A 100 kV FET Switch for a Klystron Anode Modulator

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Abstract

To replace vacuum tubes in klystron anode modulators, a semiconductor switch which consisted of 125 MOSFETs and had a unique dual latch gate drive circuit was designed and tested utilizing a dummy load. The test included a voltage distribution measurement, single pulse switching test, and continuous mode operation test. All the tests were successfully completed and the switch exhibited the performance as expected specifications. For the next step, we are planning to combine the switch with an actual klystron.

1 Introduction

Vacuum tubes have been widely used for anode modulators of klystrons. However, a vacuum tube has a drawback of limited service life. JAERI and Toshiba have started to develop an all-solid-state modulator and we are planning to apply it to the future accelerator system. The key to the success is the development of the semiconductor switch, the specifications of which are summarised in Table 1. One of the features is a high voltage such as 100 kV. This feature requires a series connection of over a hundred switching devices. Another feature is long pulse width such as 7 ms. This means the difficulty of using usual pulse transformers for triggering. To solve this problem, we developed a unique dual latch gate drive circuit.

This paper describes the design of the switch and the test result of dummy load switching test.

Table 1. Specifications of the Switch

Voltage		DC 100kV
Current	peak	1 A
	steady state	3 mA
Pulse Repetition Rate		50 pps
Pulse Width		7 ms
Rise/Fall Time		300 μs

2 Switch Design

2.1 Switching Device Selection

Typical electrical specifications of various kinds of semiconductor switching devices are shown in Table 2. From the viewpoint of voltage, GTO thyristor is the best among them, but it is too large and too expensive. The same argument can be applied to IGBT. Voltage of the transistor is too low. Therefore MOSFET is considered to be the best by taking every factor into consideration.

Table 2. Comparison of Various Semiconductor Devices

Device	Transistor	GTO Thyristor	MOSFET	IGBT
Type Name	2SC5144	SG3000J X24	OF11M10 0A	ST1000 EX21
Voltage	600 V	6000 V	1000 V	2500 V
Current	20 A	3000 A	11 A	1000 A
Turn On Time	not specified	10 μs	59 ns	2.2 μs
Turn Off Time	2.65 μs	30 μs	84 ns	1.7 μs
Drive	Current	Current	Voltage	Voltage
Judgement	×	×	○	×

2.2 Gate Drive Circuit

For the triggering of series connected switching devices, three basic approaches can be taken. 1)Individual gate drive circuit triggered by light. This method provides the completely isolated triggering for each device. But this method is too complicated and it requires isolated power supply for each gate driver. 2)Slave triggering. It is a technique for obtaining turn-on of all the devices by applying a trigger signal to only one device. This method involves time delay and transient over-voltage substantially. So it is not suited to many series connection case. 3)Pulse transformer. This method is the simplest way for triggering. But it is difficult to generate long pulse when the switching device is self-commutation device such as MOSFET because of the saturation of the pulse transformer. To solve this problem we adopt a dual latch gate drive circuit as shown in Fig. 1.

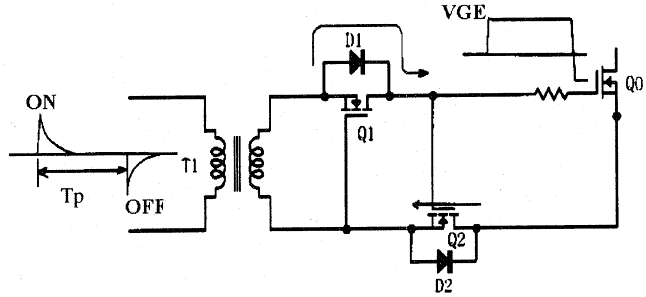

Fig.1 Principle of the dual latch gate drive circuit.

The principle of the dual latch gate drive circuit is as follows. Pairs of positive and negative pulses are applied to the primary of the pulse transformer, where the time delay Tp from the positive pulse to the negative pulse is the pulse width. The pulse shape of each pulse is steep rise and slow decay. We now consider the circuit function when a positive pulse is applied. FET Q1 is negative biased so that it stays in off state, while FET Q2 is positive biased so that it turns on. Therefore the current flows through the diode D1 which is a parasitic diode of Q1 and the FET Q2 as indicated by the arrows in Fig. 1. Consequently the main FET Q0 is positive biased and it turns on. When the input pulse is removed, the FET Q1 and Q2 are zero biased and they keep off state. Therefore the gate charge of the FET Q0 remains and it keeps on state. When a negative pulse is applied FET Q0 is negative biased by the contrary effect.

As described above, a long pulse can be easily obtained by utilising this dual latch gate drive circuit.

2.3 Switch Construction

The switch consists of 125 FETs, which are divided into 5 groups each of which is mounted on a circuit board. The schematic diagram of the circuit board is shown in Fig.2. Primary windings of the transformers are connected in series and connected to the secondary winding of another pulse transformer, the primary winding of which is connected to external terminals of the circuit board. At the center point of the series connected circuits, the primary and secondary circuits are connected so as to reduce the electrical stress between windings.

