Subnanosecond switching of standard thyristors triggered in impact-ionization wave mode by a high-voltage PCSS driver

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Abstract. Power thyristors triggered in impact-ionization wave mode are capable to replace spark gap switches, bringing major advantages into repetitive pulsed power industrial applications. Low power thyristors remained for the moment out of the research focus, most likely because of the challenging driver, which must provide a sufficiently fast and powerful triggering pulse. This paper describes subnanosecond switching of standard off-the-shelf low-power thyristors in impact-ionization wave mode, running by the PCSS trigger generator based on the laser diode and GaAs switches. Several types of thyristors with a rated voltage from 0.6 kV to 2.2 kV have been tested running by both a commercial FID and by the tailored PCSS generators. The triggering and current flow stages were examined. For the 1.6 kV thyristor (TO-247 package), the following parameters have been obtained: switching time 250 ps, dI/dt up to 12 kA/µs, amplitude 85 A and FWHM about 60 ns. In this mode, the first 10¹³ pulses have not revealed any thyristor degradation.

1. Introduction

The commutation time of the high-voltage solid-state switches is one of the key parameters for pulsed power systems and this switch characteristic can hardly be overestimated. Numerous recent pulsed power applications, both in industrial and environmental domains, benefit from the ability of the solid-state switch to be turned on as fast as possible [1–3]. Such technologies, some still under development, require pulses with a rise time of a few ns and voltage amplitude of several kV. The most important among these are pulsed electric field (PEF) treatments and processing in the bio-based industry [4] and medicine as well as various cold plasma applications in food, agriculture [5] and special material surface modifications [6]. It is worth mentioning that some exotic applications, such as a Pockels cell driver, require even faster rise times of hundreds of ps at the kV-level voltage at a low-impedance load [7].

Conventional high-voltage solid-state switches suffer from an insufficiently low commutation time, as required by most modern pulsed power applications. By conventional switches, we understand semiconductor devices historically used for commutation in power electronics: bipolar junction transistor (BJT), silicon controlled rectifier (SCR) or thyristor and metal oxide semiconductor field-effect transistor (MOSFET). Their typical switching speed is limited as follows: the switching time is...
more than \(\sim 10 \text{ ns}\) and the current time rate-of-change \(dI/dt\) is about \(1\ \text{kA}/\mu\text{s}\). The switching speed of the high-voltage devices has been continuously improved by the implementation of new driver circuits \([8, 9]\), by developing highly integrated structures \([10, 11]\) or by using new principles of operation \([12]\).

Unfortunately, these developments face issues caused either by the limitations of semiconductor physics or by the expensive process of designing and fabrication of more complex semiconductor structures.

Research conducted by Grekhov et al \([12]\) resulted in demonstrating the first closing semiconductor switch. This switch provides \(dI/dt\) of \(100\ \text{kA}/\mu\text{s}\), subnanosecond switching time and low turn-on resistance at the blocking voltage of several kV \([13]\) and the authors termed it the “Shock-Ionized Dynistor” (SID). The switching occurs due to the initiation of the impact-ionization wave in the semiconductor structure by applying an overvoltage pulse with the voltage rise time rate-of-change \(dV/dt\) of more than \(1\ \text{kV}/\text{ns}\). The wavefront speed is faster than the saturated carrier velocity in silicon, which leads to subnanosecond switching time capability. Later, a series of pioneering works carried out by Rukin et al \([14, 15]\) have confirmed the ability of standard power thyristors to operate in the impact-ionization wave mode.

However, a literature review did not reveal any research on low-power off-the-shelf thyristors triggered in impact-ionization wave mode. This may be caused by the main disadvantage of this switching technique: the triggering generator which, due to its required specification, is usually quite complex and expensive. Thus, impact-ionization devices cannot yet compete in the low-power domain with commercially available fast switches, such as the Solidtron, developed by Silicon Power \([16]\).

From the above, it is clear that the development of a compact, robust and reasonably priced trigger generator for impact-ionization triggering would be a game-changer in modern solid-state based pulsed power and its applications. Recently, however, such a trigger generator has been developed by a team from the Tomsk State University (TSU) (Russia) as a circuit based on a conventional semiconductor laser and a combination of two gallium arsenide (GaAs) devices: (i) S-diode described in \([17]\) and (ii) high-gain photoconductive semiconductor switch (HG PCSS) similar to one mentioned in \([18]\).

2. Experimental arrangement

2.1. Tested thyristors

Since to the best of the authors’ knowledge the low-power commercial thyristors were never tested before in impact-ionization wave mode, there are no recommendations available in the literature regarding the optimum types and their required characteristics. However, based on our previous research \([14, 15]\), we assumed the rated voltage of \(\sim 2\ \text{kV}\) as a logical starting point for selecting the thyristors used in this study. The five types of standard thyristors presented in figure 1 have been chosen based on their frequent usage and hence their availability.

