COMPACT, HIGH CURRENT, HIGH VOLTAGE SOLID STATE SWITCHES FOR ACCELERATOR APPLICATIONS

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Abstract

Most switches used for high current, high voltage accelerator applications are vacuum or gas switches, such as spark gaps and thyratrons. Recently, high voltage IGBT based switches have become common, but are limited in current and are not compact. This paper will describe a compact, high current, high voltage solid state switch. These switches have been tested to 50kV, to greater than 12kA, to greater than 50kA/µs, to 360Hz, and to $3x10^8$ pulses, without failure. They have been used in accelerators to drive klystrons and kickers, and have been used as crowbars while offering advantages over thyratron switches for cost, lifetime, size and weight. The switches are based on series connected fast thyristors with $3cm^2$ die in a $20cm^2$ package. This package is more compact than TO-200 Puk sized devices, and does not require compression for proper operation. Each package is rated for 4kV, 14kA and 30kA/µs. One example, a 48kV switch which includes the trigger and snubber circuits, fits in a volume of 200mm x 85mm x 65mm, and requires only a fiber-optic trigger input. Such switches have been used on SRS and EMMA at Daresbury Laboratory in the UK, and at several US national laboratories.

BUILDING A PULSED POWER THYRISTOR MODULE

Our design for a solid state thyratron replacement is based on fast thyristors connected in series and controlled using a compact self-powered trigger circuit. When we began developing this concept, the technology for a suitable fast thyristor existed using a dense gate structure with planar passivation on NTD silicon wafers. However, there was no suitable thyristor packaging method that could handle the high current, high voltage, high di/dt and high dV/dt seen in pulsed power applications. So we decided to develop our own modules for thyristor packaging.[1]

The following parameters were used to develop our module design:

- Use soldered connections. Wire-bonds are not suitable for pulsed power.
- Keep the internal inductances and capacitances low. Even small additional capacitance and inductance can measurably slows turn-on.
- Keep the thermal resistance to heat sink low. The use of a high thermal conductivity ceramic such as AlN can provide excellent voltage hold-off with low thermal resistance.
- Use materials with low CTE. Thermal stress will limit the lifetime of the thyristor.
- Use vacuum encapsulation. Voids in the epoxy can cause early device failure or prevent operation at full device voltage rating.

Figure 1 shows an example of one of our module designs. This module contains two thyristors in series with an inductance <15nH. Table 1 provides a list of general operational parameters of the thyristor in the module. Equation 1 provided a model for the resistance of the thyristor in a module during turn on from the start of current conduction.

Figure 1: Dual thyristor module design.

Table 1: General Operational Parameters (per thyristor)

Parameter	Value
Peak Blocking Voltage	5kV
Peak Forward Current	14kA
Peak Reverse Current	10kA
di/dt	30kA/µs

$$r(\tau) = [\ 10000{*}e^{-\tau/2ns} + 2000{*}e^{-\tau/20ns} + 2{*}e^{-\tau/80ns} + 0.01\ ]\Omega \quad (1)$$

TURNING A MODULE INTO A SWITCH

Switches comprising devices such as thyristors traditionally require high-voltage isolated power for each device in series. Our solid state switch design involves a compact self-powered trigger circuit that uses snubber energy to drive the thyristor gate, eliminating the need for isolated power.[2] Figure 2 shows a schematic of the self-powered circuit. We further shrink the gate drive circuit by coupling the snubber current to the thyristor gate, command triggering 1 out of 6 modules and auto-triggering the rest without any change in performance. Figure 3 shows a schematic of the auto-trigger circuit.

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This means we need only to trigger a couple stages at the lowest voltage side of the switch which significantly reduces the triggering requirements. With these design improvements the switch can be triggered by a single fiber-optic signal.

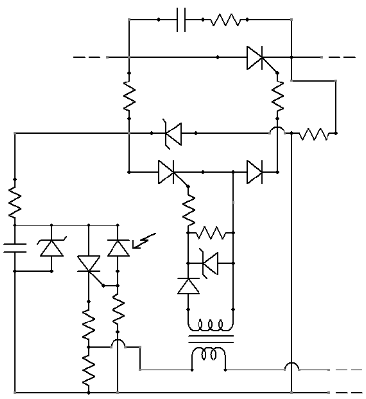

Figure 2: Self-powered trigger circuit.

