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Impact-Ionization Switching of High-Voltage Thyristors Connected in Parallel

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Abstract—Thyristors triggered in impact-ionization wave mode is a promising switching method in pulsed power technology. This triggering approach enhances the current capability of standard thyristors, allowing switching a current pulse with an amplitude of 200 kA and a current rise time rate-of-change (dI/dt) of 58 kA/ μ s. Thyristor wafer area can be considered as one of the factors that are limiting the peak current amplitude and dI/dt . Switching thyristors in parallel is a possible solution to overcome these limitations. However, no evidence was found in the literature for successful parallel switching of standard thyristors in impact-ionization wave mode. In this research, the possibility of parallel switching of two standard thyristors rated for 2.2 kV with a wafer diameter of 32 mm was investigated. A Marx generator equipped with a peaking module was used to charge the thyristor equivalent capacitance (1 nF) up to double its static breakdown voltage with a voltage rise time rate-of-change (dV/dt) of more than 1 kV/ns, as required for impact-ionization triggering. The diagnostic system includes two wideband voltage probes with a sub-nanosecond time response, which allows simultaneous measurement of a voltage drop across each thyristor connected in parallel. Two stages of thyristor operation were investigated: (i) a triggering stage, without energy switching, when a DC bias voltage is applied; and (ii) a current flow stage, with energy switching, when an RLC discharge circuit is connected. In these experiments, thyristors change from blocking to conducting state within 400 ps, switching a current pulse with an amplitude of 11 kA and a dI/dt of 6 kA/ μ s (circuit limits). The current imbalance between the thyristors was less than 10%. To the best of the authors' knowledge, it is the first time reported that high-voltage thyristors connected in parallel have been successfully triggered in impact-ionization wave mode.

Index Terms—High dI/dt , impact-ionization wave mode, pulsed power systems, subnanosecond switching time, thyristors.

I. INTRODUCTION

WHEN a fast overvoltage pulse (having a rise time rate-of-change of more than 1 kV/ns) is applied to a high voltage p-n junction a delayed impact-ionization breakdown occurs. As discovered by Grekhov in 1979 [1], this breakdown facilitates subnanosecond switching of a semiconductor device. Recently, the application of this breakthrough technique

has been successfully demonstrated [2] for standard (i.e., off-the shelf) high-voltage thyristors.

Standard thyristors triggered in impact-ionization wave mode have subnanosecond switching time and dI/dt capability hundreds of times higher than the rated values. In this mode of switching, a fast overvoltage pulse (with $dV/dt > 1$ kV/ns) is applied to the main electrodes in the forward direction, while the gate terminal remains in the open state. Under this condition, the electron-hole plasma is generated directly in the depletion region by the impact-ionization of silicon (Si) atoms under a high electric field.

According to several experimental and theoretical research [3] and [4], impact-ionization switching happens only on a certain part of the wafer area. Therefore, during switching, the area of the p-n junction contains two parts: (i) a conductive, or “active” area, where impact-ionization breakdown occurs and (ii) a non-conductive, or “passive” area, which is equivalent to a charged capacitor. As it was demonstrated in [4], the switching time is determined by the discharge time of the passive area through the active area, with a typical value of 100 ps.

Besides subnanosecond switching, impact-ionization triggering also allows to generate very intense current pulses with high dI/dt , which can find application in several important research domains, such as high-energy-density physics [5], inertial fusion [6], and X-pinch [7], [8]. Additionally, various major industrial applications, including magnetic pulse forming and welding, electromagnetic launching, rock fracturing [9] and mining, all require repetitive generation of current pulses in the range of hundreds of kAs [10].

In order to fulfill the demand for high currents (100s kA) with a very high dI/dt (10s kA/ μ s), semiconductor switches have been intensively studied, as reported in [11]–[19]. These switches are mainly based on reverse switching dynistors (RSDs) [11]–[17] and high-voltage thyristors triggered in impact-ionization wave mode [3], [18], [19]. This literature indicates that impact-ionization switches exhibit dI/dt of more than 10 kA/ μ s, whereas RSDs typically show only a few kA/ μ s at currents above 100 kA.