![Figure 1. The appearance of the thyristors being tested.](image-url)
Table 1 lists some important parameters of the thyristors tested during the present studies. According to their datasheets, the thyristors have the following critical values: the maximum repetitive peak forward-blocking voltage $V_{DRM}$ is from 0.6 kV to 2.2 kV; the on-state current of short-time duration $I_{TSM}$ is from 200 A to 600 A; the critical rate-of-rise of on-state current $dI/dt$ is from 0.05 kA/µs to 0.25 kA/µs with the forward breakdown voltage $V_{br}$ of between 1.7 kV and 2.7 kV being measured at a leakage current level of 1 mA.

Table 1. Some parameters of the thyristors shown in figure 1 triggered by the gate electrode.

| Reference No. | $V_{DRM}$ (kV) | $I_{TSM}$ (A) | $dI/dt$ (kA/µs) | $V_{br}$ (kV) | $R_{GC}$ (Ω) | Package       |
|--------------|---------------|--------------|-----------------|--------------|-------------|--------------|
| #1           | 2.2           | 200          | 0.25            | 2.7          | 16          | ISOPLUS i4-PAC|
| #2           | 1.6           | 300          | 0.15            | 1.9          | 50          | TO-247AC     |
| #3           | 1.2           | 300          | 0.15            | 1.8          | 43          | TO-247AC     |
| #4           | 1.2           | 200          | 0.15            | 2.0          | 50          | 3L TO-220AB  |
| #5           | 0.6           | 600          | 0.05            | 1.7          | 50          | TOP3 Ins.    |

Direct measurements have revealed the existence of the internal gate-cathode resistor $R_{GC}$ of about 50 Ω (see table 1) for all thyristors used in this research. This makes it unnecessary to install an external resistor for preventing the thyristor’s self-turn-on when a DC voltage is applied. Moreover, an impact ionization triggering mechanism does not require the gate electrode at all; therefore, for convenience the gate electrode of all thyristors in this work has been cut out, thus obtaining a proper connection of the voltage probe.

2.2. Trigger generators

The investigated thyristors, when they block the nominal voltage, can be represented as a capacitive load, with a capacitance of about 10 pF. To initiate an impact-ionization wave, a trigger generator must therefore be powerful enough to charge this equivalent capacitance up to about $2V_0$ with $dV/dt \geq 1$ kV/ns, where $V_0$ is the thyristor static breakdown voltage. Two trigger generators have been used as a pulsed power driver in this study: (i) a commercially available generator manufactured by FID GmbH (Germany) and (ii) a prototype system developed by TSU. For simplicity, in what follows we will refer to these units as “FID generator” and “PCSS generator”.

Table 2. Specifications of the FID generator when operated on a 50 Ω load.

| Parameter               | Value                     |
|-------------------------|---------------------------|
| Voltage amplitude (kV)  | 1-5                       |
| Polarity                | Positive                  |
| Rise time (10-90%) (ps) | 300 for 3-5 kV            |
|                         | 400 for 1-3 kV            |
| Pulse duration (FWHM) (ps) | 700-1000              |
| Maximum PRF (Hz)        | 1000                      |
| Dimensions (mm)         | 258×103×300               |

2.2.1. FID generator. To prove the concept of triggering low-power thyristors in impact-ionization wave mode, the FID generator model FPG 5-1PM1 is used. The FID generator is capable of delivering up
to 5 kV voltage pulses into a 50 Ω load. According to its operation manual, the FID generator specifications are as listed in table 2.

2.2.2. PCSS generator. The modular design of the PCSS generator increases its flexibility. The generator consists of three modules: a power supply circuit (PSC), a switch circuit (SC) and a load circuit (LC). The PSC module ensures the logic of operation and supplies the SC module, which forms an output pulse across the LC module. Output parameters of the PCSS generator with a capacitive load of 200 pF are listed in table 3. Operated in this mode, the lifetime of the PCSS generator is more than $10^6$ pulses.

| Parameter                        | Value       |
|----------------------------------|-------------|
| Voltage amplitude (kV)           | 1 and 3     |
| Polarity                         | Positive    |
| Rise time (10-90%) (ns)          | 1           |
| Pulse duration (FWHM) (ns)       | 2           |
| Maximum PRF (Hz)                 | 400         |
| Dimensions (mm)                  | 180×60×40   |

Table 3. Specifications of the PCSS generator on the 200 pF load.

The SC module contains an important element of the PCSS generator, which mostly define its output parameters. This is a micro-assembly of three semiconductor components (see figure 2). The GaAs S-diode forms the short rise time pulse of current required to pump the laser: the pulsed laser diode SPL DS90A_3 by OSRAM Opto Semiconductors. This laser generates the optic pulse triggering the GaAs PCSS, which delivers a high-voltage pulse with subnanosecond rise time into the load. Two different PCSSs with respectively 1 kV and 3 kV blocking voltages have been developed and tested. Both the S-diode and the PCSS dies are designed, fabricated and tested by TSU.

