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Research Article

High current pulse forming network switched by static induction thyristor

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Abstract

A high-current pulse forming network (PFN) has been developed for applications to artificial solar-wind generation. It is switched by static-induction thyristor (SIThy) and is capable of generating pulsed current of ~9.7 kA for a time duration of ~1 ms. The SIThy switch module is made that it can be controlled by an optical signal and it can be operated at elevated electrical potential. The experiments reported in this paper used two switch modules connected in series for maximum operating voltage of 3.5 kV. The experimental results have demonstrated a pulsed high-current generator switched by semiconductor devices, as well as the control and operation of SIThy for pulsed power application.

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Keywords: Pulsed power; Pulse forming network; Power semiconductor device; Thyristor; High voltage

1. Introduction

Pulsed power is electrical energy released in a very short period. It is characterized by instantaneous high power and short pulses. It has applications in a variety of fields including material, environment, accelerator, space, and bio-medical science [1−6].

One of the potential pulsed-power applications is the artificial solar-wind generation, which is being developed as a research platform for studying magnetic sail. It requires a pulsed power source that can drive a current on the order of 10 kA for at least a few milliseconds [7−9].

Switching devices are the key components in pulsed power generators. Traditional high-current switches are either spark gaps or ignitrons, but they are not suitable for applications that require repetitive and stable performance. Solid-state switches are more preferable, especially semiconductor devices. Although semiconductor power devices have been widely used in pulsed power circuits [10−13], those with high-current capability are not so popular because of the limitations in the current density that can be switched by a semiconductor. Among various types of semiconductor power devices, thyristors are relatively high current-capable switches due to their special junction structure, especially the static-induction thyristor (SIThy) which has balanced specifications between switching speed and current capability [14−16].

A joint study has been carried out for initial development and test of a pulse forming network switched by static-induction thyristors. The objective is to demonstrate a high-current pulsed power source based on solid-state switch and to evaluate the performance and limitation of the switching device. This paper reports the technical details on the circuits and the controls, followed by the typical experimental results and discussions.

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2. Experimental setup

2.1. Pulse forming network (PFN)

In order to obtain a millisecond-order, near-squarewave output pulse, the logical choice would be using a PFN. An alternative approach might be switching on and off of a capacitor discharge, but it will require high current switching-off, which is usually more difficult than switching-on, and a relatively large capacitor to sustain a stable output current for a millisecond. So, although the static-induction thyristor we are using as the switch has the capability of switching-off, we are only using it as the switching-on device and the pulse length is determined by the PFN.

We have chosen a resistive load of 0.167 Ω as a dummy to represent the artificial solar-wind generator. To match the characteristic impedance of the PFN, the inductance is found to be $L \approx 5.6$ μH, for capacitance of $C = 200$ μF. The PFN consists of 14 stages giving a theoretical output pulse length of ~0.93 ms. The equivalent circuit for the PFN-based generator is shown in Fig. 1, where S_1 and S_2 are mechanical switches for charging and dumping purposes respectively. Figs. 2 and 3 show the illustration and the picture of the whole system which was originally developed for other applications and is now reused for this study.

2.2. Static induction thyristor (SIThy)

Static induction thyristors (SIThys) are used as the closing switch for the PFN. The pnpn structure of the SIThy, as shown in Fig. 4(a), has a unique configuration that allows relatively fast switching and low switching loss. It also makes SIThy a normally-on device. Therefore, a negative voltage on the gate is always required in order to block the current between the anode and the cathode. This negative bias wipes out carriers from the semiconductor and forms a depleted region near the cathode. For switching-on, a pulsed current is injected through the gate which populates the semiconductor and creates a current pass between the electrodes.

The SIThy devices used in this experiment, shown in Fig. 4(b), are made by NGK Insulators Ltd. The specifications are listed in Table 1. For the PFN switch, we have used two devices connected in series for two reasons. First, the operation voltage is planned to go higher than the rated voltage of a single device, although the maximum voltage used in this experiment is 3.5 kV, as will be seen below. Second, the switching performance is better for relatively lower operation voltage compared with that closed to the rated voltage.

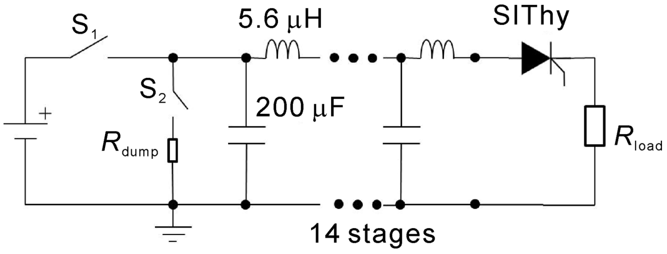

Fig. 1. Circuit diagram for the PFN-based pulsed high-current generator.