Series connection is a method to increase the blocking voltage of the switch and consequently reach higher currents. As reported in [19], a stack of nine high-voltage standard thyristors triggered in impact-ionization wave mode, with blocking voltage of 20 kV and a wafer diameter of 40 mm, can switch current pulses with an amplitude of 45 kA and dI/dt of 134 kA/ μ s. Another paper [3], reported encouraging results for a stack of two thyristors of 56 mm diameter: at

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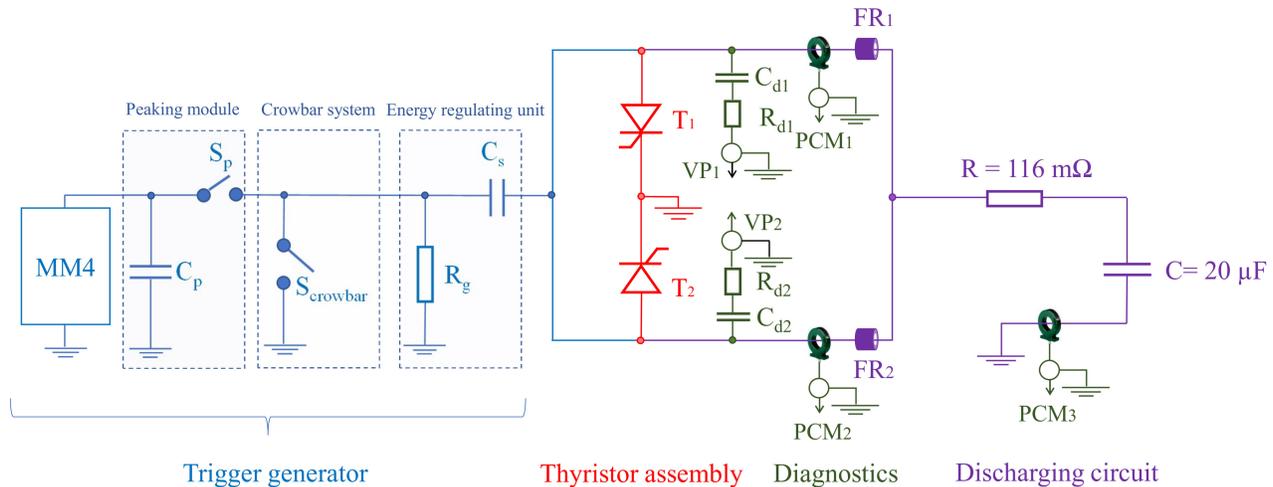


Fig. 1. Equivalent electrical circuit of the experimental arrangement.

a blocking voltage of 5 kV, the current had an amplitude of more than 200 kA, with a di/dt of more than 50 kA/ μ s and full width at half maximum (FWHM) of 25 μ s. These results indicate that impact-ionization switching of a commercial thyristor is a promising method to build a very high-current semiconductor switch for pulsed power systems. Although high-voltage switches based on series-connected thyristors have been described in the aforementioned research, high-current switches remain barely studied.

The present authors recently reported, the successful triggering in the impact ionization wave mode of the largest commercially available thyristor (100 mm / 5.2 kV) [20]. Although this work demonstrated a possible way ahead towards a fast high-current switch, this approach is far from offering a cost-effective and easily maintainable solution. On the contrary, the switching of parallel-connected thyristors in impact ionization wave mode would be a more encouraging approach, due to its lower cost and the possibility of eliminating the thyristor area limitation.

This paper demonstrates the parallel switching of standard thyristors in impact-ionization wave mode, which is a promising solution to meet the high current demands (in repetitive mode) of the modern applications of pulsed power technology. As will be demonstrated, proper triggering conditions lead to equal current distribution among the thyristors triggered in impact-ionization wave mode. In the present work, two thyristors T333-250-22 (\varnothing 32 mm, 2.2 kV) are connected in parallel and triggered by a specially designed trigger generator ($dV/dt \sim 2$ kV/ns). A switching time of ~ 400 ps is observed for each thyristor. Using the new switch, a capacitor bank (~ 50 J) was discharged into a resistive load with an efficiency of more than 90%. A current pulse with an amplitude of 11 kA and di/dt of 6 kA/ μ s was measured, representing the discharge circuit limit; the current imbalance between the thyristors was less than 10%. The following sections present both the experimental arrangement and the results obtained. The paper ends with conclusions and a suggestion for the way ahead.

