DESIGN OF A GATE-TURN-OFF (GTO) SWITCH FOR PULSED POWER APPLICATION*

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Abstract

A Gate-Turn-Off (GTO) thyristor switch and its gate drive circuit have been developed as a replacement for the thyratron switch used in the positron converter solenoid lens power supply at the Advanced Photon Source (APS) to deliver a current pulse of 6000 A at 60-Hz repetition rate. This paper discusses the characteristics of the GTOs under consideration, the gate drive circuit, and some test results.

1 INTRODUCTION

In the APS linac, a solenoid coil placed downstream of the tungsten target focuses the positron beam. A current pulse goes through the solenoid coil to produce the focusing magnetic field. The current pulse is generated by a resonant pulse generating circuit[1], as shown in Figure 1. The switch closes to discharge a capacitor bank into the solenoid coil to produce the required current. The design specification calls for a current pulse with an amplitude of 6000 A and a 10-μs base width. The voltage required to achieve this current is about 9400 volts.

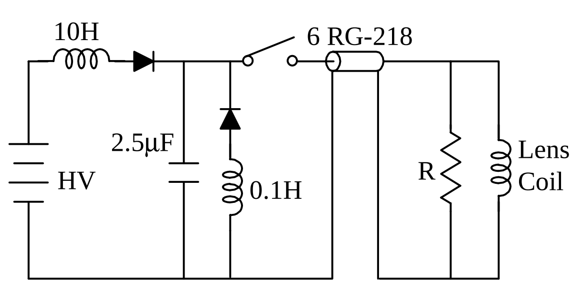

Figure 1. Circuit diagram of the pulser.

A deuterium-filled ceramic thyratron, EEV CX1174, has been used as the switch to initiate the discharge. Due to the resonant nature of the circuit, a reverse voltage, close to 80% of the initial forward voltage, appears across the thyratron immediately after the current pulse. This negative voltage is dangerously close to the maximum allowable reverse voltage of the thyratron. Any increase in the current will cause the thyratron to backfire (not able to block the reverse voltage). The direct consequence of the thyratron backfire in operation is to trip the interlock to shut down the power supply because of increased charging current. Also, the backfire can be detrimental to the thyratron's lifetime. To stop thyratron backfiring, the supply has to be operated at a reduced current level; however, this is not desirable for operation. Even with the reduced current, there have been two thyratron failures. Each time the failed thyratron had only 200 million pulses, equivalent to a little more than 900 hours, 60 Hz continuous operation. To improve the reliability of the operation, a new switch is needed to replace the thyraton.

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2 GTO SWITCH

The moderate requirements (6000 A and 2 kA/μs initial current rise rate) of the current pulse make it possible to use solid state devices as a replacement for the thyratron. The possible choices are either a thyristor-diode combination or GTO thyristors. The GTOs seem to be a better choice since they can be turned off by a negative gate pulse and, hence, make the circuit less complicated.

A 47-mm symmetrical type GTO, WG10045R36, is recommended by the manufacturer, Westcode. It is rated at 4.5 kV forward blocking voltage and 3.6 kV reverse blocking voltage. We chose this GTO because a similar 66-mm GTO has been studied by E. Carlier et al., at CERN for a 20-kA pulse with positive results.

2.1 *Test Set-up*

Ten GTOs were ordered. After receiving the GTOs, initial bench tests were done to study their characteristics. To simulate the conditions these GTOs will see in the real circuit, a test circuit was set up to produce a 10~12-μs half-sine current pulse with a single or multiple GTOs. The test circuit is shown in Figure 2. The inductor, L_s, is mostly stray inductance in the connections. Since the voltage across the capacitor will reverse after each pulse, a large resistor, R, several hundred ohms, has to be used in the charging line to protect the high voltage supply. Because of its low power rating, the resistor limits the test to the single-shot mode or very low repetition rate.

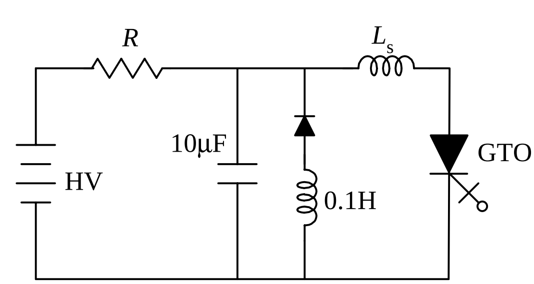

Figure 2. GTO test circuit.

2.2 GTO Switching Characteristics

Figure 3 shows a set of GTO voltage and current waveforms with associated switching losses. These waveforms show the GTO's switching characteristics, such as the turn-on delay, turn-on time, and voltage drop. These characteristics are important in determining if they are suitable for this particular application.

