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Development of a high-power solid-state switch using static induction thyristors for a klystron modulator

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ABSTRACT

We developed a solid-state switch with static induction thyristors for the klystron modulator of the L-band electron linear accelerator (linac) at the Institute of Scientific and Industrial Research, Osaka University. This switch is designed to have maximum specifications of a holding voltage of 25 kV and a current of 6 kA at the repetition frequency of 10 Hz for forced air cooling. The turn-on time of the switch was measured with a matched resistor to be 270 ns, which is sufficiently fast for the klystron modulator. The switch is retrofitted in the modulator to generate 1.3 GHz RF pulses with durations of either 4 or 8 μs using a 30 MW klystron, and the linac is successfully operated under maximum conditions. This finding demonstrates that the switch can be used as a high-power switch for the modulator. Pulse-to-pulse variations of the klystron voltage are measured to be less than 0.015%, and those of RF power and phase are lower than 0.15% and 0.1°, respectively. These values are significantly smaller than those obtained with a thyratron; hence, the stability of the main RF system is improved. The solid-state switch has been used in normal operation of the linac for more than a year without any serious trouble. Thus, we confirmed the switch's robustness and long-term reliability.

1. Introduction

Klystrons are widely used as RF power sources for particle accelerators, including electron linear accelerators (linacs). A klystron modulator is a power supply for a klystron, in which the pulse-forming network (PFN) is charged to a high voltage; then, a high-voltage and high-current square-pulse is generated using a high-speed switch called the thyratron [1]. The pulse is supplied to the klystron via a step-up transformer, and a high-power RF pulse is generated to accelerate the electron beam in the linac. Space, time, and energy stabilities of an electron beam that is accelerated with the linac are dependent on the stabilities of the RF power and its phase, and both of them depend on the voltage that is applied to the klystron [2]. Therefore, a modulator is designed and manufactured in such a way that the plateau of the high-voltage pulse is flat and the reproducibility of the pulse height is high.

Crucial factors that determine the stability of the modulator are the accuracy of the high-voltage power supply for the PFN and the stability of the high-speed switch for the discharge of the PFN circuit. An inverter-type high-voltage power supply was recently used for the modulator [3]; in this arrangement, the charging voltage of the PFN is determined by the amount of electric charge per pulse and the number of charging pulses from the power supply. Because it is difficult to raise the clock frequency of the inverter power supply substantially higher, a fractional accuracy of the order of 10^{-5} is attained by reducing the charge per pulse when the voltage of the PFN comes close to a set value. The thyratron is a discharge tube filled with hydrogen or deuterium gas. The thyratron can switch a current of several kA at a holding voltage of several tens of kV in the switching time of a few nanoseconds; therefore, thyratrons are widely used as switches for klystron modulators. The thyratron, however, has drawbacks in that it generates strong electrical noise, the gas pressure must be adjusted periodically, it can fire without any trigger (although this happens rarely), and the statistical fluctuation in the operation is

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unavoidable due to the use of discharge phenomena. To solve these problems, solid-state switches and klystron modulators that use them have been developed, although such modulators are not very common because only a few solid-state switches are commercially available that meet the specifications for klystron modulators.

The first klystron modulator with a solid-state switch for an electron linac was developed, to our knowledge, in the early 1990s at the FOM Institute for Plasma Physics for the FEL facility, FELIX [4,5]. The switch is made of 32 thyristors connected in series to operate at a maximum voltage of 40 kV and a maximum current of 2.6 kA. The following activities began increasing in approximately 2000 [6]. In Europe, ABB Switzerland Ltd. fabricated various types of solid-state switches using thyristors or Insulated Gate Bipolar Transistors (IGBTs) [7]. In the United States, Diversified Technologies Inc. developed solid-state switches using IGBTs for klystron modulators of the linac at MIT-Bates [8,9]. Applied Pulsed Power Inc. developed a switch with thyristors [10]. Stangenes Industries developed a Marx modulator without PFN using IGBTs [11]. Lawrence Livermore National Laboratory and Stanford Linear Accelerator Center developed a new type of modulator that has an inductive voltage adder topology and uses metal–oxide–semiconductor field-effect transistors (MOS-FETs) or IGBTs [12]. In Japan, a klystron modulator of the induction-adder type using IGBTs was developed at the High Energy Accelerator Organization (KEK) for the Japan Linear Collider (JLC) Project [13]. Another modulator of a different type with IGBTs was developed and used at the Superconducting RF Test Facility (STF) at KEK [14]. These semiconductor devices for switching, including thyristors, IGBTs, and MOS-FETs, have both advantages and disadvantages for meeting the specifications and requirements for various klystron modulators.