II. EXPERIMENTAL ARRANGEMENT

The overall experimental arrangement, including the trigger generator, thyristor assembly, discharge circuit and the diagnostics is presented in Fig. 1.

A. Trigger generator

The thyristor driver, illustrated in Fig. 1, is assembled from the Marx generator (MM4), peaking module, energy regulating unit and crowbar system.

The MM4 Marx generator has 4 stages, and each stage can be charged up to 40 kV. Having a total equivalent capacitance of 500 pF, the MM4 generator is capable of delivering up to 6.4 J into a load. The values of charging and discharging resistances are 47 k Ω and 10 k Ω , respectively. Self-breakdown spark gaps with air at atmospheric pressure are employed as closing switches.

The peaking module unit (Fig. 2) consists of a peaking capacitor (C_p) made from three capacitors connected in series with a total capacitance of 186.6 pF, and a pressurized spark gap (S_p). An external air supply system provides air at a pressure of up to 7 bar. The peaking module components are installed inside a 3-D printed insulator. This insulator is employed to eliminate the possibility of flashover on peaking module components. For insulation purposes, the volume housing the peaking module containing the capacitors is filled with transformer oil. To reduce the parasitic inductance, the external part of the abovementioned insulator is shielded with copper foil playing the role of a current return electrode.

In order to regulate the energy delivered to the load from MM4, series capacitors (C_s) are installed in the experimental arrangement, as presented in Fig. 1. Also, the grounding resistor (R_g) is used to ensure that the left side of C_s is near ground potential and thus the voltage across C_s is almost equal to the charging voltage across C. This allows to reach a higher voltage with a higher dV/dt across the thyristors.

To reach the equal current distribution among two parallel thyristors, the impact ionization mode requires a high value

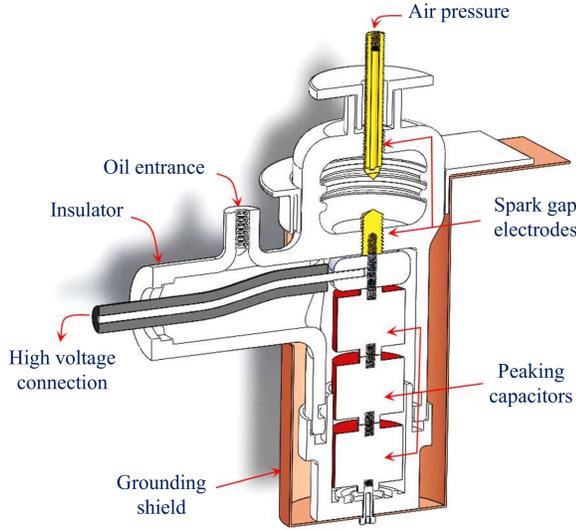


Fig. 2. A 3D model of the peaking module unit.

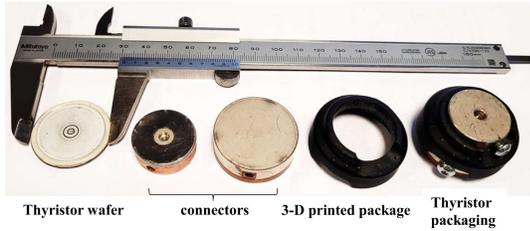


Fig. 3. Appearance of the T333-250-22 thyristor wafer (2.2 kV / 32 mm) in a customized package.

for the dV/dt , thus inherently increasing the energy required from the trigger generator. However, after switching, a post-trigger excessive energy delivered by the Marx generator may damage the thyristors. Therefore, a crowbar system - $S_{crowbar}$, a spark gap switch in Fig. 1 - was installed to ground the peaking module output, thus preventing any damage to the thyristors. The crowbar system is based on a self-breakdown spark gap filled with air under atmospheric pressure. The distance between spark gap electrodes is 12 mm.