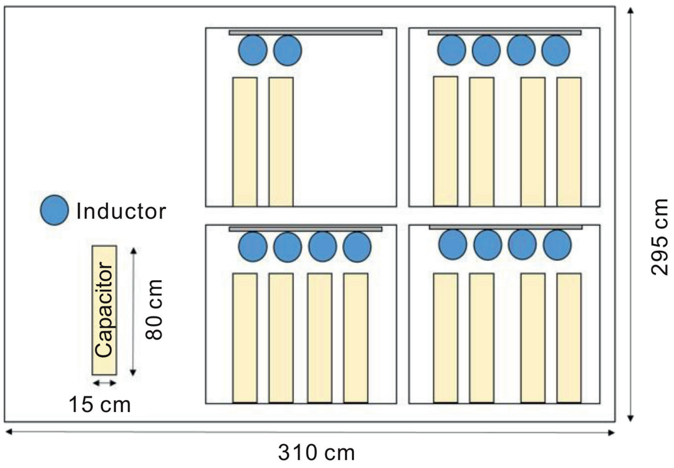

Fig. 2. Illustration of the pulse forming network (PFN).

2.3. Gate circuit

SIThy is a current driven device. In other words, the gate is electrically connected with the semiconductor, in contrast to the MOS devices. Therefore, when a negative voltage is applied to the gate, it drains the carriers out of the channel and reversely biases the junction between the gate and the cathode. The resulted depletion layer near the cathode can hold the main voltage applied between the anode and the cathode. Therefore, the role of the gate circuit is to ensure this negative bias during the off-state and, for switching-on, to remove the depletion layer by injecting enough carriers into the device as quickly as possible.

A gate circuit has been developed for achieving these functions. It uses a negative voltage source for the bias and a positively charged capacitor, switched by a MOSFET, for the current injection. As explained above, the switching-off is not important here, so the negative bias is allowed to slowly come back to the gate after the MOSFET is turned off.

Fig. 3. Picture of the pulsed power generator using the PFN.

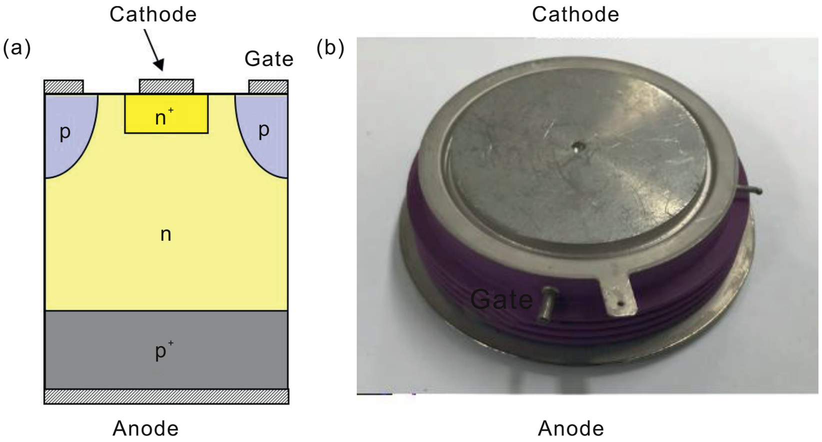

Fig. 4. (a) Schematic structure and (b) appearance of the static induction thyristor.

Table 1
Specifications of the static induction thyristor.

Model	RT-103
Maximum blocking voltage	4 kV
Maximum current	5.5 kA
Maximum di/dt	<100 kA/μs
Dimensions	ϕ 92 mm × 26 mm

It is important that the switch is not connected to the ground, as seen in Fig. 1. In addition, the series connection of more than one switches requires that the gate circuit be operated on elevated electrical potential, i.e., it has to be isolated from the ground. The isolation is carried out by using optical fiber and insulated transformers, where the fiber is for the signal transmission and the transformer is for the gate power delivery.

The schematic of the gate circuit is shown in Fig. 5. It is made on a printed circuit board, as seen in Fig. 6 with an SIThy installed. The switch module is made so that it can be easily stacked on top of each other when necessary, for operation under high voltage.

