V_1 \) [17, 20, 21]. The distance between the bottoms is taken from the consideration that the discharge initiation voltage in the trigger unit be close to minimum of Paschen’s curve [22]. For the thyratron under description the auxiliary discharge is initiated when the voltage of the power supply reaches a value of \( V_1 = (320–350) \) V. After that we increase the voltage \( V_1 \) to provide the required working point at the current-voltage characteristic of the auxiliary discharge. The recommended auxiliary current is in a range of \( i = (20–30) \) mA that corresponds to the discharge burning voltage \( V_d = (310–340) \) V [18, 21].

As figure 1 shows, the main fraction of the auxiliary current \( i \) flows from the hollow anode \( A_1 \) to the hollow cathode \( C_1 \) and closes to the grounded cavity C through the trigger resistor \( R_T \). This current is denoted as \( i_1 \) and \( i_1 = i \). For the switch triggering, the cavity \( C_1 \) has to be in communication with the main cathode cavity C. Such a communication is provided due the aperture in the flat part of the electrode \( C_1 \). The aperture diameter is 5 mm and the thickness of the flat part is 4 mm. Then a small fraction of the auxiliary current also flows via the aperture to the cavity C. This is the so-called
parasitic current which is denoted in figure 1 as \( i_2 \), where \( i = i_1 + i_2 \). Typical values of the parasitic current are in a range of \( i_2 = (10–20) \mu \text{A} \).

The principal idea of triggering lies in the fact that the trigger discharge plasma has to be generated in the main cathode cavity \( C \) when the trigger pulse arrives to the trigger unit. One of the widely used methods of triggering is to apply the trigger pulse directly to the trigger resistor \( R_T \), i.e. to the gap between the electrode \( C_1 \) and the main cathode cavity \( C \) [16, 18]. Then in the course of the breakdown, the discharge plasma appears in the cavity \( C \) and the high-current discharge in the main gap is ignited. In this method of triggering, the process of breakdown in the trigger system under the effect of the trigger pulse is actually the process of intensification of the primary flowing parasitic current \( i_2 \). The delay time of triggering \( t_d \) is the time interval between the instant of arrival of the trigger pulse and the instant of the beginning the current in the main gap of the switch. It seems to be evident that to decrease the delay time and jitter in this time we have to select the regime of the auxiliary discharge in which the parasitic current is rather large and sufficient for a fast initiation of the trigger discharge.

On the other hand, a high value of the parasitic current is undesirable since the availability of this current leads to lowering the static breakdown voltage of the main gap [23–26]. Hence, the regime of burning the auxiliary glow discharge and the geometry of the aperture in the electrode \( C_1 \) should be selected in such a manner that the influence of the parasitic current on the static breakdown voltage to be minimal. Ideally, the parasitic current has to be as low as possible.

The novel method for triggering that allows obtaining a low delay time of triggering the switch with a low parasitic current is shown in figure 1. The essence of the method is that the trigger pulse is applied to the electrode \( A_1 \). The operation of the trigger unit and of the device as a whole can be described in brief as follows.

In the initial conditions, the voltage of power supply \( V_1 \) has the positive polarity so that the cavity \( A_1 \) serving as a hollow anode of the auxiliary glow discharge and the cavity \( C_1 \) plays the role of a hollow cathode. Then the negative glow plasma is sustained in the cavity \( C_1 \) and the cavity \( A_1 \) is filled with the positive column plasma. The current at the cathode surface is mainly determined by the ion flow from the negative glow region and the parasitic current \( i_2 \) also forms due to the ion flow through the aperture. The ions are accelerated in the cathode fall of the glow discharge and the beam of the accelerated ions enters into the gap between the electrodes \( C \) and \( C_1 \) which represents some sort of a vacuum ion diode. The parasitic current value is low since this current is provided by the ions.

To trigger the thyatron, we apply the pulse \( V_T \) of a negative polarity to the electrode \( A_1 \). As far as the low-current auxiliary glow discharge burns in the trigger unit, the pulsed trigger discharge is readily initiated between the cavities \( A_1 \) and \( C_1 \). After applying the trigger discharge, the cavity \( A_1 \) starts playing the role of a hollow cathode and the cavity \( C_1 \) turns into a hollow anode. At the first temporal stage, the trigger discharge current flows through the trigger resistor \( R_T \) and because of the voltage drop at this resistor the potential of the electrode \( C \) becomes positive with respect to the anode cavity \( C_1 \). This positive potential extracts the electrons from the hollow-anode plasma and the trigger discharge current is completely intercepted to the cavity \( C \) via the aperture [24]. Hence, the process of the trigger current interception results in generation of the pulsed discharge plasma in the cavity \( C \) and in the thyatron triggering.