B. Main Circuit

In the present work, two commercially available thyristors T333-250-22 with the rated blocking voltage of 2.2 kV and wafer diameter of 32 mm are connected as illustrated in Fig. 1 (T_1 and T_2). The thyristor wafers are assembled in new packages (Fig. 3) to decrease parasitic inductance of the voltage probe connection and increase the accuracy of the measurement. In addition, the new packaging reduces the clamping force required, making it easier to perform the experiments. In order to eliminate the chance of thyristor optical triggering, the new packages were 3D-printed in opaque plastic.

The discharge circuit is assembled from a capacitor bank (C) of 20 μF and a load resistor (R). The film capacitors are shielded with copper foil to reduce the inductance of

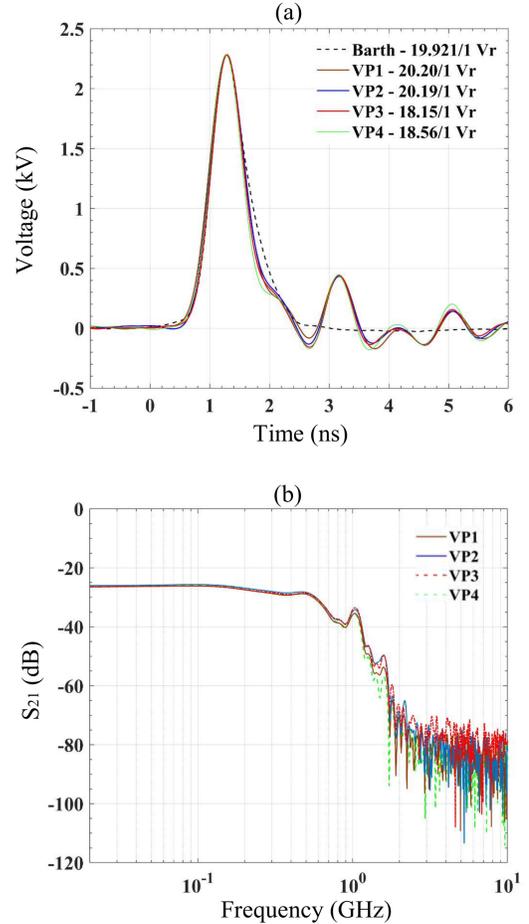


Fig. 4. The main results obtained during the calibration of the four voltage probes: (a) time domain, (b) frequency domain.

the discharging loop. A stainless-steel ribbon (R) of 116 m Ω is employed to prevent any reverse current flowing through thyristors. Two parallel ferrite rings (FR) decouple the triggering pulse from the discharge circuit.

The measurement system includes two parallel Pearson current monitors (PCM_1 and PCM_2 in Fig. 1) to monitor the current distribution among the two parallel-mounted thyristors. Another Pearson current monitor (PCM_3) measures the total current. The measurement of the triggering voltage pulse is achieved by two home-made high bandwidth voltage probes (VP) having a rise time less than 350 ps. The voltage probe is based on a resistive divider and consists of a 1 k Ω ceramic resistor (R_{d1} and R_{d2}) used as a high voltage arm and a 50 Ω coaxial cable as a low voltage arm [21]. In this voltage probe, the cable braiding is extended up to half of the 1 k Ω resistor to compensate its parasitic inductance. In order to decouple the voltage probe from the bias voltage, 100 pF capacitors (C_{d1} and C_{d2}) are attached to the high voltage arms of the two probes. Four such voltage probes were manufactured and calibrated using an FID generator (FPG 5-1PM1) and a Barth attenuator of 142 series (30 GHz, 26 dB). The FID generator is capable of delivering a 5 kV voltage pulse with a rise time of 350 ps into a 50 Ω load. The signals obtained from the