Between circuit boards, we connected resisters which damp the surge current caused by the discharge of stray capacitors between boards. The value of them is 80 Ω each.

Five circuit boards are stacked, assembled in a frame, and mounted in an oil tank. Figure 3 shows the circuit boards and the frame. In this figure, two horns appeared above are terminal bushings.

3 Test Results

3.1 Voltage Distribution Characteristics

Before the switch was immersed in oil, a voltage distribution

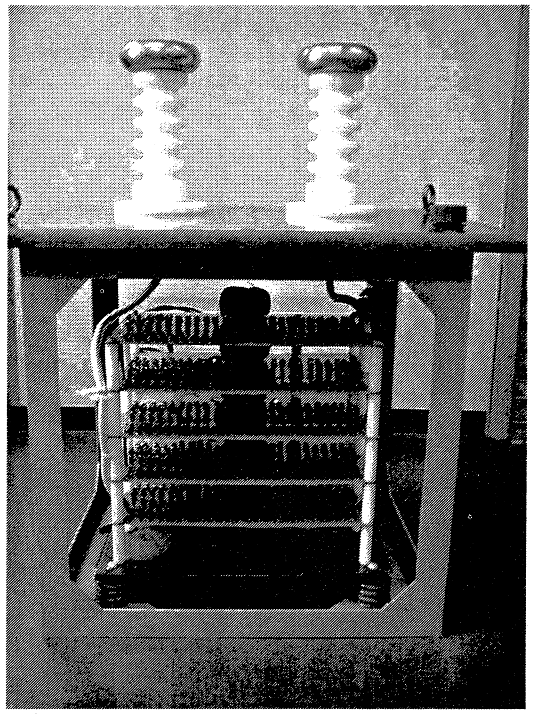

Fig. 3. The switch assembled in the frame.

was measured. The result is shown in Fig. 4. Deviation was within 3% and abnormal voltage distribution could not be observed.

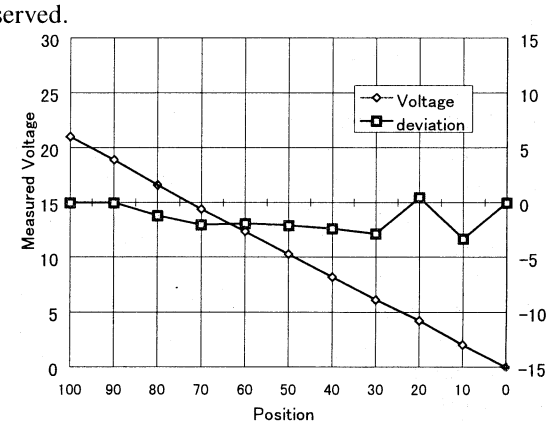

Fig. 4. Voltage Distribution Characteristics

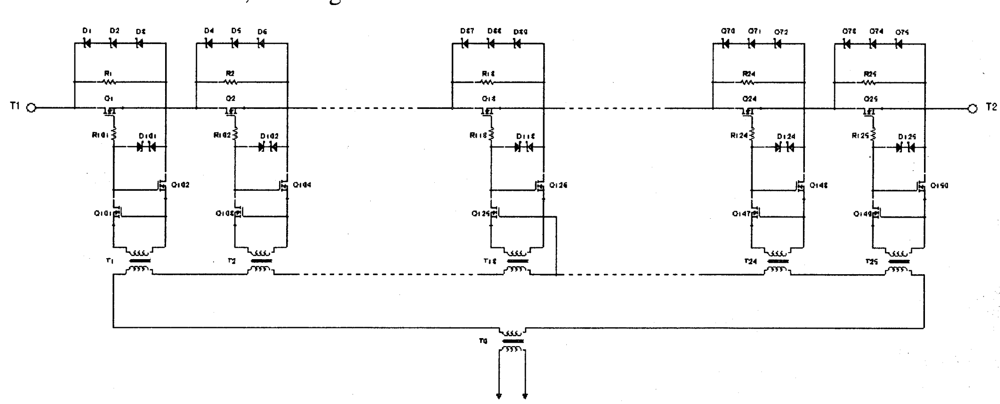

Fig. 2. Schematic diagram of a switch circuit board.

3.2 Single Shot Switching Test

Figure 5 shows the switching test circuit, where R1, R2, and C1 are a dc current limiting resistor, a pulse current limiting resistor, and a simulated stray capacitance, respectively. In addition to them, a surge blocker was connected between the cathode terminal and the earth terminal to reduce the surge current caused by the discharge of a stray capacitance between the switch and the oil tank.