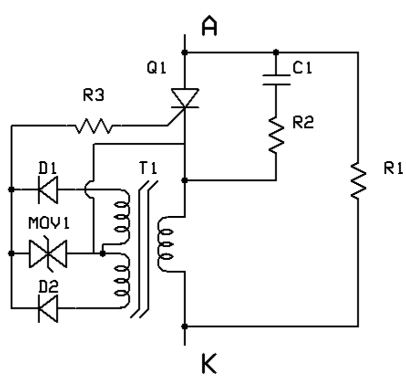

Figure 3: Auto-trigger circuit.

We design our switches to operate at half the peak current rating of the thyristor modules. The switches can also conduct reverse current, making them very tolerant of potential fault conditions. These things combined with the compact size of the gate drive circuit makes it easier to replace a thyratron with a solid state switch in accelerator applications.

REPLACING THYRATRONS IN LINAC MODULATORS

One of our first thyratron replacement projects was an E2V CX1836/A in a linac modulator at the Advanced Photon Source located at Argonne National Laboratory (ANL). The APS modulator has a 704nF 4Ω PFN and operates at 30Hz. The switch, shown in figure 4, uses twelve modules in series. The switch is controlled using an external trigger signal coupled to the thyristor gates rather than the auto-trigger circuit. Figure 5 shows the primary transformer voltage taken at ANL. This data was provided by Dr. Alex Cours of ANL.

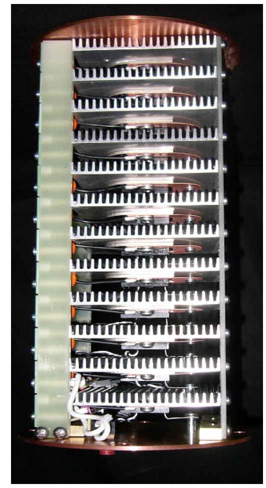

Figure 4: S56-12 solid state thyratron replacement.

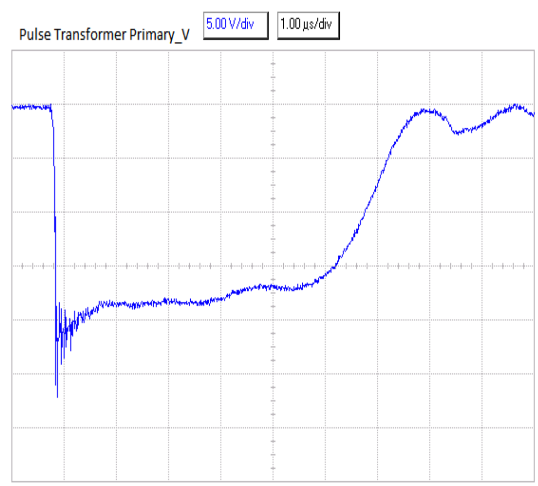

Figure 5: Test results at ANL using S56-12 showing primary pulse transformer voltage at a 1000:1calibration.

HIGHER FREQUENCY OPERATION

Our most recent thyratron replacement work involved developing a solid state switch for use in a klystron modulator at SLAC. The PFN has the same specifications as the one at ANL (704nF, 4Ω PFN) but with a couple important differences. It must operate at 120Hz, under resonant charging, with < 2ns of turn-on jitter.

Operating conditions required by the SLAC modulator meant that we needed to significantly reduce the thyristor turn-off time. While the turn-off time for the ANL switch can be as long as 5ms, this new switch must be off in 100µs. By reverse biasing the gate with sufficient current, the thyristor turn-off time could be met even under 100A switch current. This requires using an externally powered gate drive circuit. With this circuit, the switch can operate at up to 600Hz.

Figure 6 shows a picture of this switch which uses sixteen stages of two thyristor modules in parallel. Figure 7 shows data from SLAC showing the operation of this switch. The data was provided by Dr. Chaofeng Huang, SLAC.

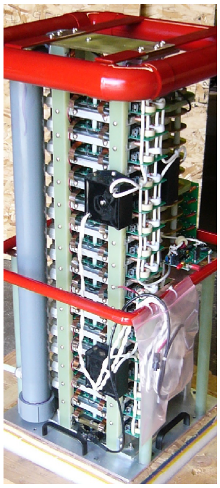

Figure 6: S60-2-16 solid state switch at SLAC.