3. Data on the device triggering with other electric circuits

The previous section describes the method for triggering when the trigger resistor \( R_T \) is inserted in the trigger circuit. The principal role of this resistor is to limit the trigger current between the electrodes \( A_1 \) and \( C_1 \) and to promote the process of interception of the trigger current to the main cathode cavity. On the other hand, in the conditions before the triggering the availability of the trigger resistor is not profitable. The problem is that the auxiliary current of the steady-state glow discharge leads to the situation in which the electrode \( C \) turns out to be at the negative potential with respect to the cavity \( C_1 \). This potential serves as an extracting voltage for the ions from the negative glow so that the parasitic current increases as compared to the conditions when \( R_T = 0 \) [17, 21]. To reduce the parasitic current it seems reasonable to insert in the trigger circuit an inductance \( L_T \) instead of the trigger resistor. Then
for the steady-state auxiliary current the potential difference between the electrodes $C_1$ and $C$ is close to zero while when the trigger pulse arrives the potential difference arises.

The circuit with the inductance and the corresponding waveforms for demonstration of the process of the current interception are shown in figure 2. In this experiments, the anode voltage is not applied and the main goal of the experiments is to understand how the trigger discharge current to the electrode $C$ appears. The presented waveforms are the voltage at the electrode $A_1$ and the currents to the electrodes $C_1$ and $C$ that are taken respectively from the current shunts $R_{sh1}$ and $R_{sh2}$.

\[ L_T = 2 \text{ mH} \]

\[ i = 20 \text{ mA}, \ V_H = 5.7 \text{ V}, \ R_{sh1} = R_{sh2} = 1 \text{ } \Omega. \]

The obtained data shows that the process of the current interception also takes place even in the case when the inductance $L_T$ is shorten, i.e. is practically reduced to zero. The physical reason for appearing a current to the electrode $C$ is the development of the discharge not only between the electrodes $C_1$ and $C$ but also over a long path via the aperture. The waveforms for these conditions are shown in figure 3.

First, let us consider the waveforms presented in figure 2. The trigger pulse arrives at the instant $t_0$. It is seen that before this instant the positive potential at the electrode $A_1$ corresponds to the discharge burning voltage, $V_d = 300 \text{ V}$. During the front of the trigger pulse $V_T$ the potential $V_{A1}$ becomes negative, i.e. the electrode $A_1$ turns into the cathode of the trigger discharge. At the instant $t_1$ the voltage $V_{A1}$ sharply decreases so that this instant has to be interpreted as the beginning of breakdown in the trigger unit. In this terminology, the time interval ($t_1 - t_0$) is the delay time to breakdown in the trigger unit. The current of the pulsed breakdown is limited by the trigger inductance $L_T$, and in accordance with the waveform $i_1$ it amounts to about 1 A. At the same time the waveform $i_2$ demonstrates the process of the current interception to the electrode $C$. There is also a current peak at the waveform $i_2$ before the breakdown. This peak is associated with the displacement current in the gap between the electrodes $C_1$ and $C$ during the front of the trigger voltage. Thus, due to availability of the trigger inductance the fast process of the trigger current interception to the electrode $C$ is observed. Just this process inevitably results in the switch triggering.

It is of interest to compare the peculiarities of the current interception in the case when the inductance $L_T$ is present in the trigger current and when this inductance is shortened. The waveform

\[ V_{A1}, \text{ kV} \]

\[ i_1, i_2, \text{ A} \]

\[ t, \text{ ns} \]
$V_{A1}$ in figure 3 also demonstrates the instant $t_1$ at which the breakdown in the trigger unit is ignited. One can observe that at this instant the current $i_1$ to the electrode $C_1$ increases sharply since this current is not limited by the inductance $L_T$. However, a small fraction of the total trigger current also closes to the electrode $C$ through the aperture. The level of this current, estimated from the waveform $i_2$, is of about 1 A. Nevertheless, as will be shown later, such a low current is sufficient for triggering the thyratron.

![Figure 3](image)

**Figure 3.** Schematic of the experiment on investigation of the trigger current interception to the main cathode cavity $C$ (a) and the related waveforms (b). Inductance is shortened ($L_T = 0$). Auxiliary discharge current $i = 20$ mA, $V_H = 5.7$ V, $R_{sh1} = R_{sh2} = 1$ Ω.

![Figure 4](image)

**Figure 4.** Electric circuit for investigations of the delay time of triggering in the case when the inductance $L_T = 2$ mH is inserted instead of the trigger resistor (a) and the related waveforms (b). $V_A$ is the anode voltage, $i_A$ is the anode current through the load resistor $R_0$. $I = 20$ mA, $V_H = 5.7$ V.
Let us consider now the conditions of the switch triggering for both electric circuits. The electric circuit with the inductance \( L_T = 2 \text{ mH} \) and the corresponding waveforms are shown in figure 4. The waveforms present the anode voltage \( V_A \), the current in the anode circuit \( i_A \) via the load resistor \( R_0 \), and the voltage \( V_{A1} \) at the electrode \( A_1 \).

