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2-kV Thyristor Triggered in Impact-Ionization Wave Mode by a Solid-State Spiral Generator

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***Abstract*—Impact-ionization wave triggering of a thyristor enables it to switch significantly higher currents with much faster rise times ($\mathrm{d}I/\mathrm{d}t$) than through conventional triggering; indeed tests on commercial components demonstrate that both current and $\mathrm{d}I/\mathrm{d}t$ can be increased an order of magnitude over their specified datasheet values by utilizing impact ionization. However, creating an impact ionization wave places stringent requirements on the generator used to trigger the thyristor—particularly the trigger pulse must have a voltage rise rate ($\mathrm{d}V/\mathrm{d}t$) of more than 1 kV/ns and an amplitude over twice the thyristors static breakdown voltage. Given the capacitance of a thyristor is relatively large, often hundreds of pF, this is difficult to achieve with many common triggering methods. In this study, we present a bespoke, cost-effective, trigger generator that has been developed based on spiral/vector inversion techniques coupled to an optimized sharpening circuit. Using this generator, both a 2-kV single thyristor and a 4-kV stack of two thyristors in series were triggered in the impact-ionization mode. The thyristors had a wafer diameter of 32 mm and capacitances of 370 pF. With a single thyristor 100 shots were performed with it switching a peak current of 1.25 kA and an associated $\mathrm{d}I/\mathrm{d}t$ of 12 kA/μs. With two thyristors, peak currents of 2.6 kA and with $\mathrm{d}I/\mathrm{d}t$ of 25 kA/μs were achieved. In all experiments no degradation of the semiconductor structure was observed. The work opens the way for developing very powerful, but still compact, solid-state trigger generators and larger pulsers for a wide range of pulsed power applications.**

***Index Terms*—High $\mathrm{d}I/\mathrm{d}t$, impact-ionization wave, pulse power system, solid-state switch, subnanosecond switching, thyristors.**

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I. Introduction

In PULSED power technology, the switches are essential elements but at the same time one of the most critical parts limiting the output parameters of all pulsed power generators. Due to the ability of gas switches to switch currents of many tens and up to hundreds of kAs having an associated current rise rate ($\mathrm{d}I/\mathrm{d}t$) of hundreds of kA/μs makes gas-discharge switches attractive for using in powerful pulsed power generators (tens to hundreds GW) operating in a single short mode. These machines serve for basic research on high-density plasmas and extreme state of matter [1]–[4]. For such extreme applications, the peak electrical parameters of the high-power drivers and, consequently of their switches, are more important than other characteristics such as repetition rate, reliability, or lifetime. However, for industrial pulsed power applications in civilian and defense domains then latter characteristics are also of high importance and cannot be neglected. Solid-state switches satisfy these demanding requirements and can be employed in different specific areas such as pulsed electric field (PEF) processing [5], plasma-chemistry technologies [6], high-speed x-ray radiography [7], and plasma-based surface modification [8]. Nowadays, most of the standard solid-state switches have limited $\mathrm{d}I/\mathrm{d}t$ ($\leq$1 kA/μs) and switching time ($\geq$10 ns) capability. Thus, the development of solid-state pulsed power technology is possible by improving the performance of solid-state switches through the implementation of new driver circuits [9], [10], developing highly integrated structures [11], [12] or using new principles of switching operation [13].

However, these approaches have several related drawbacks, such as limitations caused by the physics of semiconductors and/or expensive fabrication processes. We believe that a delayed impact-ionization breakdown of the high-voltage p-n junction discovered by Grekhov *et al.* [13], [14] is one of the most promising approaches for the developing of a pulsed power semiconductor switch. In this operating mode, switching occurs by initiation of an impact-ionization wave in the semiconductor structure by applying an overvoltage pulse having a voltage rise rate ($\mathrm{d}V/\mathrm{d}t$) of more than 1 kV/ns. This leads to subnanosecond switching time and high $\mathrm{d}I/\mathrm{d}t$ capability are possible because the speed of the wavefront is several times faster than the saturated carrier velocity in silicon (Si). This mechanism was explained by Kardo-Sysoev [15] and then revised by Ivanov *et al.* [16]. A series of works carried out by Gusev *et al.* [17], [18]

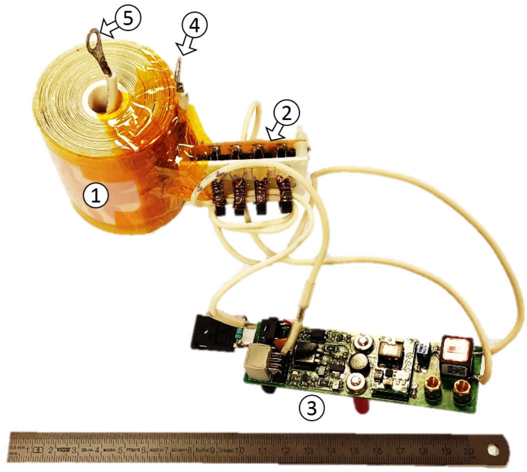

Fig. 1. Photograph of the spiral generator: 1—spiral stripline, 2—solid-state switch, 3—DB, 4—grounded output terminal, and 5—high-voltage output terminal.