Another candidate for a semiconductor device that is suitable for the solid-state switch is the Static Induction Thyristor (SI-thyristor) because it has fast switching characteristics as well as a high holding voltage and a high current [15,16]. Two types of solid-state switches with different types of SI thyristors were developed for the JLC project and were successfully tested at KEK; these meet the specifications that the hold-off voltage is 45 kV, the peak current is 6 kA, the pulse duration is 6 μs, and the repetition rate is 50 pps using forced oil cooling [17,18].

The L-band electron linac at the Research Laboratory for Quantum Beam Science, which is attached to the Institute of Scientific and Industrial Research (ISIR), Osaka University, is a 40 MeV, 1.3 GHz RF linac that is operated for various research studies by means of pulse radiolysis in the time range of nanoseconds down to sub-picoseconds [19,20]. It also supports the development of and applications for a terahertz (THz) free electron laser (FEL) [21]. Among these studies, the FEL is most sensitive to the stability of the electron beam accelerated with the linac. To obtain a highly intense and stable FEL beam, the energy and the intensity of the electron beam must be constant in an electron pulse of several microseconds duration, and pulse-to-pulse intensity fluctuations are required to be small. To enhance the stability of the electron beam, the klystron modulator was upgraded in such a way that the fluctuations of the charging voltage of the PFN are reduced to 0.008% (peak-to-peak). Nevertheless, pulse-to-pulse fluctuations of the height of the high voltage pulse applied to the klystron are measured to be almost ten times greater than are those of the charging voltage. Because the thyratron is considered the source of the instability, we have developed a solid-state switch that is expected to be more stable.

In this paper, we will describe the development of the solid-state switch using SI thyristors and the evaluation of its performance in terms of the stability of the klystron voltage, the RF power and phase, and the energy of the electron beam.

2. Static induction thyristor

As mentioned previously, thyristors and IGBTs are commonly used for solid-state switches of klystron modulators. The switching times of these devices for high voltage and high current are, however, not sufficiently fast for our klystron modulator, providing the klystron with high-voltage pulses of either 4 or 8 μs duration. The SI thyristor is a type of PIN diode that is equipped with the gate [15]. The characteristics that are measured from a test sample for pulsed-power applications are reported to be as follows: the hold-on voltage is 5.5 kV, and the turn-on time is 35 ns, with di/dt=95 kA/μs [16]. Because these values are sufficient for our purpose, we decided to develop a solid-state switch using SI thyristors. Although they are not available on the market, we obtained SI thyristors by courtesy of Shindengen Electric Manufacturing Co., Ltd., which is developing such devices.

Two important specifications of the SI thyristors that we use are listed in Table 1, although the details are not available yet from the manufacturer: the maximum blocking voltage is 3.2 kV, and the maximum average current is 50 A (root-mean-square). We expect, however, that a much higher current can flow if the pulse duration is short and the repetition rate is not so high that the average power consumption in the SI thyristor does not exceed the value in the slow operation. Characteristics of an SI thyristor are measured with square pulses of 2 kV, 1 kA, and a 2 μs duration; these are generated with a five-stage PFN that has a characteristic impedance of 1 Ω and a matched terminator. Fig. 1 displays the results of the measurement, showing a voltage waveform between the anode and cathode of the thyristor and a current waveform through it. The voltage that is applied to the PFN is 2 kV, and no current flows at first. When the thyristor is turned on by a trigger signal applied to the gate, the voltage drops quickly and then gradually decreases to a constant level of approximately 100 V, whereas the current rises up quickly to 1 kA and then maintains a constant level of 0.82 kA. In this measurement, the switching time of the thyristor, which is defined as the time for a voltage change of from 90 to 10% of the initial value, is found to be 360 ns. The voltage between the anode and cathode is 96 V in the steady state; from this, the turn-on resistance is calculated to be 0.12 Ω in the steady state. The results of the measurement are summarized in Table 2.

Table 1
Manufacturer's specifications for the SI-thyristor.

Blocking voltage	3.2 kV
Average current (r.m.s.)	50 A

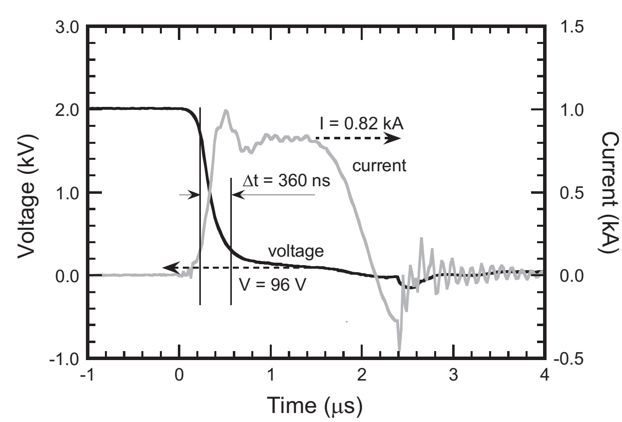

Fig. 1. Switching characteristics of a SI-thyristor measured with a five-stage PFN and a 1 Ω matched resistor to generate a 2 μs pulse.