High Power Solid State Switch Module[*]

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Abstract

A high voltage, high di/dt, solid state switch module has been developed. This compact module can be used to replace thyratrons in high power modular applications. The module contains multiple silicon thyristors packaged in a low inductance series configuration with a strip-line output connection. A self powered gate drive is triggered by a 15V, 1A pulse. Each module has a rating of 8000 volts and is capable of conducting 6000 amperes over a 10 micro-second pulse with maximum repetition rates of over 120 hertz. The modules have demonstrated a 70ns turn-on delay time and operation at 25 kA/us, limited by the external circuit. Switches rated for over 50kV have been assembled using a modular design to easily connect the modules in series. These modules are suitable for pulse modulators for high power RF and microwave amplifiers used in particle accelerators, radars, medical and defense applications, medium and high power lasers, pulsed magnet drivers, and other high power applications. The performance of the modules under normal and fault conditions is described.

I. BACKGROUND

Development of solid state replacements for high power switching applications presently accomplished primarily by gas type switches has been attempted for some time. Previous work [1] has demonstrated the feasibility of this achievement in a volume comparable to that of the gas type switches to be replaced, using small, high voltage thyristors specifically designed for short pulse, high current applications. This paper describes the performance of a compact module developed using thyristors different than those described in Ref 1.

This solid state switch module consists of two silicon thyristors in series, designed specifically for high di/dt, high voltage, pulsed power applications. The module can be provided with a self powered gate drive circuit, an air-cooled electrically-isolated heat sink, and a clamp for connecting to the low inductance high current strip-line. The self powered gate drive circuit connects directly to the module and requires only a 1 ampere, 15 volt, trigger signal. The electrically-isolated air-cooled heat sink can be floated with the module for high voltage switching applications. Together these provide a compact high-power solid state switch.

The silicon thyristors are n-type with gates similar to those found in traditional GTO thyristors. They are designed for high peak current and low on-state voltage drop, combining the performance of SCR type thyristors with high di/dt capability. These silicon thyristors are developed as a replacement for gas type switches commonly used in pulsed power applications.

The size of the module, combined with its low internal inductance, allows for easy assembly of high voltage switches. For example, using 9 modules, a 50kV solid state switch has been assembled, capable of replacing a 50kV thyratron and occupying no additional volume.

II. MODULE CHARACTERISTICS

Two thyristors in series provide increased voltage stand-off capability. Voltage balancing across the two thyristors is assured by the self powered gate drive circuit, allowing the module to achieve the combined voltage rating of 8000 volts. Module maximum ratings are listed in Table 1.

Table 1: Module Maximum Ratings

Rating	Value
Peak Non-Repetitive Off-State Voltage	8000V
Peak Repetitive Off-State Voltage	7000V
Peak Non-Repetitive Current	14000A
Peak Repetitive Current	7000A
Peak di/dt	30kA/µS
Maximum RMS On-State Current	100A
Maximum Operating Junction Temperature	120ºC
Peak Reverse Voltage	10V

Module operational characteristics are listed in Table 2. Actual performance of the module depends on several factors, including the rate of rise of the trigger signal, inductance of the circuit and frequency. The test circuit for the operational characteristics in Table 2 was a balanced 1.5 microfarad pulse forming network providing a 3 microsecond square pulse into a 1 ohm load. The

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actual resistance used was 0.7 ohms to assure a slight reverse current. Tj is the junction temperature.

Table 2: Module Operational Characteristics

Rating	Value
Trigger Isolation Voltage	60kV
Module Thermal Impedance	0.03ºC/W
Gate Drive Circuit Shunt Capacitance	6.8nF
Typical Leakage Current (Tj=80ºC)	40µA
Turn-On Delay	60nSec
Turn-On Delay Jitter	<2nSec
Turn-Off Time (Tj=80ºC)	0.8mSec

These ratings and operational characteristics demonstrate that the module is a suitable replacement for gas type switches. The module, seen in Figure 1, has overall dimensions of 80mm by 62mm by 13mm. The self powered gate drive circuit increases the overall height to 40mm and the overall width to 76mm. These dimensions are compact enough to allow easy assembly of multiple modules in series to create even higher voltage switches.