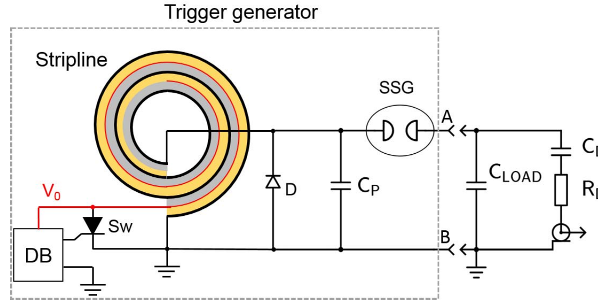

Fig. 2. Trigger generator circuit. Stripline-schematic cross section view of spiral pulse forming line, DB—driver board, SW—solid-state switch, SG—spiral generator, D—high voltage diode, C_P—peaking capacitor, SSG—sharpening spark gap, C_{LOAD}—capacitive dummy load, C_D, and R_D—elements of voltage probe.

demonstrated the capability of commercially available high-power thyristor to be operated in impact-ionization wave mode. Moreover, further work [19] proved that a switch based on off-the-shelf thyristors can both work in impact-ionization wave mode and have a long lifetime, e.g., more than 10^6 shorts were performed without degradation at a peak dI/dt of two orders of magnitude higher than the critical datasheet value.

Despite the promising results of impact-ionization approach, a significant flaw of this technique is associated with the high cost and complexity of trigger generators that can provide required triggering conditions [13]. As a consequence, the present work main aim is to develop a simple and inexpensive pulsed power trigger unit based on a spiral generator designed by the Imperial College [20], which can be used to trigger a commercial 2.2 kV thyristor with 32 mm in diameter in the impact-ionization mode. After presenting the trigger generator design, as well as the switching characteristics of the developed switch prototypes are provided and discussed. Both conclusions and the way ahead are presented at the end of this article.

II. Trigger Generator Design, Methodology, and Practical Arrangement

The trigger generator was developed at Imperial College London and is based on an all-solid-state powered spiral generator described in great detail in [20]. The spiral generator also known as vector inversion generator (VIG), was originally proposed by Fitch and Howell [21]. The Imperial College generator (see Fig. 1) consists of a spiral stripline (1) with a grounded (4) and a high-voltage (5) output terminal, a solid-state switch (2) and a driver board (DB) (3) for charging the stripline and triggering the switch. The spiral stripline consists of a pair of copper tapes (foils) with an insulation layer mounted between them and with the assembly being wrapped around itself with an extra layer of insulation. The spiral stripline has a 60 mm output diameter, with a 40 mm mean diameter D and a 70 mm width (with 50 mm being the copper width). The geometry of the spiral effectively forms two striplines with a shared middle conductor (see the red spiral line in Fig. 3) that is charged to voltage V_0 by the dc power supply integrated into the DB (see Fig. 2). The charged conductor is connected by the solid-state switch (Sw in Fig. 2) based on four SP205-01 thyristors [22] connected in series to the outer grounded conductor (see the black spiral line in Fig. 2). Thus, they form an active layer (see the orange-colored layer in Fig. 2) of the spiral. The other layer, between the charged conductor and the other side of the grounded conductor, is the passive layer (shown as the gray-colored layer in Fig. 2). At the inner end of the spiral, the charged (red) conductor is open, i.e., not connected to anything, and the grounded conductor is connected to the pulse sharpening circuit (see Fig. 2).

Following the original paper where the spiral generator was first described [21] the principle of functioning is as follows. With the input switch open, the electric field vectors in the active and passive layers have equal magnitudes and opposite directions. Once the switch closes, the passive layer is assumed to be unaffected, as the voltage wave propagates along the active layer. This wave is then reflected by the open connection at the other end of the charged conductor, overturning the direction of the electric field vector in the active layer, so that the vectors in each layer coincide in direction. As the wave reaches the input switch, the output voltage reaches a peak $V_{\mathrm{OUT}} = -2\epsilon_{\mathrm{eff}} N V_0$, where ϵ_{eff} is the voltage multiplication efficiency and N is the number of turns of the spiral. The rise time of the output voltage, $t_R = 2N\pi D/c_{\mathrm{eff}}$, is the time taken for the voltage wave to travel backwards and forward through the spiral, where D is the mean diameter of the winding and c_{eff} is the wave propagation velocity in the spiral.