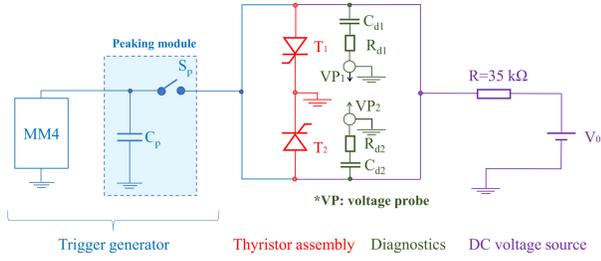


Fig. 5. Equivalent electrical scheme for the non-energy parallel switching arrangement of thyristors in impact ionization wave mode.

voltage probes were successfully compared with the signals measured by the Barth attenuator as illustrated in Fig. 4(a). The results indicate an agreement between the signals obtained from the voltage probes and the signal obtained from the Barth attenuator. In the frequency domain, the voltage probes attenuation is illustrated in Fig. 4 (b); the frequency is limited by the rise time of the FID generator used for calibration.

The overall experimental arrangement of Fig. 1 operates as follows. The capacitor bank (C) is firstly charged to 2.2 kV providing the bias voltage to the parallel thyristors (T_1 and T_2). Then, a triggering voltage pulse generated by the MM4 and enhanced by the peaking module is applied on the thyristors T_1 and T_2 . The energy delivered from the trigger generator is adjusted by the energy regulating unit and the crowbar system to safely run the parallel-mounted thyristors. Under this safe trigger condition, a successful subnanosecond switching in impact-ionization wave mode is achieved. Finally, simultaneous closure of the two thyristors generates in the discharge circuit (C, R, T_1 and T_2) a high-current pulse with a corresponding high di/dt . In following sections, two different switching modes (i.e. non-energy and energy switching) are described in detail.

III. NON-ENERGY SWITCHING MODE

In order to analyze the triggering condition of parallel thyristors, an experimental arrangement is assembled for non-energy switching mode study. The principal objective of this study is to determine the trigger requirements for parallel switching of the thyristors. In this experiment, a DC voltage source, connected to a resistor, provides the bias voltage of 2.2 kV directly over the thyristors assembly, as presented in Fig. 5. The 35 k Ω resistor is employed to protect the DC voltage source from the voltage impulse generated by the trigger generator. Two different experiments are detailed below.

In the first experiment, the MM4 was equipped only with a peaking module, which shortened the rise time of the voltage pulse delivered to the thyristors assembly. However, after their switching, the excessive energy stored in the MM4 induces an unwanted current with high amplitude over the parallel thyristors. This unwanted current has a high di/dt due to a low inductance of the trigger circuit loop. Such a high current with a high di/dt leads to a high residual voltage on the thyristors after switching (Fig. 6) and consequently it damages the thyristors. The issue of high residual voltage

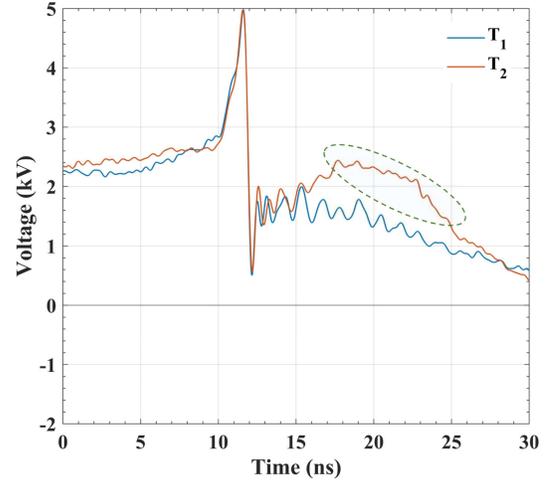


Fig. 6. The voltage waveforms across thyristor T_1 (1) and T_2 (2) in the experiment in which, after switching, the thyristor T_2 was damaged.