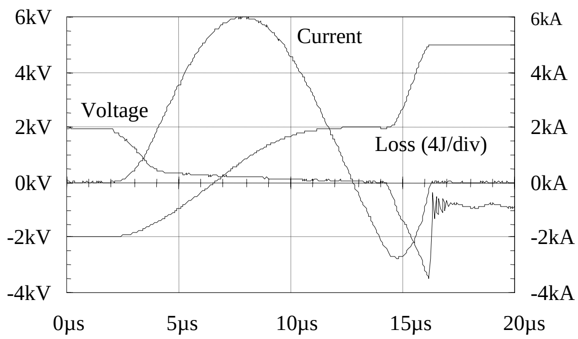

Figure 3. GTO voltage, current, and switching losses.

A. Turn-on Delay

The GTO's turn-on delay, t_d, is defined as the time between when the gate current rises to 10% of its peak and when the GTO anode voltage falls to 90% of its initial level. The tests show that t_d depends mostly on the current level. Figure 4 shows the measured average turn-on delay versus the peak current and the maximum deviation. The maximum deviation is over 100 ns, big

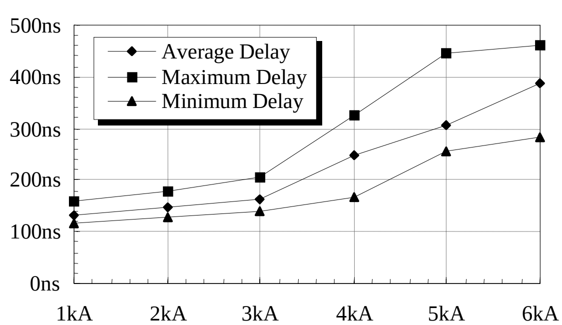

Figure 4. GTO turn-on delay versus peak current.

enough to cause the voltage on the slower GTOs to jump up, as shown in Figure 5, if no measures are taken to prevent it. Two methods were tested to improve the voltage sharing during the turn-on process. One was to adjust the timing of the gate pulse of each GTO to compensate for differences in turn-on delay. The other was to use snubber capacitors to prevent instant voltage change. Figure 5 shows voltages of two GTOs with less than 40-ns turn-on delay difference connected in series. In this case, a 50-ns adjustment in gate pulse could not eliminate the instantaneous voltage increase on the slower GTO. However, when a 0.25-µF snubber capacitor was used with each GTO, the voltage-sharing problem was completely eliminated. The shortcoming of using snubber capacitors is that they reduce the GTO turn-on

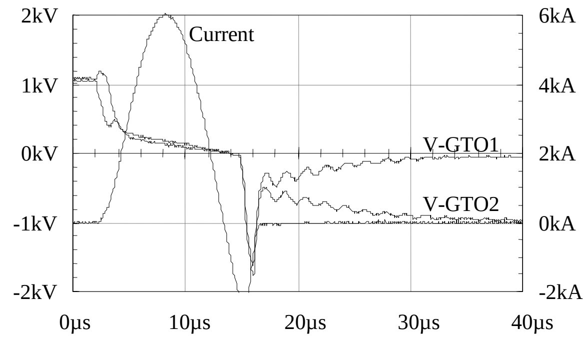

Figure 5. Two GTOs in series.

speed and, consequently, increase the switching losses. The best way to solve the problem is to adjust gate timing for large delay differences and use a small snubber capacitor to compensate for small differences.

B. Turn-on Time

Westcode defines the GTO turn-on time as the time from 10% of gate current to 10% of the anode voltage. Our tests show that for the first 2 µs after receiving the gate pulse, the GTO's impedance decreases rapidly. When the anode voltage falls to 20%, the rate of change slows down dramatically. By the time the voltage falls to 10%, the current is already at the peak. This slow voltage change rate is the main contributor to high turn-on energy losses, which limit the GTO's operating frequency.

C. Voltage Sharing

Since more than one GTO will be used in series, it is important that the GTOs share the voltage in both forward and reverse directions. Our tests show that in the forward direction the GTOs share the voltage reasonably well even without snubber circuits. A 10-MΩ snubber resistor across each GTO can make the voltage uniformly shared by the GTOs. In the reverse direction, however, the GTOs have large differences in the impedance in steady state. Some GTOs have such low impedance that they do not take any reverse voltage when used in series with others. In fact, some impedance is so low that a 1-MΩ snubber resistor can not improve the sharing at all. The voltage waveforms in Figure 5 are obtained under such conditions.

It appears that the reverse voltage sharing capability is closely linked to the GTO's peak reverse current, I_{RRM}. Out of ten GTOs, seven have reverse currents, measured at 25ºC by Westcode, in tens of microamperes, and the other three in hundreds of microamperes. Only GTOs with similar reverse current can share the reverse voltage.

D. Switching Losses

The bench tests show that these GTOs are relatively slow in turn-on and have high forward voltage drops. Hence, they have large switching losses. The measured total switching losses are as high as 14 joules per pulse, as shown in Figure 1. The loss during the first 2 µs is only

10% of the total loss. About 50% of the losses occur during the time when the GTO voltage drop changes slowly; another 40% happens during the turn off. The turn-off switching losses largely depend on the external circuit and are independent of the number of GTOs connected in series. When two GTOs tested in series, the total energy loss increased by 4 joules. All the increases happened during the turn-on process and are due to the increased voltage that is required to compensate for the additional GTO forward voltage drops. The average loss in turn-on is 6.5 joules per GTO. The total turn-off losses are about the same as when only one GTO is used.