Simple design, compact size, and low price are the main advantages of this all-solid-state spiral generator compared to semiconductor opening switch (SOS) generators which were used in the pioneering research [17] for triggering thyristors in impact-ionization wave mode.

In the present study, commercially available power thyristors of the hockey puck type T333-250-22N were chosen

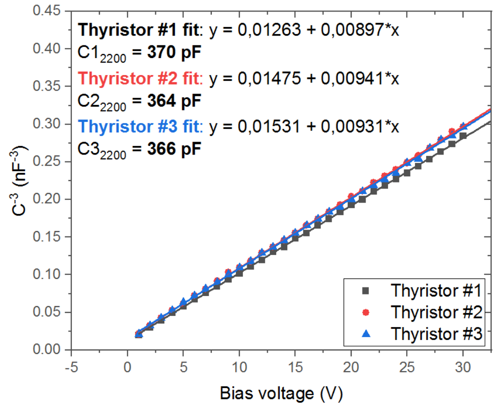

Fig. 3. Plot of the equivalent thyristor capacitance to minus-third power C^{-3} versus the bias voltage.

for the test. They have a wafer diameter of 32 mm and the following datasheet characteristics [23]: repetitive peak OFF-state voltage 2.2 kV, mean ON-state current 250 A, critical dI/dt 0.8 kA/μs. In the nonconducting state, the thyristor has an equivalent capacitance of about 370 pF at the bias voltage of 2.2 kV.

To determine the equivalent capacitance of the thyristor in the nonconductive state at the bias voltage of 2.2 kV, the following method was implemented. First, the equivalent thyristor capacitance C was measured at the low bias voltage from 1 to 30 V with step 1 V. Then the capacitance to minus-third power C^{-3} was plotted as a function of the bias voltage (see Fig. 3). Finally, these data were linearly fit and extrapolated to 2.2 kV bias voltage to estimate the equivalent thyristor capacitance at this voltage. As one can see in Fig. 3, all three thyristors tested have similar behavior at the low bias voltage and correspondingly a similar capacitance of about 370 pF at 2.2 kV.

According to the fit equation (see Fig. 3), the capacitance expression for the thyristor 1 at a bias voltage of 2.2 kV is $C1_{2200}^{-3} = 0.01263 + 0.00897 \cdot 2200 = 19.75$ nF^{-3}, thus $C1_{2200} = (C1_{2200}^{-3})^{-1/3} = 370$ pF.

The thyristor equivalent capacitance is an important parameter in the present investigation, since a large capacitive load, comparable in value to the equivalent capacitance of the pulsed generator, would affect its output pulsed parameters. In the present case, the pulsed parameters of the trigger generator connected directly to the tested thyristor were below the values required to start the thyristor in impact-ionization wave mode. Therefore, at the beginning of the research, the study was focused on developing a peaking circuit of the trigger generator (see Fig. 2) when operating on a capacitive dummy load $C_{\mathrm{LOAD}} = 400$ pF. The main goal was to increase the output parameters of the trigger generator up to the level required. To be sure that the parameters of the trigger pulse are optimal, the trigger generator equipped with the peaking circuit was tested using real load—a single 2.2 kV thyristor. Finally, a single thyristor and a stack of two series-connected thyristors were both tested, switching high currents (∼2.5 kA) at a high dI/dt (25 kA/μs). In both cases, to control the possible thyristor's degradation, the thyristor leakage current was measured at the nominal operating voltage before and after a series of 100 pulses.

To evaluate the switching efficiency, the voltage across the thyristors $V_T(t)$ and current $I_T(t)$ flowing through them were both measured. Furthermore, the power dissipated in the thyristor $P_T(t) = V_T(t) \cdot I_T(t)$ and the energy loss $W_T(t) = \int P_T(t)dt$ were also both determined. The efficiency of the thyristor was calculated as $\eta = 1 - W_{T0}/W_0$, where $W_0 = C_0 V_0^2/2$ is the energy stored in the switched capacitor C_0 (see Figs. 6 and 10), and $W_{T0} = W_T(T_0)$ is energy loss in the thyristor during the discharge time T_0.

Thyristors were tested without a case, since the parasitic inductance of the connection loop of the high-frequency voltage probe is in this way kept to a minimum, which has a positive effect on the measured signals (for example, voltage ringing is thus reduced). When removed from case, the thyristor wafer has a photosensitive rim, which increases the leakage current when exposed to light. To avoid this unwanted effect, before installation in the clamping system, the photosensitive rim of the wafer was covered by elastic material (Patafix), which has excellent adhesive and insulating properties. The wafer thus covered has the same value of the leakage current as the thyristor in a standard package.