The instant \( t_m \) at the waveforms corresponds to the beginning of the drop in the anode voltage and to the beginning of the current rise via the load. As a matter of fact, at this instant the switching process in the main gap of the thyratron starts. Hence, the time interval \( t_d = (t_m - t_0) \) is the delay time to breakdown for the thyratron triggering. It is seen that this delay time consists of two temporal components. Initially at the instant \( t_1 \) breakdown arises in the trigger unit and after the time interval \( (t_m - t_1) = 32 \text{ ns} \) the gas discharge plasma forms in the main gap. It seems to be remarkable that for the method of triggering under discussion the breakdown in the trigger unit initiates the breakdown in the main gap very fast, i.e. after several tens of nanoseconds.

One of the features of the thyratrons with a hot cathode is that during the switching stage the positive anode voltage penetrates into the trigger system. This is accompanied by appearing a nanosecond high-voltage spike at the trigger electrode. For example in the thyratron TP1I-10k/50, an amplitude of such a spike can reach of 12 kV [27]. Similar positive voltage spike is also observed at the waveform \( V_{A1} \) for the proposed method of triggering. In the electric circuit where the main cathode cavity is grounded, the spike amplitude is at a level of only 5 kV. The physical reason for this effect is that at the switching stage the discharge develops not strictly between the electrodes A and C but also over a long path to the trigger electrode \( A_1 \). Then a small fraction of the switching current flows into the trigger pulse generator thus forming the voltage spike. After completing switching process, the high conductive plasma bridges the gap between the electrodes A and C so that this current disappears. To encourage the process of bridging the gap it seems desirable to provide the conditions in which the cathode spot is initiated at the electrode C at the instant close to \( t_m \) that is at the very beginning of the switching process.

As shown in figure 3, the trigger discharge current can be intercepted to the main cathode cavity even in the conditions when the electrodes C1 and C are connected to each other. It is of interest to test the thyratron with such an electric circuit. The data on triggering for the case when \( L_T = 0 \) are illustrated by the waveforms shown in figure 5.

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**Figure 5.** Electric circuit for investigations of the delay time to triggering in the case when the inductance \( L_T = 0 \) (a) and the related waveforms (b). \( V_A \) is the anode voltage, \( i_A \) is the anode current through the load resistor \( R_0 \), \( i = 20 \text{ mA} \), \( V_H = 5.7 \text{ V} \).
An important parameter of triggering is the jitter of the delay time. To illustrate the jitter, twenty-five waveforms are superimposed at the oscilloscope screen in figure 5. The waveforms look like coinciding with each other. However when the time scale is decreased to 10 ns/div, the jitter becomes visible distinctively. Then figure 6 shows the delay time of triggering versus the voltage at the hydrogen reservoir jointly with the scatter bars for both electric circuits.

\[ t_d = 108 \text{ ns} \]

\[ t_d = 80 \text{ ns} \]

\[ t_m - t_1 = 60 \text{ ns} \]

\[ \Delta t_d = 3 \text{ ns} \]

**Figure 6.** Delay time to breakdown in the main gap of the switch and the related jitters in this time versus the voltage at the hydrogen reservoir for different trigger circuits. \( i = 20 \text{ mA} \)

In the switch design, the electrodes \( C_1 \) and \( C \) are intentionally disconnected by means of the ceramic insulator. Such a design offers a possibility to use many methods of triggering. On the other hand, one more modification of the switch to the case in which these electrodes are directly connected with each other seems to be rather attractive as far as the switch design can be essentially simplified due to the absence of the insulator. Data on the triggering in figure 5 for the conditions of the connected electrodes shows that the delay time is increased \( t_d = 108 \text{ ns} \) as compared to the previous circuit where \( t_d = 80 \text{ ns} \). Such an increase occurs due to the second component in the delay time, \( (t_m - t_1) = 60 \text{ ns} \). Nevertheless, the jitter in the delay time is quite acceptable and amounts to \( \Delta t_d = 3 \text{ ns} \).

The above described examples are related to the maximum voltage at the hydrogen reservoir that is to the maximum operating pressure. It is apparent that a decrease in pressure leads to increasing the delay time. However, as figure 6 shows, this increase is not essential and for \( L_T = 2 \text{ mH} \) in the whole range of pressure we have the delay time in a range of \( t_d = (80–100) \text{ ns} \). The physical reason of increasing the delay time for the circuit with \( L_T = 0 \) is understandable. In this case the intercepted trigger current, which is responsible to the switch triggering decreases in comparison with the case \( L_T = 2 \text{ mH} \).

4. **Summary**

This paper presents a method of nanosecond triggering for the modified version of the commercially produced pseudospark switch TP11-10k/50. Different electric circuits for triggering have been proposed and investigated. In the circuit, where the so-called trigger resistor or the trigger inductance are available, in the whole range of hydrogen operating pressure, the range of the delay time of triggering corresponds to \( (80–100) \text{ ns} \) with a jitter of \( (3–6) \text{ ns} \). In another electric circuit, where the trigger resistor is shortened, the delay time increases to about \( (110–140) \text{ ns} \). However, the jitter remains at approximately the same level.

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