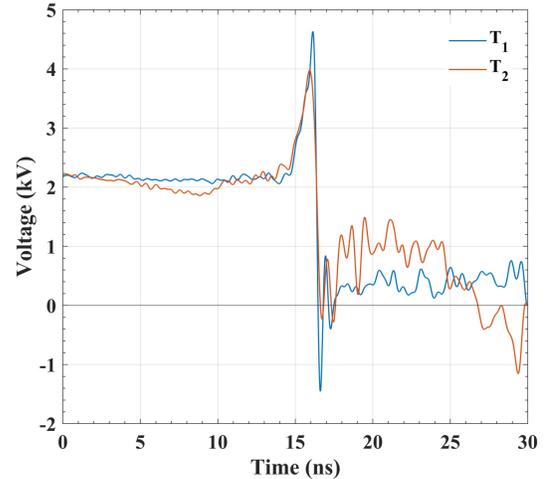


Fig. 7. The voltage waveforms across thyristor T_1 (1) and T_2 (2) during the experiment in which the thyristors, after successfully switching the current, remained undamaged.

after switching the thyristors is caused by the characteristics of the trigger circuit and therefore, a modification of the trigger generator is required.

To resolve the above-mentioned issue, the trigger circuit is modified as follows. Firstly, to regulate the energy from MM4, 4 series-connected capacitors of 140 pF in total are mounted between the peaking module and the thyristors assembly (C_s in Fig. 1). In addition to the series capacitors, a grounding resistor of 1 M Ω is added to the trigger circuit (R_g in Fig. 1). This grounding resistor ensures charging of the series capacitors to the charging voltage across C, to reach a higher dV/dt during the generation of the trigger pulse. Secondly, to limit the unwanted current from MM4 after thyristors triggering, a crowbar system consisting of a switching spark gap ($S_{crowbar}$ in Fig. 1) was installed. The crowbar system protects the thyristors from damage after switching by chopping the unwanted current of the trigger generator.

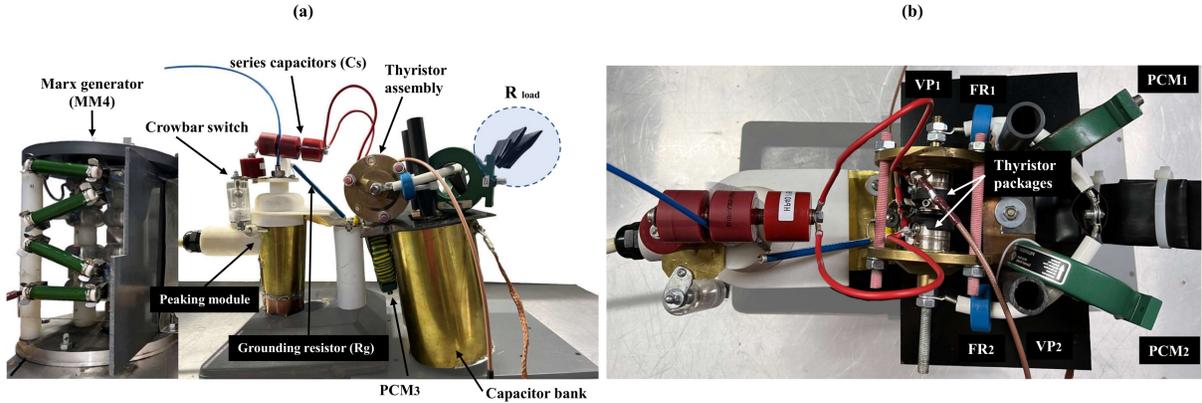


Fig. 8. The experimental arrangement of energy switching mode: (a) the front view, (b) the top view (the cable connections and insulation barriers were removed to increase visibility of components).

The trigger pulses recorded during two experiments can be seen in Fig. 6 and Fig. 7. In the first experiment, without trigger circuit modification, a high residual voltage (more than 2 kV) appears over the thyristor T_2 after switching, as seen in Fig. 6. Based on our assumption, this voltage is caused by the current flowing through the thyristor immediately after switching. This current generated by the high-energy trigger system is expected to have high dI/dt (due to the low-inductance trigger circuit). Thus, it is assumed that imposing a high dI/dt current after triggering leads to the thyristor T_2 being damaged. On the contrary, by employing the crowbar system and the energy regulating unit, the parallel thyristors have been safely triggered in impact-ionization wave mode. As seen in Fig. 7, the abovementioned modification in the circuit leads to an approximately 50% reduction in the residual voltage. Eventually, this leads to a safe and reproducible parallel switching of both thyristors in impact-ionization wave mode.

