

DEVELOPMENT OF A SOLID-STATE SWITCH FOR KLYSTRON PULSE MODULATORS

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Abstract

A high-voltage, high-power solid-state switch to replace thyratrons for line-type klystron modulators is currently being developed. We have designed and built a compact solid-state switch consisting of 15 static-induction(SI) thyristors stacked in series. We have demonstrated that the solid-state switch can reliably operate at a 43 kV hold-off voltage, a 5.4 kA peak current, a 6 μ s pulse-width, and 25 pps, and can withstand load faults. This paper describes the design and results of testing the solid-state switch.

1 INTRODUCTION

Recently, a variety of semiconductor switches became available along with the development of semiconductors as well as the progress of switching technology. SI-thyristors are the most suitable devices to generate high-power pulses among semiconductor switches because of their high-power handling and fast turn-on capability. We are trying to develop a solid-state switch using SI-thyristors to replace thyratrons, which improves the reliability and maintainability of klystron pulse modulators. Semiconductor switching technology plays an essential role in the development of klystron pulse modulators for large-scale linear accelerators, such as Japan Linear Collider[1] as well as compact linear accelerators[2].

2 SOLID-STATE SWITCH

2.1 Specification

As a first step in the solid-state switch development, we designed a solid-state switch to meet the requirements of approximately one hundred-megawatt peak power klystron modulators for the KEKB injector linac or the Accelerator Test Facility (ATF) injector linac. The specifications of the solid-state switch are given in Table 1.

2.2 Switching Devices

Considering a single series connection design, a switching device requires high voltage, very large current, and high di/dt ratings. The reverse conducting SI-thyristor RS1600PA40T1, which was developed specifically for pulsed power applications by NGK Insulators Ltd., was chosen as a switching device[3]. This

SI-thyristor has a rated hold-off voltage of 4 kV, a press-pack ceramic housing, and a buried gate structure which makes it possible to realize a high peak current, low losses and fast turn-on capabilities. A maximum peak current of 10 kA and a maximum di/dt of 110 kA/ μ s were obtained at a performance test using a very low-inductance circuit[4]. From the test results, it was confirmed that the SI-thyristors are the most suitable devices for closing switches to replace thyratrons.

Table 1: Solid-State Switch Specifications

Hold-off voltage	45 kV
Peak current	6000 A
Pulse-width	6 μ s
Repetition rate	50 pps
Cooling	Forced oil cooling
Devices	RS1600PA40T1(4 kV)

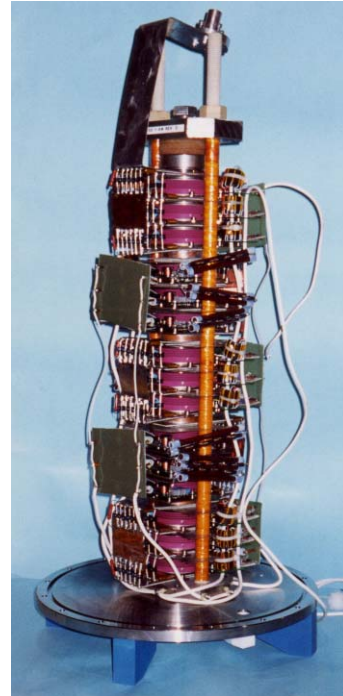


Figure 1: Solid-state switch assembly

2.3 Switch Design

The stack assembly is shown in Fig. 1. The basic circuit diagram of the solid-state switch is shown in Fig. 2. The switch consists of five units stacked in series to achieve the desired voltage rating. Each unit consists of

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three devices, each having its own circuit board containing a gate driver circuit. A resistor capacitor network for voltage sharing and diodes for protecting the device from over-voltage were connected in parallel with each device. DC power and a trigger signal for each gate driver circuit are fed through individual input ferrite core transformers on the circuit board to isolate from high-voltage. The primary windings using a high-voltage silicon cable were connected in series. Although the device includes freewheeling diodes to flow a reverse current, it does not withstand a peak reverse current of over approximately 4 kA. To protect the devices from over reverse currents, shunt diodes (VMI 50UF) were connected in parallel with the devices as well as each unit. Shunt diodes (HVAC 60HV50K) were also connected in parallel with the solid-state switch.