Two high-voltage probes were connected in parallel to the thyristor. The first is a commercially available Agilent 10076B (bandwidth 100 MHz), and the second is a homemade resistive divider resolving the pulse with a rise time of about 200 ps (bandwidth 1.75 GHz) [24]. The high-voltage arm of this divider contains a low-inductance resistor R_D (see Figs. 2, 6, and 10) partially covered by the cable braiding to compensate for any parasitic inductance, with the low-voltage arm formed by a coaxial cable with 50 Ω impedance. The capacitor C_D (see Figs. 2, 6, and 10) isolates the divider from the charging dc voltage V_0. The divider serves to record the triggering pulse on the thyristor switch with a total duration of ≤3 ns. The 10% to 90% rise time of the divider determined during its calibration, close to 200 ps. The diagnostics include 18-GHz attenuators and digital real-time oscilloscope Tektronix TDS 7704B 7-GHz. The thyristor current was measured using a low-inductance resistive shunt previously calibrated by a Pearson 411 current sensor with a bandwidth of about 20 MHz.

III. Results and Discussion

A. Trigger Generator

The operation principle of the trigger generator assembly can be explained using the circuit diagram presented in Fig. 2. The DB consists of three items: a high-voltage dc power supply, that can charge up to 5 kV, a driver for the solid-state switch Sw, and an optically triggered control unit. First, the stripline is charged up to 4.5 kV. Then the switch Sw is closed, initiating a wave process in the stripline that eventually leads to the generation of a bipolar voltage pulse at the stripline output terminal. This terminal is connected to the peaking module represented by capacitor C_P and the sharpening spark gap SSG. The diode D prevents a negative voltage pulse

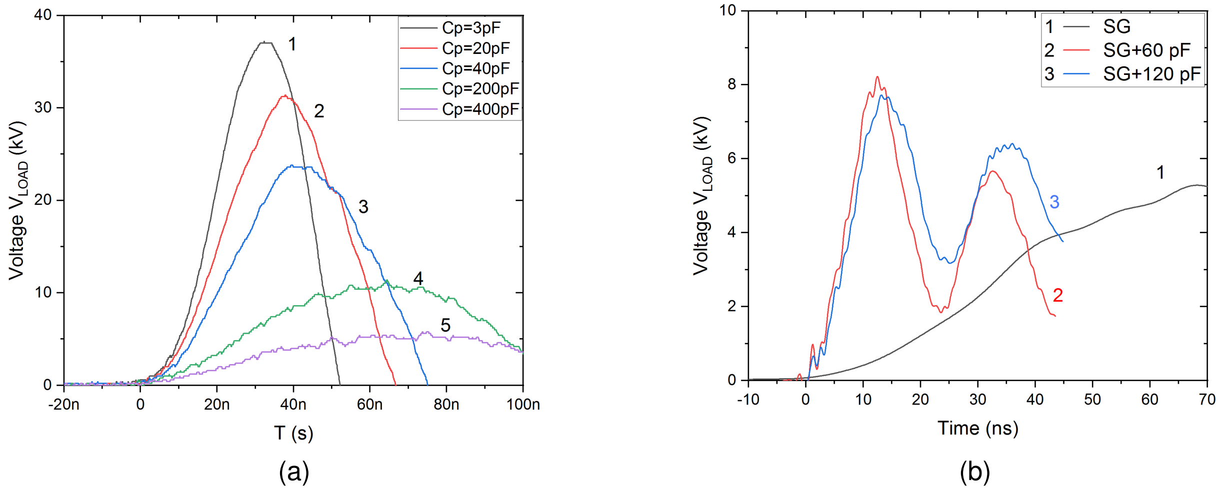

Fig. 4. Voltage impulse across different peaking capacitors C (a) directly driven by the spiral generator (1—C_p = 3 pF, 2—C_p = 20 pF, 3—C_p = 40 pF, 4—C_p = 200 pF, 5—C_p = 400 pF) and voltage impulse across the 400 pF dummy load and (b) directly driven by the spiral generator (1) and using the peaking circuit (2, 3).

being delivered into the load in case the SSG is misfiring. Under normal operation, the positive voltage across C_P, up to 40 kV for $C_P = 3$ pF, causes a self-breakdown of the SSG. Lastly, a fast rise time high-voltage impulse is applied to the capacitive load C_{LOAD}, which is connected to the trigger generator by terminals A and B. The voltage across the load is measured by the voltage probe (C_D and R_D) described in Section II.