![Figure 2. Assembling of the output part of the PCSS generator, including the S-diode, laser diode and PCSS; the semiconductor elements are protected by coating with the transparent silicone compound.](image)

An electrical diagram of the SC module of the PCSS generator is presented in figure 3 (marked by a dashed rectangular). The circuit functions as follows. When the MOSFET is turned on, the capacitor C0 is charging up to a voltage V1 of between 200 V and 300 V within about 50 ns. This voltage is applied to the S-diode, which goes into a conductive state in less than 1 ns, forming a current pulse that pumps the laser. The amplitude of this pulse is about 50 A and its duration is about 1 ns. The optic pulse in its turn initiates the switching of the PCSS. During this process, the PCSS resistance decreases from several MOhm to a few Ohms within a time of less than 1 ns.

The PSC module can charge the capacitor C1 in about 200 ns up to the voltage V2 of 6.5 kV depending on the voltage required for the PCSS. The capacitor C2 is charged through the resistor R1 up to the bias voltage applied to the thyristor DUT. When the PCSS is turned on, the two capacitors
C1 and C2, become connected in series. This leads to the appearance of a fast-rising voltage pulse at the investigated thyristor DUT. The parasitic inductance L1 decreases the rise time of this voltage pulse, which is critical for impact ionization triggering. Therefore, the parasitic inductance L1 must be reduced as much as possible.

2.3. RLC load circuit

To test the thyristors at the current flow stage, an RLC discharge circuit board has been developed. The capacitive bank C3 in figure 3 is varied from 1 to 10 parallel-connected ceramic capacitors (type 2225 X7R, 2.5 kV, 10 nF) and it can be charged up to the voltage V3 of 3.0 kV. The resistive load $R_{\text{load}}$ is formed using thick-film ceramic resistors (type 4527, 6.8 $\Omega$) connected in parallel. The estimated value of the total parasitic inductance L3 is about 30 nH.

![Figure 3. Simplified circuit diagram of the output part of the PCSS generator loaded on the tested thyristor (DUT) which is connected to the RLC circuit and diagnostic system.](image)

To minimize the influence of the RLC circuit on the triggering pulse, a decoupling element must be introduced. At the beginning of the present research, a saturable magnetic switch (MS) was used. Having almost no effect on the discharge current amplitude, MS provides low decoupling efficiency though. Therefore, later on during the studies, MS has been replaced by the high-voltage diode D1. The diode increases the amplitude of the triggering pulse, at the price of a lower discharge current amplitude when compared with MS.

2.4. Diagnostics

To measure the voltage across the thyristor a house-made voltage probe (VP) was used. This VP represents the 1 kOhm resistor $R_{\text{vp}}$ inserted into a 50 Ohm coaxial cable, that gives an attenuation of 26 dB. The rise time of the VP is less than 300 ps and this has been confirmed by a calibration test using the FID generator (see table 2). The capacitor $C_b$ is required for blocking the DC voltage applied on the thyristor.

The low inductance shunt resistor $R_{\text{sh}}$ is used as a current probe (CP) to measure the current through the thyristor. The shunt is made of either 9 or 18 parallel-connected resistors (type 4527, 6.8 $\Omega$) and it has a total resistance of 0.8 $\Omega$ and 0.4 $\Omega$, respectively. The calibration revealed the shunt transient time is just about 1 ns.

Two real-time Tektronix digital oscilloscopes DPO 70604 (6 GHz, 25 Gs/s) and TDS 694C (3 GHz, 10 Gs/s) are used in recording the voltage and current signals. To attenuate the measured signals to the level required by the oscilloscope's input, a set of commercially available high-voltage attenuators with a bandwidth of up to 30 GHz was employed.
3. Results and discussions

3.1. FID generator

We used the FID generator to validate the main possibility of a standard low-power thyristor to operate in impact-ionization wave mode. The generator was set to the maximum output voltage of 5 kV, loaded with a 1 kΩ resistor and connected directly to the thyristor by a 50 Ω coaxial cable. The voltage probe mentioned above measures the voltage across the thyristor.

As one can see in figure 4 (a), without DC voltage bias, thyristors #1 and #5 (see their reference numbers in table 1) show no fast switching. Under the same conditions however, thyristors #2-4 are transitioning into a conductive state within about 350 ps. A possible explanation of this could be a high equivalent capacitance of the thyristors without DC bias. The value of about 300 pF is measured for thyristors #1 and #5, while for thyristors #2-4 it is from 150 pF to 200 pF. This makes it difficult if not even impossible to run the unbiased thyristors using the FID generator because this unit does not provide sufficient power.