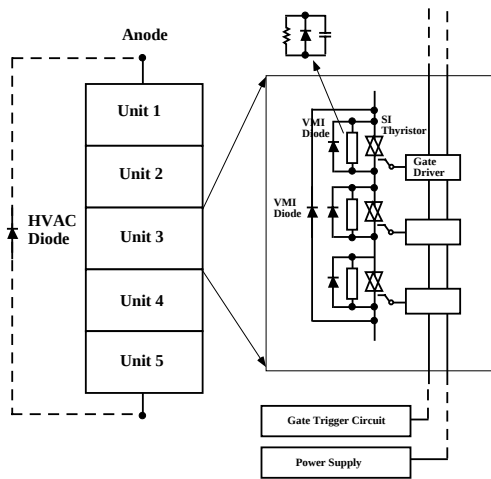


Figure 2: Basic circuit diagram of the solid-state switch assembly

The SI-thyristor is a normally-on type device. To make a hold-off state, a bias voltage of -10 V is applied between the gate and cathode electrodes. A gate circuit driving a large gate current with a short rising time is essential to obtain a fast switching time of the device. Thus, it is important to reduce the total inductance in the gate circuit and to apply a much higher voltage to the gate. A gate drive circuit using MOSFET gate switches was developed. To reduce the total inductance in the gate circuit, each gate driver is integrated directly around each device. Figure 3 shows the gate voltage and current waveforms when no anode current was flowing. The peak output voltage of the gate driver circuit was 160 V and then the peak gate current reached 150 A.

The stacked device are housed in a single cylindrical tank with a diameter of 350 mm and a height of 820 mm. The tank is filled with oil to insulate and cool the internal devices with the aid of a simple closed-loop cooling system.

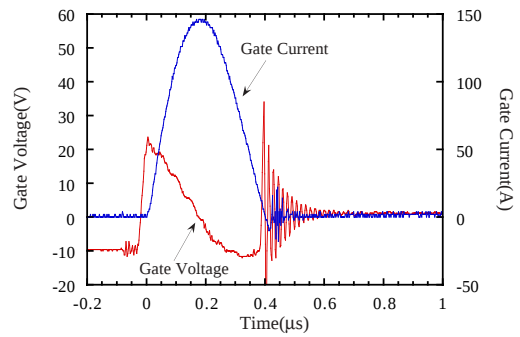


Figure 3: Gate voltage and current waveforms

3 TESTS AND RESULTS

The performance of the solid-state switch was studied with a line-type 5045 klystron modulator at ATF.

3.1 Test Circuit

Figure 4 shows a circuit diagram of the klystron modulator. The klystron modulator consists of an inverter high-voltage charging power supply, pulse-forming networks (PFNs) with a total capacitance of $0.81 \mu\text{F}$, a solid-state switch and a 1:15 pulse transformer. The power supply charges the PFNs up to 43 kV with a charging time of 18 ms. After a hold time of 1 ms, the switch is triggered and an output pulse is applied to the SLAC 5045 klystron. The anode voltage of the switch was measured with a high-voltage probe (Iwatsu model HV-60) and the anode current of the switch was measured with a current transformer (Pearson model 3025) which was installed in the return line of the PFNs.

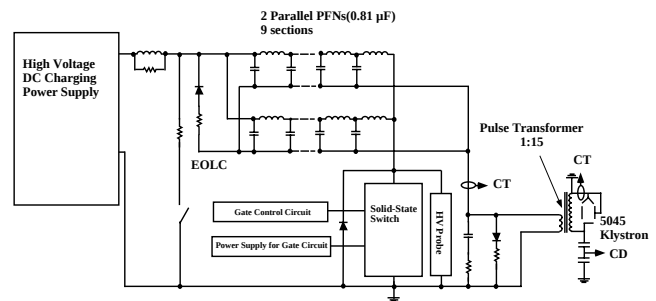


Figure 4: Simplified circuit diagram of the klystron modulator

3.2 Dead-Short Circuit Test

Prior to a performance test, a dead-short circuit test was carried out. To make a dead-short circuit, the primary side of the pulse transformer was shorted. Figure 5 shows the results at a PFN charged to 44 kV. The anode current oscillates and the peak reverse current reached 11 kA, which was twice the normal anode current. After 5 pulses, the forward leakage current characteristics of the solid-state switch were checked against the initial ones. There was not change.