In the nonconducting state, the semiconductor structure of the thyristor under test has a capacitance of about 370 pF. Therefore, the output characteristics of the trigger generator and its upgraded circuit were tested on a capacitive dummy load. Preliminary tests of the spiral generator connected directly to the 400 pF capacitive dummy load showed the dV/dt of 0.1 kV/ns, which is not sufficient to trigger the thyristor to operate in impact-ionization wave mode. To increase its dV/dt capability, a peaking circuit with an intermediate capacitive storage represented by a piece of 50 Ω cable was therefore implemented as shown in Fig. 2.

A piece of coaxial 50 Ω cable serves as an intermediate capacitive storage denoted as the peaking capacitance C_P. In addition, the use of a flexible cable connection from the trigger generator to the thyristor is both convenient and practical. The high-voltage cable core is connected to the high-voltage electrode of the dummy load (or to the thyristor anode in real thyristor testing) through a sharpening spark gap (SSG in Fig. 2). The cable braiding is connected to the grounded electrode of the dummy load (or to the thyristor cathode during thyristor testing). The sharpening spark gap is made from two identical metallic electrodes (for simplicity the electrodes are two screws) mounted inside a 3-D-printed case, and operated under an air pressure of up to four bar.

It is well known that a spark gap can provide a long lifetime when it operates at a low level of switching charge. Therefore, a spark gap used in the low-energy trigger circuit could be a suitable approach for a "hybrid" switch in applications where stability and repetition rate are not critical. However, further research should be focused on all-solid-state trigger generators to realize all the advantages of thyristors triggered in impact-ionization wave mode.

A voltage pulse of the spiral generator has a positive and negative half-sine parts, which are almost equal in amplitude. Therefore, the self-trigger SSG may electrically break at the wrong moment of time, i.e., during the negative part of the output pulse. To cutoff the negative part of the pulse, two series-connected 20 kV diodes (type 550S20) are introduced in the circuit were connected in parallel with the spiral generator.

The optimal parameters of the peaking circuit were investigated. For that, we varied the intermediate storage capacitance by adjusting simultaneously the number of cables connected in parallel from 1 to 3 and their length from 20 up to 40 cm. As a result, it was found that the peaking circuit significantly improves at the same time both triggering characteristics: the dV/dt from 0.1 to 0.8 kV/ns and peak voltage V from 5 to 8 kV for the entire range of the peaking capacitance C_P from 20 up to 120 pF [see Fig. 4(b)]. However, the range 20–60 pF is preferable to be used since it allows obtaining a higher peak voltage amplitude on the sharpening spark gap SSG [see Fig. 4(a)], thus contributing to its stable operation.

When testing the trigger generator with a single 2.2 kV thyristor, the two capacitance values of the peaking circuit 20 and 60 pF were compared. As can be seen from the curves in Fig. 5, a voltage dV/dt of 1.7 kV/ns is obtained with the thyristor at $C_p = 20$ pF, which leads to a 10% to 90% switching time of 0.7 ns and allows to start the thyristor even in the absence of a bias voltage (see Fig. 5). Conversely, by increasing C_p to 60 pF does not lead to fast switching. Therefore, in further testing the thyristors, only the peaking circuit with $C_p = 20$ pF was used, provided by a single 20 cm piece of the 50 Ω cable.

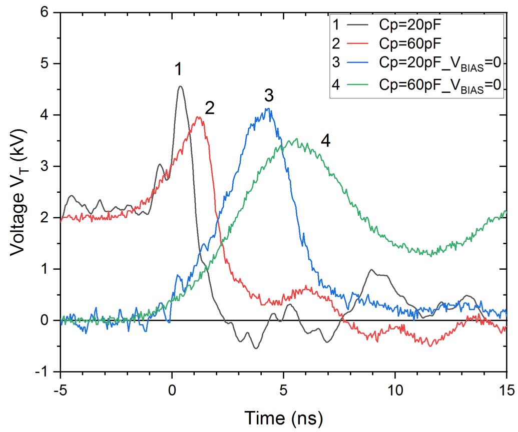

Fig. 5. Voltage impulse across single 2.2 kV thyristor driven by the trigger generator with the peaking capacitor $C_p = 20$ pF (1, 3) and $C_p = 60$ pF (2, 4) under a bias voltage of 2.2 kV (1, 2) or without it (3, 4).

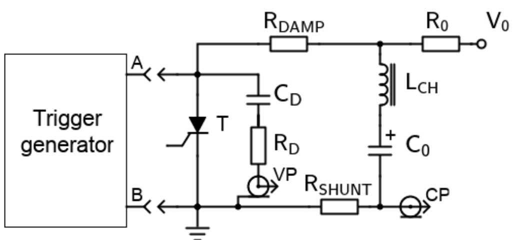

Fig. 6. Electrical circuit diagram of the experimental setup for testing a single 2.2 kV thyristor.