![Voltage waveforms across the thyristors when triggered using the FID generator: (a) no voltage bias; (b) voltage bias equal to V_{DRM} (thin lines).](image)

Figure 4. Voltage waveforms across the thyristors when triggered using the FID generator: (a) no voltage bias; (b) voltage bias equal to V_{DRM} (thin lines).

Applying a forward bias equal to V_{DRM} reduces the thyristor’s equivalent capacitance to somewhere between 10 pF and 40 pF that increases the dV/dr and maximum amplitude of the triggering pulse, and which leads to the fast switching of all investigated thyristors. Figure 4 depicts the voltages across the biased thyristors #1-5 when triggered by the FID generator. The dV/dr value of the triggering pulse is between 1 kV/ns and 3 kV/ns and the maximum voltage across the thyristors of between 2 and 3 times higher than V_{DRM}. The measured switching time (from peak to zero voltage) is as follows: between 240 ps and 280 ps for thyristors #2-4, 480 ps for thyristor #5 and 800 ps for thyristor #1. Right after the switching moment, the residual voltage is about zero for all thyristors. Oscillations may be caused by the thyristor’s case parasitic inductance, which is hard to avoid.

Thyristor #2, with a rated voltage of 1.6 kV, has been tested in the current flow mode in the RLC circuit shown in figure 3. Triggering occurs by the 5-kV output pulse from the FID generator. The capacitor C3 = 10 nF is initially charged up to 1.6 kV with the resistor R_{load} = 6.8 Ω preventing any major current oscillations. The parasitic inductance L2 = 30 nH limits the maximum dI/dt at the level of about 53 kA/µs. In order to isolate the trigger generator from the RLC circuit at the triggering stage, a single turn magnetic switch is used instead of the diode D1.

When the RLC circuit is connected to the thyristor #2, the triggering pulse changes its shape (see figure 5 (a)) in comparison with the bare thyristor results (see figure 4 (b), red curve), however, it is still capable to initiate the impact ionization wave providing dV/dr of 2.5 kV/ns and an overvoltage 2.2 V_{DRM}, that leads to a switching time of only 250 ps. Under these conditions the thyristor #2 is able to switch the current pulse shown in figure 5 (b) with the following parameters: current rise time rate-
of-change (10% to 90%) – 12 kA/µs, current amplitude – 85 A, pulse duration – 53 ns (FWHM). According to the voltage drop (see the blue curve in figure 5 (b)), the thyristor resistance is 5.4 Ω at the moment of maximum current. More than $10^3$ pulses were performed at 1 pps, after which no change in the leakage current was observed. The leakage current of 3 µA at 1.6 kV corresponds to the values of the new thyristor #2.

**Figure 5.** Voltage (blue) and current (red) waveforms of the thyristor #2 (30TPS16) when triggered using the FID generator: (a) triggering stage; (b) current flow stage.

### 3.2. PCSS generator

Rather modest results have been obtained using the PCSS generator as a driver. No thyristors have been triggered at zero bias voltage. Also, only two thyristors (#1 and #2) show fast switching at $V_{DRM}$, but thyristor #1 fails after several pulses. Therefore, only thyristor #2 could be tested.

The configuration of the test bench for these tests was identical to that used in the FID generator experiments described in section 3.1 ($V_C=2.2$ kV). The triggering pulse delivered by the PCSS generator into thyristor #2 is shown in figure 6 (b); we observed a $dV/dt$ about 1 kV/ns and an overvoltage of $1.8V_{DRM}$. Although a switching time of about 600 ps and a residual voltage of about 1 kV seem critical for operation in current flow mode, thyristor #2 withstood $10^3$ current pulses at 1 ppm at the following pulse parameters: current rise time rate-of-change (10% to 90%) – 9 kA/µs, current amplitude – 62 A, pulse duration – 90 ns (FWHM).

**Figure 6.** Voltage (blue) and current (red) waveforms of the thyristor #2 (30TPS16) when triggered by the 3-kV PCSS generator: (a) triggering stage; (b) current flow stage.
Increasing charging voltage $V_{C1}$ leads to improvement of triggering, but at the same time, it decreases the lifetime of the PCSS: it was permanently damaged at $V_{C1} = 3.5 \text{kV}$. Thus, developing a reliable high-voltage PCSS will contribute to the impact-ionization triggering technique.

4. Conclusions

The work presented demonstrates the triggering of the low-power thyristors in impact-ionization wave mode, which increases the $dV/dt$ capability by two orders of magnitude. In addition, a circuit with a capacitive store has been tested for the first time as a driver of the impact-ionization triggering. Finally, the concept of using a high-voltage PCSS to initiate impact-ionization waves in thyristors has been demonstrated. Improvements in the switching characteristics of both the PCSS and of the off-the-shelf thyristors operated in the impact-ionization wave mode are currently on the way to be implemented in practice.

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