When several devices are stacked together, it is important to have them synchronized. However, there might be a slight difference between the SIThy devices that may result in timing

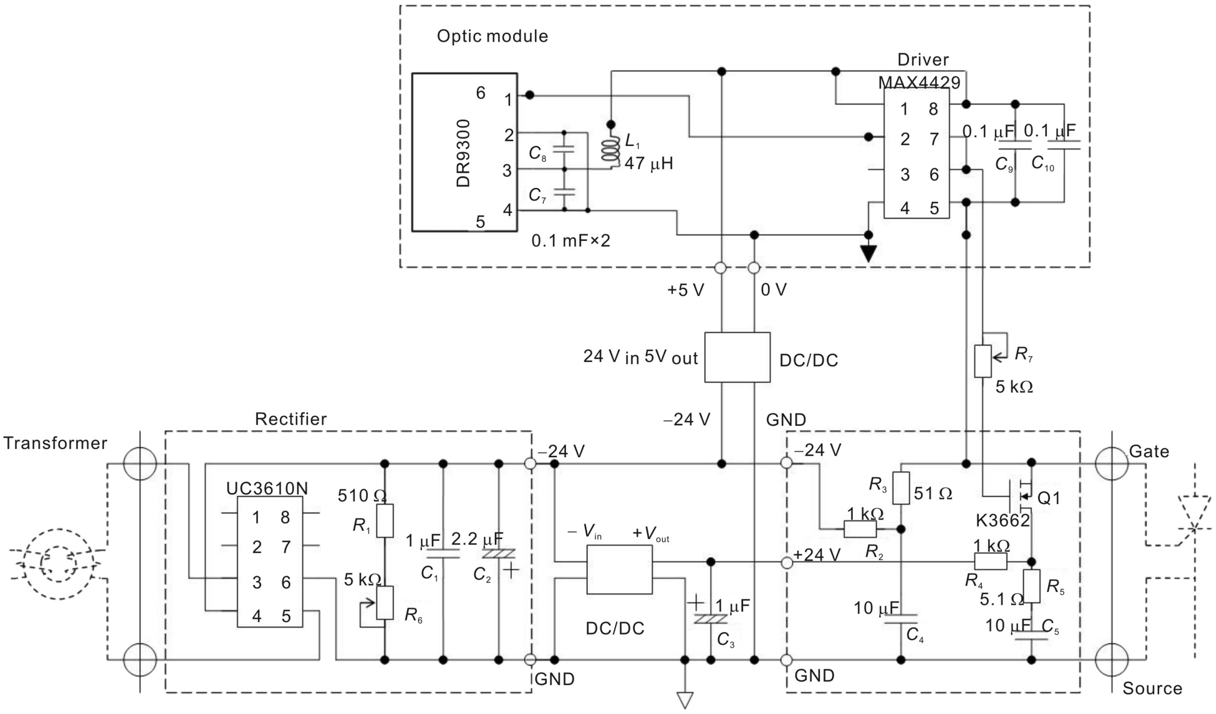

Fig. 5. Gate circuit schematic.

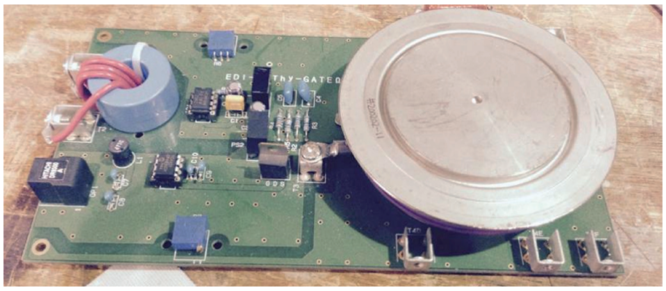

Fig. 6. Gate circuit with an SIThy installed.

variation. To compensate this timing variation, each gate circuit is designed so that the relative time delay between the optical signal and the gate pulse is adjustable in a range of about 10 ns.

The experiments described below use two SIThys connected in series. The gate voltage waveforms for the two devices are shown in Fig. 7. It is seen that the gate voltage is kept near −25 V during the SIThy off-state. When it is switched on, the gate voltage quickly rises to a very low positive value (junction forward drop) in a few hundreds of nanoseconds. The waveforms were obtained without applying main switch voltage.

2.4. Load resistor

This experiment requires a resistive load with low resistance, low inductance, and high-current capability that matches the impedance of the PFN as closely as possible. To achieve the expected resistance of 0.167 Ω, we have used the off-the-shelf sheet resistors (TKK, ASW 11025) of 0.2 Ω and stacked five pieces of them as shown in Fig. 8.