Seven GTOs are planned to be used in series to handle the voltage with safe margin, especially in the reverse direction. Based on the bench test, the predicted total energy loss is between 50 and 60 joules per pulse. This means more than 3-kilowatt power dissipation in GTOs if operated at 60 Hz. Adequate cooling will be very important to prevent the GTOs from overheating.

3 GTO GATE DRIVE

3.1 Multiple-Channel Timing Circuit

A multiple-channel timing card is designed to generate on/off trigger pulses for each GTO with proper delays for each edge with respect to the master trigger signal. The output pulse of each channel can be up to 12.75 µs wide. The leading edge is for the turn-on, and the trailing edge is for the turn-off. The key component of this circuit is an Altera EPM8542 EPLD that can be programmed independently for each channel. The delay timing information is coded with an 8-bit dip switch. A 4-bit dip switch controls which channel is to be programmed. A toggle switch is used to indicate whether it is for leading edge or trailing edge. The timing information can also be pre-programmed in the EPLD as the default value. A 20-MHz clock is used in the circuit, resulting in 50-ns minimum adjustment step. For finer adjustment, a faster clock and a longer dip switch can be used; however, an EPLD with a larger capacity may be needed.

Fiber optic links are used for both input and output to provide the high voltage isolation and to eliminate the electromagnetic interference.

3.2 Gate Drive Circuit

A direct drive design is used in the gate drive circuit to eliminate the stray inductance of the transformer coupling. The isolation between high voltage and low level electronics is provided by an isolation transformer, which also works as a part of the DC/DC converter. For turn on, Westcode recommended a current pulse more than 75 A, many times more than what is required for general use, to minimize the spread in the GTO turn-on delay. The amplitude of the turn-off pulse is mainly limited by the capacity of the power supply. A MOSFET H-bridge is used to drive the GTO gate. To reduce the voltage loss in the switch, each switch has two MOSFETs in parallel. The power to the drive circuit is delivered by a PWM controlled Fly-back DC/DC converter operated at 95 kHz. Figure 6 shows a gate pulse and Figure 7 shows the block diagram of the gate drive circuit.

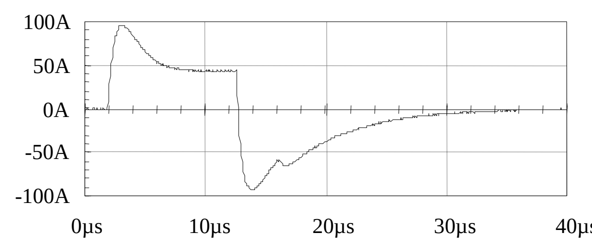

Figure 6. GTO gate current.

4 CONCLUSION

These GTOs can deliver more than 6000-A pulses although they are relatively slow and have high on-state voltage drops. The switching losses are greater than expected, but can be minimized by properly designed gating control and snubber capacitors. The initial tests indicate that they can be operated at 60 Hz with adequate cooling. Their lifetime should be much longer than that of a thyratron switch.

REFERENCES

[1] G. Stange, “An Inexpensive Positron Converter of High Reliability and High Yield,” *IEEE Transactions on Nuclear Science*, Vol. NS-26, No. 3, June 1979.

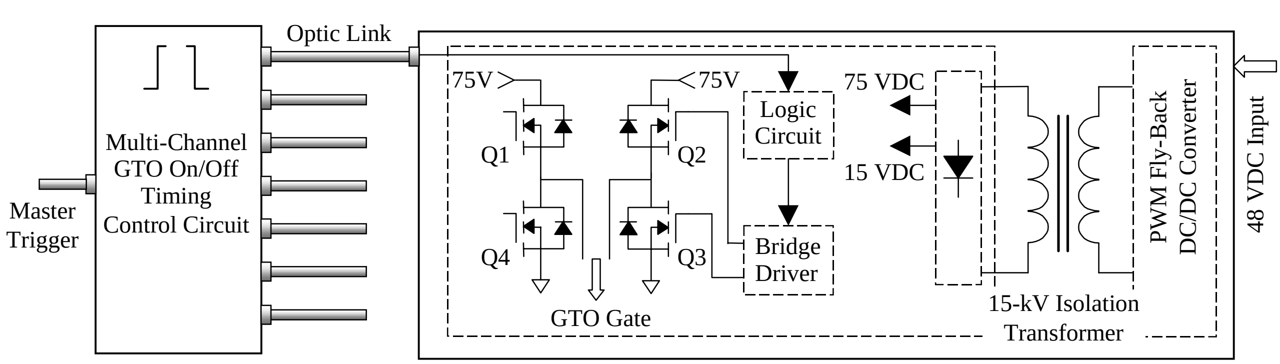

Figure 7. Block diagram of the GTO gate drive.