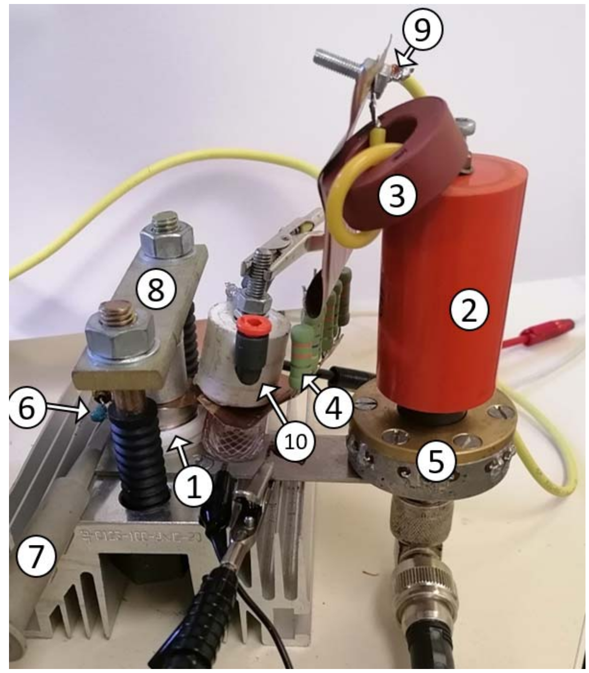

Fig. 7. Photograph of the practical experimental arrangement. 1—thyristor under the test T333-250-22N, 2—high-voltage film capacitor, 3—saturating choke, 4—damping resistor, 5—resistive shunt, 6—home-made voltage probe, 7—high-voltage probe Agilent 10076B, 8—clamping system, 9—node of high-voltage power supply connected through a charging resistor (not shown), and 10—sharpening spark gap.

B. 2 kV Switch

An electrical equivalent circuit diagram of the 2 kV switch test bench is shown in Fig. 6, with the actual arrangement presented in Fig. 7. This circuit operates as follows. The trigger generator is connected to the anode and the cathode terminals of the thyristor under test T via output terminals A and B, respectively. The thyristor gate terminal remains floating, although there is an internal gate-cathode connection with a resistance of 11 Ω.

During the initial stage, the capacitor C_0 is charged to a positive polarity of 2.2 kV, with this voltage applied to the anode. At this moment the saturating choke L_{CH} is magnetized in a direction that prevents the current flow from the trigger generator to C_0.

During the triggering stage, a positive voltage impulse is applied to the anode by the terminal A of the trigger generator. To initiate the impact-ionization switching, the trigger generator must deliver a pulse, which increases the voltage across the thyristor up to double the stationary breakdown voltage (i.e., about 4.5 kV) with a dV/dt of more than 1 kV/ns. Under these conditions, the thyristor goes into a conductive state in less than 1 ns. Finally, the choke L_{CH} saturates, and the forward current flows through the thyristor as R_{SHUNT}-C_0-L_{CH}-R_{DAMP}-T.

The discharge circuit (see Fig. 6) contains three elements connected in series: a high-voltage film capacitor $C_0 = 300$ nF that generates the current, a damping resistor R_{DAMP} to absorb the pulse energy and a saturating choke L_{CH} to decouple the trigger generator from the capacitor C_0 during the triggering phase. The discharge current is measured by a homemade low-inductive resistive shunt R_{SHUNT} described in Section II via the current probe (CP) connection. At the same time, a voltage across the thyristor is measured by the voltage probe Agilent 10076B (not shown in Fig. 6).

To charge the capacitor C_0, the high-voltage power supply Spellman SL-150 (V_0 in Fig. 6) was connected through the 200 kΩ charging resistor R_0 that limits the charging current. The connection node was chosen between the dampening resistor R_{DAMP}, and the decoupling choke, L_{CH}. Connecting the high-voltage (HV) source at the indicated node allows, before each subsequent switching on of the thyristor, a resetting of the decoupling choke with the charging current of the capacitor, which is opposite to the main discharge current.

The resistance of the damping resistor was selected $R_{DAMP} = 0.3$ Ω in such a way that the total resistance with the resistive shunt R_{SHUNT} is damping the discharge current oscillations, reducing the reversed current through the thyristor. If the reversed current is too high, the thyristor recovery leads to a current cutoff and an overvoltage across the thyristor, a phenomenon that may cause an irreversible electrical breakdown.