There was no degradation of the thyristors after the successful experiment, as their leakage current tested at a nominal voltage of 2.2 kV remained unchanged. Based on this, the experimental arrangement for energy switching was prepared, as discussed in detail in the next section.

IV. ENERGY SWITCHING MODE

To change from non-energy switching to energy switching, the discharge circuit and the current measurement units were added to the previous experimental arrangement, as shown in Fig. 1 and Fig. 8, with details presented in Section II.

In this experimental phase, the capacitor bank (C in Fig. 1) is charged up to 2.2 kV. A steep overvoltage pulse from the trigger circuit is applied over the two thyristors connected in parallel. This triggering pulse is measured independently for each of the two parallel-connected thyristors using the wide bandwidth voltage probes described above. The measured triggering pulses are illustrated in Fig. 9. The curves begin with a DC bias voltage of 2.2 kV, followed by a pulse with a dV/dt (10% to 90%) of 1.66 kV/ns and 1.29 kV/ns, respectively. The peak voltage is reaching 3.8 kV and 4.5 kV for the thyristors T_1 and T_2 , respectively. A switching time

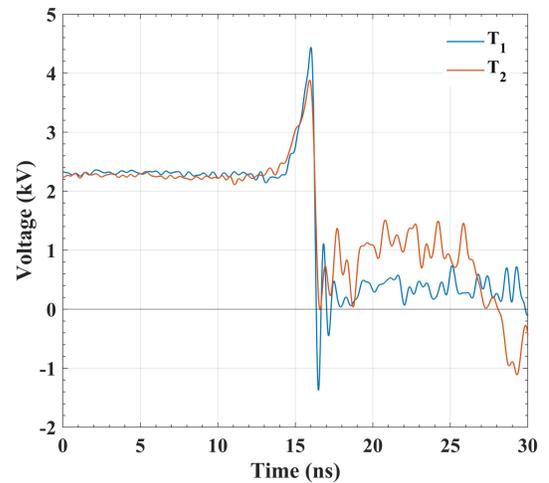


Fig. 9. The voltage waveforms across thyristors T_1 (1) and T_2 (2) in the energy switching mode.

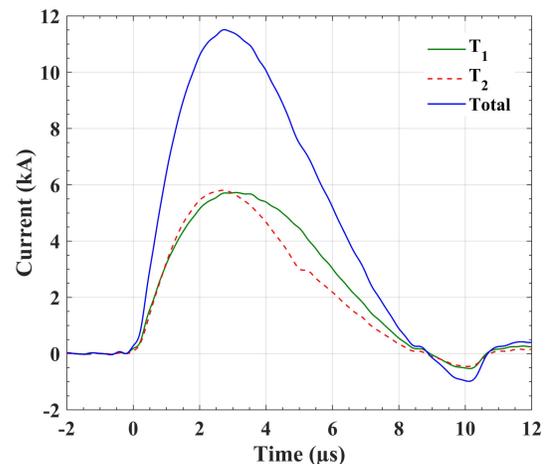


Fig. 10. The waveforms of the currents flowing through the thyristors T_1 (1) and T_2 (2) and of the total current (3) through the discharge circuit.