3. Experimental results

Experiments have been carried out using the experimental setup described above. The load voltage was measured by a voltage probe of TekP5100 (Tektronix). The load current was obtained by dividing the load voltage with the load resistance, the value of which had been carefully calibrated before the experiment. The waveforms were recorded by a digital oscilloscope of WaveJet324A (LeCroy).

Fig. 9 shows the load voltage waveforms obtained with different charging voltages of 1000−3500 V. The maximum current obtained on the load is as high as ~9.7 kA with a pulse length of ~1 ms. An apparent dip is observed at about 300 ns which might be caused by the non-uniform wiring in the PFN (between different decks). This effect, along with a slight impedance mismatching, has led to a second pulse of nearly 20% as large as the first one.

The total energy delivered to the load is calculated to be 14 kJ, which is about 82% of the energy initially charged in the capacitor, for a charging voltage of 3.5 kV. The energy loss is considered to be mostly caused by the switch.

The behavior of each SIThy has been monitored by using a differential high-voltage probe (Yokogawa, 701926). The results are shown in Fig. 10, for a charging voltage of 2 kV. The

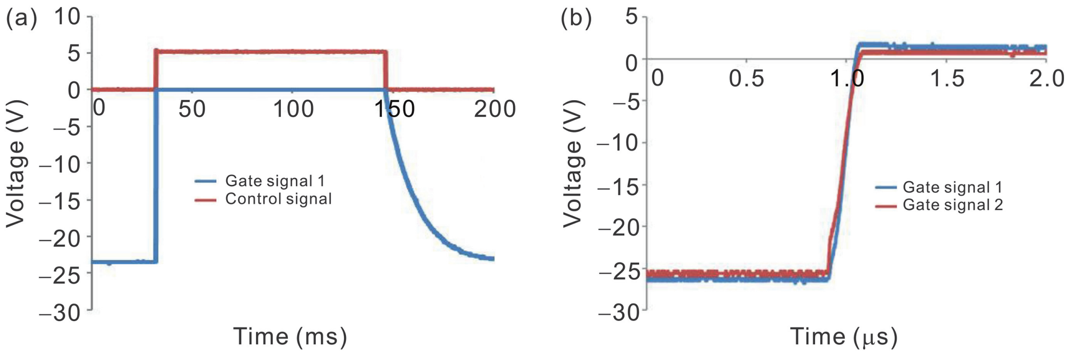

Fig. 7. Typical SIThy gate voltage waveforms for two SIThys connected in series. (a) Trigger signal and driver output, (b) rise time of both drive circuit outputs.

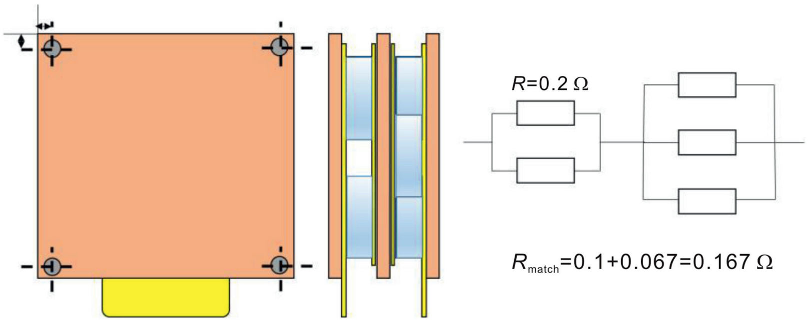

Fig. 8. Load design and assembly.

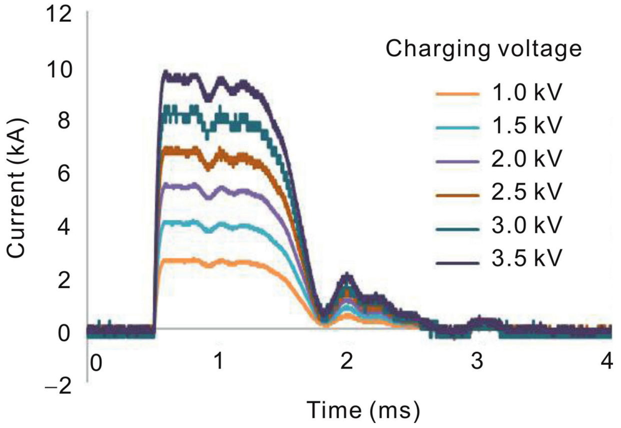

Fig. 9. Waveforms of output current, obtained with different charging voltages.