Fig. 8 shows the voltage signal on the single 2.2 kV thyristor triggered by the trigger generator. The oscillogram shows that at a dV/dt of about 1 kV/ns, charging voltage increases from $V_0 = 2.2$ kV to a maximum $V_m = 4.4$ kV. This is sufficient

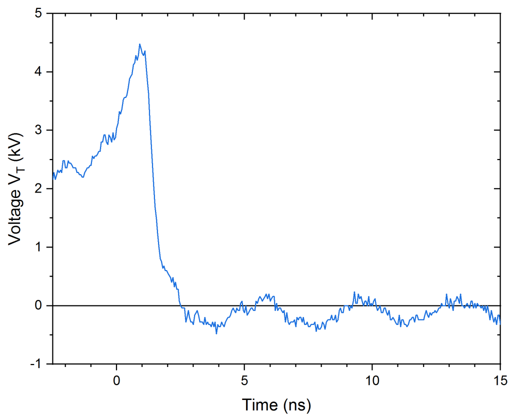

Fig. 8. Voltage pulse across the 2.2 kV thyristor at the current switching experiment, which is shown in Fig. 6.

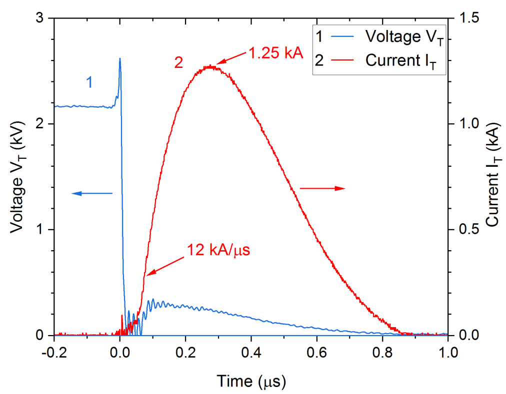

Fig. 9. Waveforms of discharge current (2) flowing through the 2.2 kV thyristor and voltage (1) across it measured by the voltage probe Agilent 10076B.

to run the thyristor in impact-ionization wave mode. The recorded signal also demonstrates a sharp drop in voltage from the peak value V_m to hundreds of V in less than 700 ps, which indirectly indicates the impact-ionization wave mechanism of switching.

The voltage signal across and the current waveforms generated through the thyristor are both shown in Fig. 9. The maximum dI/dt is 12 kA/μs and the current peak amplitude is 1.25 kA. The thyristor resistance at the moment of maximum current is $R_{\text{IMAX}} = 0.25\ \Omega$. The Joule energy dissipated in the thyristor during the positive part of the current is $W_{T0} = 0.137$ J, which corresponds to a switching efficiency of $\eta = 0.9$. After 100 pulses performed in this mode, the thyristor leakage current has not changed in comparison to the initial value of 4 μA at a $V_{\text{BIAS}} = 2.2$ kV. The number of tests performed was limited due to the unsuitability of the experimental arrangement for the very demanding long-term lifetime testing. The trigger generator introduced a main limitation due to its pulse repetition frequency (PRF) of about 0.2 Hz. Installing a higher-power charger in the spiral generator would allow the thyristors to be tested at a higher PRF.

C. 4 kV Switch

In these experiments, the switch tested consisted of two 2.2 kV thyristors connected in series. The testing circuit presented in Fig. 10 is similar to the previous one. For the experiments, the charging voltage of the capacitor C_0 is 4.4 kV. To equally distribute the voltage between the two thyristors, the resistors R_1 and R_2 with a nominal value of 15 MΩ were connected in parallel to each thyristor. A low-frequency voltage probe was connected in parallel to the "lower" thyristor, the one closer to the ground potential (T_1 in Fig. 10). The high-frequency resistive divider can be connected in parallel to either the lower thyristor or in parallel with the whole switch consisting of two thyristors.

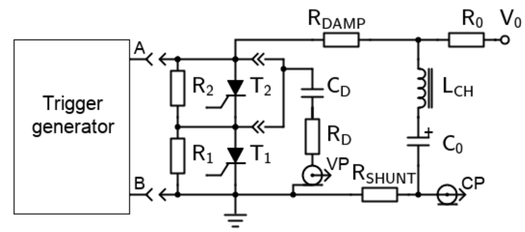

Fig. 10. Equivalent electrical circuit for the 4 kV switch consisting of two 2.2 kV thyristors.

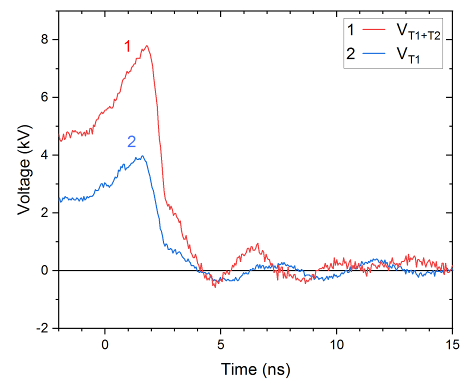

Fig. 11. Waveforms of the voltage across the whole 4 kV switch (1) and a lower 2.2 kV thyristor, which is close to the ground (2).