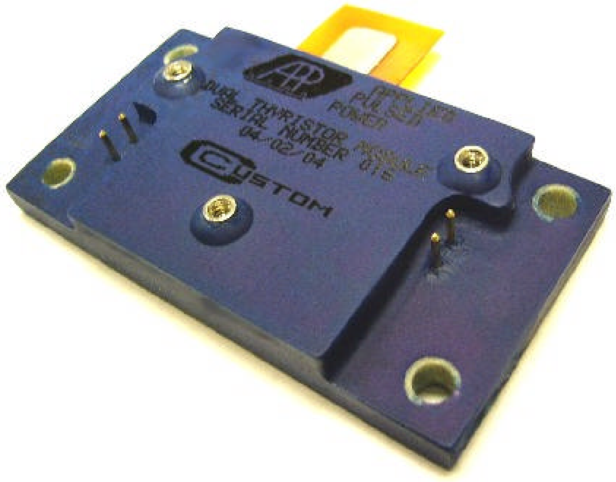

Figure 1. Picture of Module

III. MODULE DESIGN

The factors controlling the design of the module included thermal characteristics, electrical connectivity to the self-powered gate drive circuit, thermal resistance to a heat sink, mounting to the aforementioned heat sink, and low inductance, high current contacts for external electrical connections. Internally, the module had to provide both as low an inductance and as large a voltage isolation as possible.

To limit the effects of thermal stress on the module, components were chosen whose coefficients of thermal expansion matched that of silicon. Insulating ceramic materials, such as aluminum oxide and aluminum nitride, and encapsulants, such as Hysol® FP4651, are suitable. By using materials that have similar coefficients of thermal expansion, there is much less thermal stress on the components in the module.

Three threaded inserts and four pin terminals on the top of the module provide electrical connectivity to the self powered gate drive circuit, allowing for separation between the gate return current path and the cathode current path. The inductive voltage drop across the cathode lead, which can be greater than 100 volts for fast rising currents, is removed from the gate circuit, easing gate drive requirements. Also, these connections provide the power to trigger the gates as well as maintain voltage balance between the two thyristors.

To provide as low a thermal resistance as possible, the silicon thyristors are soldered directly to a metallic pad bonded to a ceramic substrate which forms the base of the module. Using four screws at the corners of the module to provide a minimal clamping force, this ceramic substrate is kept in contact with the heat sink. The metallic pad, solder, and ceramic substrate, are kept minimally thin to provide as low a thermal resistance from the thyristors to the heat sink as possible. The minimum for the ceramic thickness is determined by the voltage hold-off required between the thyristor and heat sink.

One of the problems in manufacturing solid state modules such as these is the large size of the solder areas, creating the possibility for formation of voids in the solder joints between the thyristor and the metallic pad. To assure that these voids are as small and infrequent as possible, the metallic pad and the thyristor are gold plated. The metallic pads are tinned prior to assembly and flux use is kept to a minimum. Further, the solder joints are made in an environmentally controlled re-flow oven. This process creates solder joint with a small void volume.

Low inductance is desirable to allow for high di/dt operation. The strip line provides a low inductance, high current connection to the circuit. Also, the module's interior electrical connections are designed to have very low inductance, allowing the module to be used in high di/dt operation.

IV. SELF POWERED GATE DRIVE

The trigger for the switch is provided by a self powered gate drive circuit [2]. This circuit uses energy provided by the off-state voltage and can be triggered using a small pulse transformer or an optical signal. This enables both thyristors in each module to be triggered from one 15 volt, 1 ampere signal. This approach makes possible compact high voltage switches requiring multiple modules connected in series and floating at potentials of up to 50 kV. Alternate approaches require separate isolated power supplies or large low leakage inductance pulse transformers to directly trigger the thyristors. The self powered gate drive circuit both assures balanced voltage between the two thyristors and provides the power to trigger the switch.

The electrical trigger signal is sent to the primary of a small pulse transformer. There are a number of secondary windings equivalent to the number of thyristors being triggered. Each secondary sends a low voltage trigger to a solid state transistor, such as an IGBT or MOSFET, discharging a capacitor through the gate of the thyristor. This produces a large, fast rising gate current to insure rapid turn on of the full area of the thyristor. The gate capacitor is connected in series with a snubber capacitor and is charged while the switch is in the off state, thus eliminating the need for external isolated power sources.

Further, the gate drive circuit assures voltage balance between the two thyristors. The threaded inserts provide electrical connection to the anode and cathode of both thyristors, across which are high value resistors used to compensate for variations in thyristor leakage current. Measured values of thyristor leakage current have ranged from under 20 microamperes up to 100 microamperes at T_J=100°C.