4. Conclusions and discussions

A pulse forming network has been developed for applications to artificial solar-wind generation. It can drive a pulsed current of ~9.7 kA, with time width of ~1 ms, through a resistive load of 0.167 Ω. Two static-induction thyristors (SIThys), connected in series, are used as a closing switch.

The results have indicated the high-current capability of SIThy and relatively fast switching it can achieve. These are usually trade-off characteristics for most semiconductor power devices. In other words, it is not difficult to find a fast switch that can handle relatively low power and a powerful switch that is relatively slow, while SIThy shows a balanced performance that fits the requirements of the system we are developing.

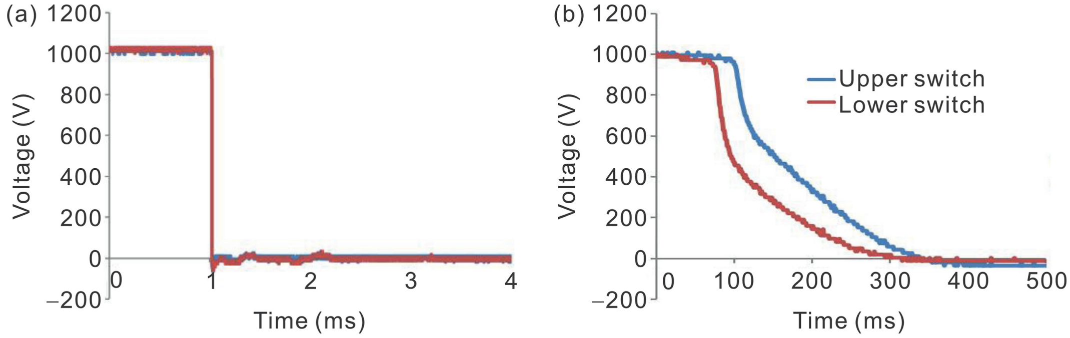

Fig. 10. Voltage waveforms obtained on each SIThy, for operation voltage of 2 kV. (a) The falling edge of the switch voltage on a millisecond timescale and (b) falling edge of the switch voltage on a nanosecond timescale.

voltage on both switches dropped in a few hundreds of nanoseconds, with a slight deviation between each other on the order of 10 ns.

To monitor the consistency of the output of this generator, we present Fig. 11 which shows four separate shots at 3.5 kV charging voltage. In this case, the small differences in the transients after the pulse have risen to be discernable, which is about 2% of the peak load current.

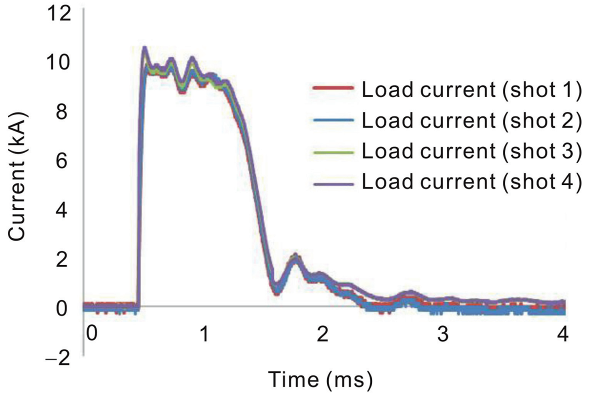

Fig. 11. Output current at 3.5 kV charging voltage, four consecutive shots.

We have put each SIThy together with its driver circuit in an integrated module which can be controlled by optical signal through a fiber. The gate power is provided through an insulated transformer. This switch module can easily stack up to handle higher voltages for other applications.

Although the system has been developed for applications to artificial solar-wind generation, which is a coaxial discharge load located in a low-pressure chamber, the main research subject at this time is the characteristics evaluation of the switch. The pulse length can be easily adjusted by adding or reducing the PFN stages and the operation voltage can be increased by increasing the number of SIThys connected in series. Future applications may need multi-device operation in parallel.

At this time, repetitive operation is not yet considered partially because of the limitation in our DC power supply. In fact, it takes about 3 min to charge the capacitors to the voltage of 3.5 kV. In addition, the energy deposition in the switch is on the order of kilojoule per pulse which makes the cooling efforts very difficult for repetitive operation.

Conflict of interest

None declared.

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