(10% to 90%) of 230 ps and 430 ps is measured for T_1 and

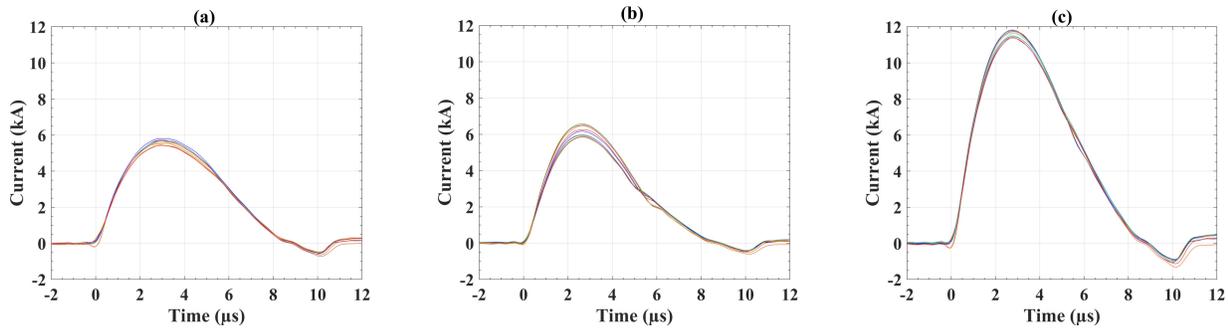


Fig. 11. A very high reproducibility of the experimental currents is observed for 10 consecutive shots for (a) currents through T_1 , (b) through T_2 and (c) total current of the circuit.

T_2 , respectively.

Fig. 10 shows the waveforms of the current flowing through the parallel-connected thyristors T_1 and T_2 . The total current flowing through both thyristors has a di/dt of $6 \text{ kA}/\mu\text{s}$, the peak amplitude of 11 kA and a pulse duration of $4.8 \mu\text{s}$ (FWHM). An energy switching efficiency of more than 90% is calculated as the ratio of the energy delivered into the load to the energy stored in the capacitor bank.

To conclude, the safe operation of the parallel thyristors and equal current distribution between them mainly depends on (i) applying a proper trigger in impact ionization wave mode and (ii) the characteristics of the experimental assembly. The former depends on the trigger generator characteristics, discussed in Section II with the effects analyzed in Section III. The latter is achievable through observing a symmetrical geometry for the thyristor assembly and implementing identical parallel current paths in the discharging circuit. Taking into account the aforementioned requirements, equal current distribution between the parallel thyristors can be obtained. The current imbalance between two parallel thyristors is less than 10% as demonstrated in Fig. 10.

Finally, to prove that experimental results are reproducible, the same experiment was repeated over 10 times. Less than 10% variation in the switched current is observed, as demonstrated in Fig. 11. Following these tests, the leakage current of the thyristor assembly was $7 \mu\text{A}$ at the nominal voltage of 2.2 kV , representing precisely the same value as it was before the experiment i.e., no degradation of the thyristors performance has been observed.

V. CONCLUSION

In this paper, the parallel switching of two high-voltage thyristors in impact-ionization wave mode is demonstrated for the first time. This success introduces a new paradigm in pulsed power applications facilitating the switching of very high currents, of the order of 100s kA , with a very high time rate-of-change of the order of $10\text{s kA}/\mu\text{s}$. The paper experimentally demonstrates that proper impact-ionization trigger conditions, combined with the very similar inductance of T_1 and T_2 current paths, leads to equal current distribution between parallel-mounted thyristors. A novel trigger generator was developed to safely trigger parallel thyristors and reach the equal current distribution. This highly cost-effective trigger

generator comprises a Marx generator equipped with a peaking module, energy regulating unit and a supplementary crowbar system. The peaking module is essential to reach high dV/dt , while the energy regulating unit and the crowbar system represent the key elements, since they ensure a safe thyristor operation by limiting the post-trigger excessive energy delivered by the Marx generator. With these important modifications, a trigger pulse having a high level of dV/dt ($\sim 2 \text{ kV/ns}$) could be applied.

The success of the present study opens the possibility of using impact ionization switches in very high-current applications such as rock fracturing, pulse magnetic welding, electromagnetic launching, etc. Experimentally proved parallel triggering would contribute to the basic understanding of the impact ionization phenomena in large-area p-n junctions, which is still a controversial theoretical issue. Therefore, numerical simulations are required during future research to reveal the limits of the impact-ionization switching mechanism. Moreover, a development of independent thyristor-driver modules, which can be connected in parallel and series stacks, certainly presents an attractive engineering task. No restrictions have been found to increase the number of thyristors connected in parallel as long as the trigger generator meets the requirements.

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