V. MODULE TESTING

The standard test circuit consisted of a 1.5 μF, 3 μsec, 5 stage, type E, pulse forming network (PFN) matched to a 0.9 ohm load. This PFN was used to test the module at pulse repetition rates of up to 120 hertz. In general, a 0.7 ohm load was used to assure a slight reverse current. A separate 1.65 μF, 3 μsec, 1 ohm PFN was used to test the modules for single pulse operation. This circuit was used with load resistances ranging from 0.1 ohm to 0.9 ohm. A third test circuit was used to investigate turn-off time. This was a simple RC circuit with a resistance of 1.1 ohm and a capacitance of 0.25, 0.5, or 1 μF.

A. Testing Turn-On Delay Time

An important characteristic of a solid state or gas type switch is the delay between the trigger pulse and the change of the switch to a conducting state. To measure this delay time, the module was tested using the 1.68 μF PFN with a load resistance of 0.9 ohms measuring the current to the gate as compared to the forward blocking voltage and the current in the load. Figure 2 shows an example of one of these tests at a 6500 volt charge.

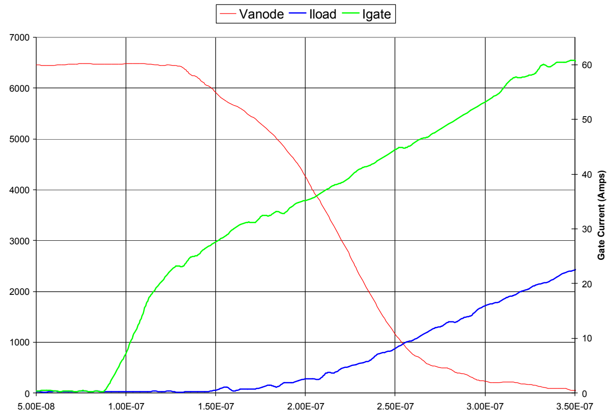

Figure 2. Gate and Load Current and Anode Voltage versus Time

B. Testing at Different Forward Blocking Voltages

One problem with many solid state and gas type switches is a variation of turn-on characteristics with forward blocking voltage, resulting in potentially undesired variation in the turn-on time. Each module was tested at differing forward blocking voltages using both the 1.5 and 1.68 μF PFN. Figure 3 shows several load current waveforms from different forward blocking voltages using the 1.68 μF PFN with a load resistance of 0.9 ohms. This data shows that there are only small differences in turn-on delay and turn-on characteristics versus voltage.

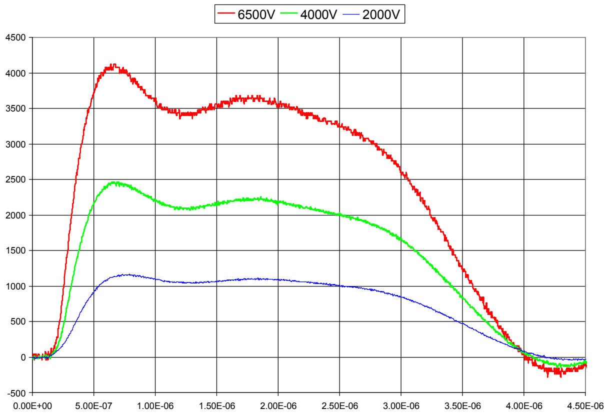

Figure 3. Load Current versus Time for Different Forward Blocking Voltages

The same type of test was performed with the 1.5 μF PFN. Figure 4 again shows several load current waveforms from different forward blocking voltages. However, the zero point of the time base is placed at the point where the current reaches the same level. These tests were done using two modules in series.

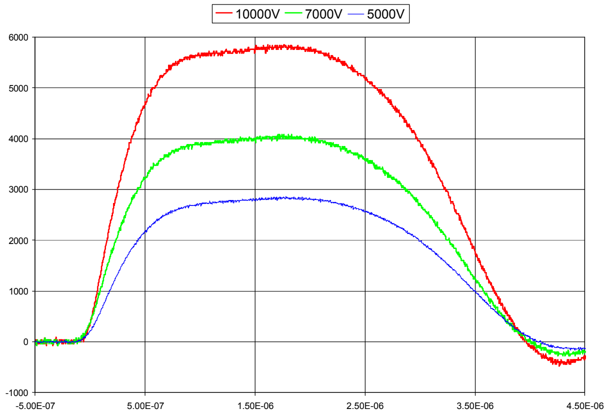

Figure 4. Load Current versus Time for Different Forward Blocking Voltages for Two Modules in Series

Another important characteristic for switches is the performance under fault conditions. To simulate a low impedance load fault, tests were performed using the 1.68 μF PFN with a 0.1 ohm load resistance. This results in a large reverse current through the switch as seen in Figure 5. Although the switch impedance is greater while conducting the reverse current, no switch modules were damaged from these tests.