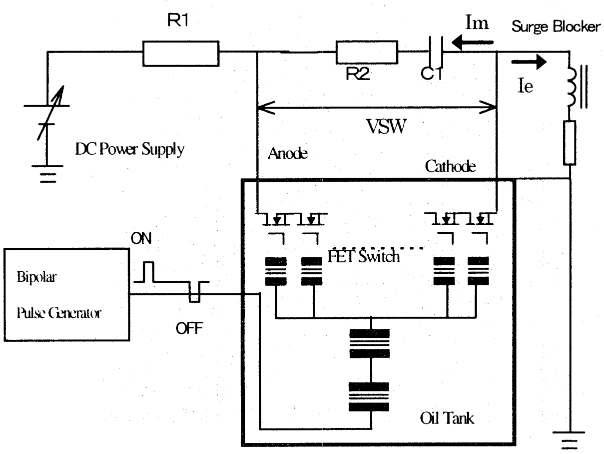

Fig. 5. Switching test circuit.

Switching waveforms are shown in Fig. 6, where Vsw, Im, and Ie are a switch voltage between anode and cathode, a switch main current, and a switch stray current, respectively and Fig. 7. We observed fast transient current, which was caused by the discharge of stray capacitance, at a very early switching period (<1 μs). The peak value of the transient current was about 8 A, which increased if we removed the surge blocker.

Ignoring fast transient, peak value of the switch was 2 A, which meets the specification. Also from Fig. 7, we can confirm the pulse width of 7 ms, which meets the specification too.

Switching losses were also measured from voltage and current waveforms by integrating the product of the instantaneous value of them and were estimated to be 220 mJ/pulse.

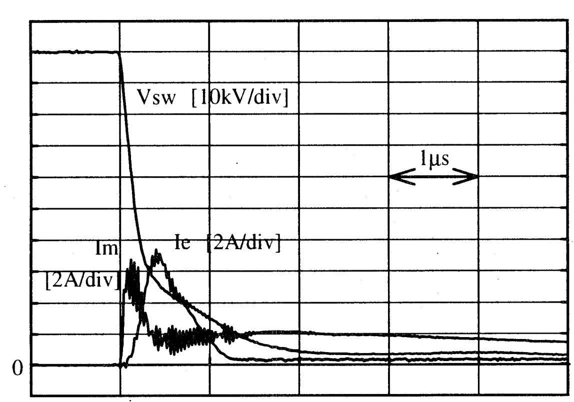

Fig. 6. Switching waveforms.
R1:33 MΩ, R2:60 kΩ, C1:250 pF

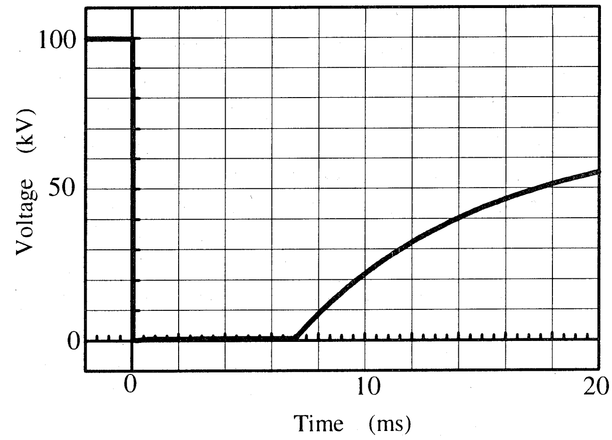

Fig. 7. Voltage waveform.

3.2 Continuous Operation Test

Finally we executed the continuous operation test, in which circuit parameters of R1 and C1 were varied to attain high repetition rate of 50 pps. Fig. 8 shows the voltage waveform of the switch. After 2.5 hour continuous operation, mean temperature rise of the switch was only 1.4 °C and no significant variation of the waveforms were observed.

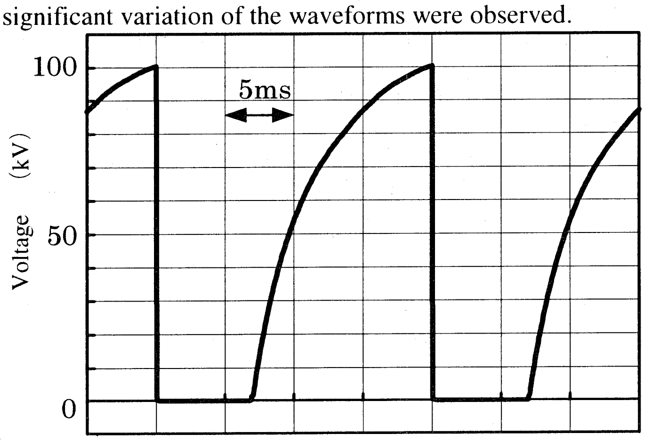

Fig. 6. Voltage waveform at 50 pps.
R1:20 MΩ, R2:60 kΩ, C1:100 pF

5 Conclusion

To replace vacuum tubes in klystron anode modulators, a semiconductor switch which consisted of 125 MOSFETs and had a unique dual latch gate drive circuit was designed and tested utilizing a dummy load. All the tests were successfully completed and the switch exhibited the performance as expected specifications. For the next step, we are planning to combine the switch with an actual klystron.