Typical voltage waveforms recorded by the high-frequency sensor are shown in Fig. 11. As can be seen, the dV/dt of the trigger pulse across the entire switch slightly increased compared to the 1 kV/ns generated by the single thyristor and reaches about 1.16 kV/ns. This effect can be explained by a decrease in the total equivalent capacitance of the assembly of two thyristors, when compared to the equivalent capacitance introduced by a single thyristor. However, the voltage pulse registered at the lower thyristor has dV/dt of about 0.7 kV/ns, which, according to [13], is close to the threshold of the impact-ionization switching mechanism. Assuming the similarity of the thyristor and diodes structure during the triggering phase, it seems that only part of the thyristor structure is switched in impact-ionization mode, as described in [16]. This effect can lead to an increase in the thyristor switching time up to 800 ps in comparison with 700 ps obtained at a dV/dt of 1 kV/ns.

The voltage impulse across the lower thyristor and the current through the switch are both presented in Fig. 12.

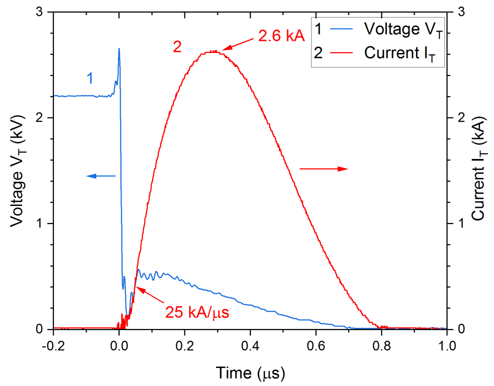

Fig. 12. Waveform of the discharge current (2) flowing through the two 2.2 kV thyristors connected in series and the voltage (1) across one of them.

When the charging voltage of the capacitor is $V_0 = 4.4$ kV, the peak $\mathrm{d}I/\mathrm{d}t$ and current amplitude reach 25 kA/μs and 2.6 kA, respectively. At this moment, the thyristor resistance is 0.12 Ω. The energy dissipated in one thyristor during the positive part of the current is 0.62 J. If we assume that the energy losses in both thyristors are equal, then the efficiency of the entire switch is $\eta = 0.79$. As in the case of one thyristor, more than 100 shots were performed with each thyristor stack. The leakage current of both thyristors was measured before and after a series of experiments. The stability of the leakage current at the nominal voltage indicates an absence of the semiconductor structure degradation throughout the complete series of tests.

IV. Conclusion

The present work demonstrates for the first time the operation of commercial 2 kV thyristors with 32 mm in diameter in the impact-ionization mode, triggered by a simple spiral generator equipped with a sharpening circuit.

Although the impact-ionization switching of standard thyristors was in principle demonstrated using an SOS generator as a driver, as presented in [17]–[19], the implementation of the stripline-based trigger generator described above is beneficial, due to the fact the system is based on cost-efficient off-the-shelf components.

The success of the present study opens the door for using impact-ionization off-the-shelf semiconductor switches in the design of pulsed power generators for a wide range of applications. In contrast to the usual spark gap, the use of this type of semiconductor switches will allow operating high-voltage pulsed generators at a very high level of pulsed PRF, well beyond kHz.

It is important to note that the presently developed trigger generator is not capable to trigger a stack of three or more thyristors connected in series. This is because the $\mathrm{d}V/\mathrm{d}t$ of the trigger pulse (even on two thyristors) is close to the threshold value. A possible solution can be the transition to thyristors of a smaller area and a higher rated voltage, which have a lower equivalent capacitance. An alternative option could be to use a trigger generator based on a spiral generator and solid-state sharpeners (for example, SOS diodes [25]), but such a system will require a radical change in both the sharpening circuit and the spiral generator.

The other main result of the present study is the design of a compact HV trigger generator that provides a sufficiently fast high-voltage pulse for allowing a commercial thyristor to be operated in the impact-ionization wave mode. Using the developed generator, both 2 and 4 kV thyristors switches were demonstrated to successfully operate in the impact-ionization wave mode. The resulting switching systems were demonstrated at a $\mathrm{d}I/\mathrm{d}t$ of up to 25 kA/μs and a peak current amplitude of up to 2.6 kA. These values are 30 and 10 times, respectively, higher than the values quoted in the commercial thyristor catalog.

Thyristors triggered in impact-ionization mode can be used as switches in the primary circuits of more powerful pulsed power generators, such as spiral or SOS generators. And those, in turn, can be used directly to drive loads or used to trigger higher-voltage and higher-current switches again in the impact-ionization mode but based on serially connected commercially available thyristors. The way ahead is to study such higher power systems.

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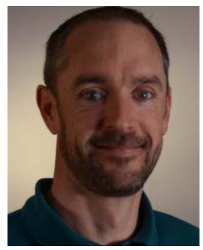

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