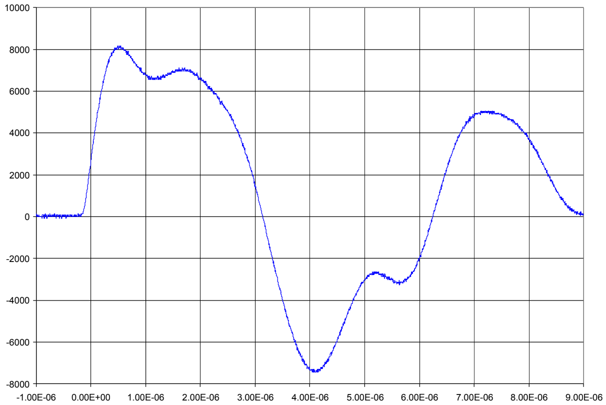

Figure 5. Load Current versus Time for a Simulated Fault Condition, PFN charged to 6.5 kV.

C. Testing of Turn-Off Time

The turn-off time is defined as the minimum time after the switch stops forward conduction that forward voltage can be reapplied without causing the solid state device to return to a conducting state. [3] This is an important characteristic, as it affects the maximum repetition rate of the solid state device. The parameters that effect turn-off time in our module are:

1. Junction Temperature
2. Forward Current Amplitude
3. Rate of Decay of Forward Current
4. Reverse Current Amplitude
5. Reverse Voltage Amplitude
6. Rate of Reapplication of Forward Blocking Voltage
7. Forward Blocking Voltage
8. Gate Impedance

To characterize the module versus these parameters, several tests circuits were used and the turn-off time versus temperature measured. Figure 6 shows the results of several of these measurements. The first two results are using the same RC test circuit, a 0.5 µF capacitor charged to 2000 volt charge with a 1.1 ohm resistance, for two different modules. The third test used a 1 µF capacitor and the forth test used a 0.25 µF capacitor, both at a 2000 volt charge. The last three tests used the 1.68 µF PFN. The fifth test was at 2000 volt charge. The sixth test was at 3000 volt charge. Lastly, the seventh test was at 2000 volt charge but with twice the reapplication rate of forward blocking voltage.

As can be seen from the data in Figure 6, turn-off time is proportional to junction temperature for all of the tests. The data indicates that the next parameter with the most effect on the turn-off time is the rate of reapplication of forward blocking voltage. This can be seen in the linear increase from the data for the first six tests to the seventh test.

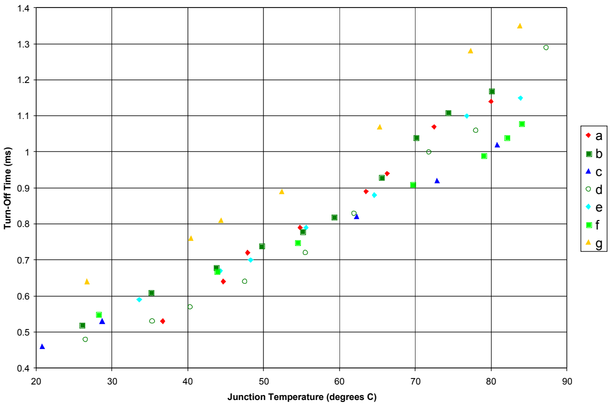

Figure 6. Turn-off Time versus Temperature

The effect of the gate impedance was also tested separately. This experiment was done using the 1.68 µF PFN at a charge of 6500 volts. With 35 ohms across the gate, the turn-off time was 0.52 milliseconds at room temperature. However, with 10 ohms across the gate, the turn-off time was 0.42 milliseconds at room temperature.

The testing determined that the three most important parameters affecting the turn-off time for this module were the junction temperature, the rate of reapplication of forward blocking voltage, and the gate impedance. The gate impedance is part of the gate drive circuit, and is chosen to provide fast turn-off times. The other two parameters are dependant on the application. These parameters limit the trigger repetition rate due to the limits caused by the rate of reapplication of forward blocking voltage and by power deposited in the silicon raising the junction temperature.

VI. SUMMARY

We have described a compact solid state switch capable of high power operation suitable for replacing gas type switches currently used in pulsed power.

VII. REFERENCES

[1] S. Glidden, "High Voltage, High Current, High di/dt Solid State Switch" in Proc. Pulsed Power Plasma Science 2001, June 2001, p. 1043.

[2} S. Glidden, "Compact High Voltage Solid State Switch", United States Patent US 6,624,684 B2 (2003)

[3] F. W. Gutzwiller (editor), SCR Manual 4rth Edition, Syracuse, NY: GE, 1967