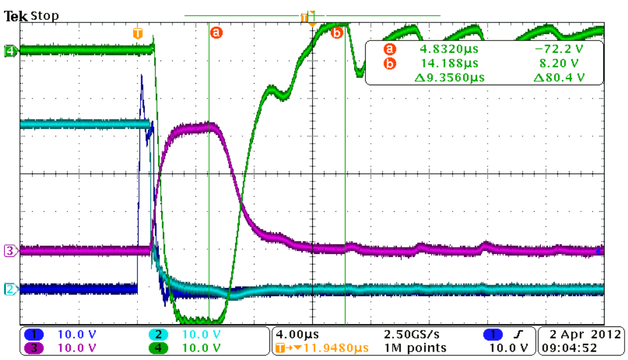

Figure 7: S60-2-16 solid state switch test results from SLAC showing pulse voltage and current. Ch1--Modulator trigger in; Ch2--PFN charging voltage (1000:1); Ch3--Switch current (180:1); Ch4--Klystron beam voltage (4860:1).

CROWBAR APPLICATIONS

Many modulators used for accelerator applications require a crowbar switch to quickly and safely dump the energy before a fault, such as an arc in a klystron, causes damage that requires a long down time and expensive repairs. Thyratrons have been used as crowbar switches in these cases. We have developed a few solid state switches for use as crowbars.

Working with CERN[3], we were able to develop a replacement of a CX1194/B. This switch uses eighteen of our S38 modules in series. The crowbar had to discharge a 4µF capacitor rated for 70kV with a 10Ω load resistor. Figure 8 shows data taken from operation of this crowbar switch at CERN. The data was provided by Dr. Gianfranco Ravidà, CERN.

FUTURE OF THYRISTOR SWITCHES

We are working on paths towards developing even faster thyristor switches. One is developing laser pumped silicon thyristors (LPST).[4] Figure 9 shows the LPST achieving 2kA in <50ns using 170nF charged to 3kV with a 0.5Ω load. The timing was from a TTL trigger and includes all throughput delays from converting the TTL to a laser pulse.

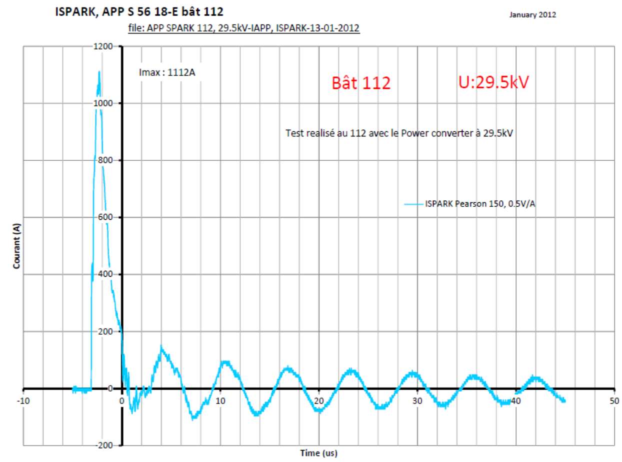

Figure 8: Crowbar operation of a S56-18 at CERN.

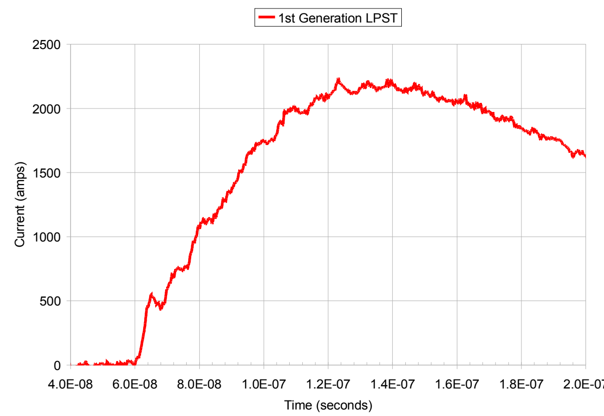

Figure 9: LPST achieving 2kA in <50ns.

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The authors would like to acknowledge Dr. Alex Cours of ANL, Dr. Chaofeng Huang of SLAC, and Dr. Gianfranco Ravidà of CERN for their contribution in developing these solid state switches for their respective applications and of the graphs showing data from these switches operating in their respective systems.

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