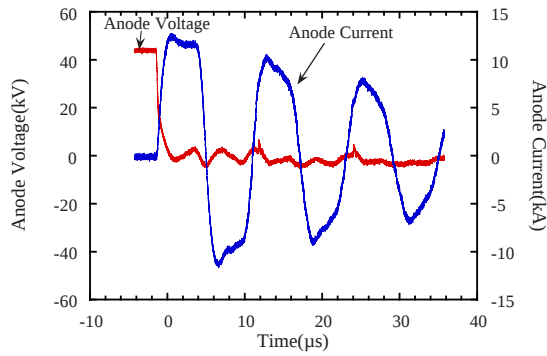


Figure 5: Anode voltage and current waveforms under the condition of a dead-short circuit

3.3 Test Results

The test was made at 25 Hz, limited by the charging capability of the inverter power supply. Figure 6 shows the typical switching voltage and current waveforms at a PFN voltage of 43 kV. A peak current of 5400 A, a maximum di/dt of 10 kA/μs and a pulse-width of 6 μs were obtained. The maximum di/dt value is limited by the circuit.

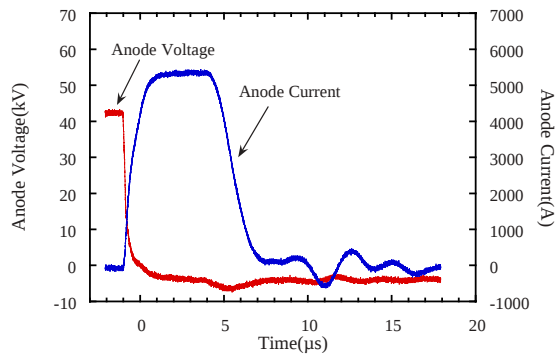


Figure 6: Anode voltage and current waveforms

A klystron arc-down occurred during testing. Figure 7 shows the anode voltage and current waveforms at klystron arc-down. It is found that klystron arc-down occurred in the back of the klystron pulse. Then, the forward leakage current characteristics of the solid-state switch were checked against the initial ones. There was not change.

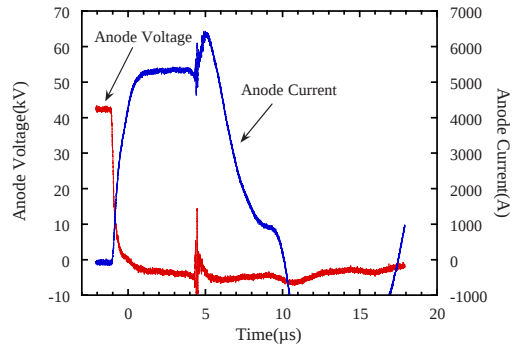


Figure 7: Anode voltage and current waveforms at klystron arc-down

4 SUMMARY

A solid-state switch using SI-thyristors was designed and tested with a klystron pulse modulator, and was successfully operated for about 5 M shots. After testing, the forward blocking voltage characteristics for all of the devices used in the switch were checked against the initial ones. There was not change. Future testing for a long time is being considered to establish the reliability of the solid-state switch.

5 ACKNOWLEDGEMENTS

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6 REFERENCES

- [1] JLC Design Study Group, JLC Design Study, KEK Report 97-1(1997).
- [2] A. Fukasawa et al., "Compact Hard X-ray Source via Inverse Compton Scattering Based on the X-band Linac" Proceeding of the 2nd Asia Particle Accelerator Conference, Beijing, China(2001)843.
- [3] N. Shimizu et al., "4kV Reverse Conducting Static Induction Thyristor," The 10th SI Device Symposium, SSID-97-6, 1997.
- [4] M. Akemoto et al., "High-Power Switch with SI-thyristors for klystron Pulse Modulators," Conference Record of the 2000 Twenty-Forth International Power Modulator Symposium, Norfolk, Virginia, USA (2000) 205.