ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-WEPMF063

THYRATRON REPLACMENT*

Ian Roth, Dr. Neal Butler, Dr. Marcel P.J. Gaudreau, Michael Kempkes, Rebecca Simpson
Diversified Technologies, Inc.,
Bedford, MA 01730 USA

Abstract

Thyratrons in high-power, short-pulse accelerators have a limited lifetime, making it desirable to replace the thyratrons with solid-state devices. Under a recently complete Small Business Innovative Research grant from the Department of Energy, Diversified Technologies, Inc. (DTI) has designed, built, and tested a solid state Thyratron Replacement switch. This switch is capable of meeting both the electrical and physical (size and cooling) requirements to deliver a form-fit-function replacement for the thyratrons used in the Stanford Linear Collider (SLC). It is expected to have an order-of-magnitude longer life than the thyratrons currently used in the SLC modulators.

This switch uses an expanded form of DTI's patented technology required to build the array of series-parallel connected switches required to meet the thyratron replacement requirements.

MOTIVATION

The market for thyratrons is in decline. As newer solid-state modulators are deployed, and older thyratron systems are taken out of service, the demand for thyratrons has diminished significantly. In response, thyratron vendors have either gone out of business or stopped manufacturing thyratrons, diminishing their availability. It is not clear how long the supply of thyratrons for these legacy systems will continue, making a solid-state thyratron replacement critical for the continued operation and support of pulsed power systems reliant on this technology.

The thyratrons in many klystron modulators also represent a major expense in operation – not only from the increasing cost of replacement, but from the labor required to replace and adjust them for proper operation during their relatively short life.

Most of these thyratron-based systems, including commercial medical accelerators, were designed decades ago, before solid-state switches were available. The cost of transitioning from thyratrons and pulse-forming networks to solid-state modulators is declining, but can be prohibitive for large facilities with multiple modulators. Consequently, DTI anticipates a wide range of benefits from the development of a cost-effective, drop-in replacement for the thyratrons in operation in commercial and scientific systems around the world.

* Work supported by US Department of Energy Grant No.: Grant DE-SC0011292.

INTRODUCTION

The Stanford Linear Collider (SLC) has used thyratrons in its klystron modulators since its inception in 1963. While the thyratrons function, they need replacement every 10,000 hours (approximately one year), at a cost of $13,000 each, plus labor. Furthermore, periodic maintenance is required to adjust their reservoir heater voltage over the thyratron lifetime. As the Stanford Linear Accelerator Center (SLAC) continues to run its accelerator over the next two decades, replacing the thyratrons with a solid-state switch that would last 25 years or more, and does not need maintenance, would provide significant savings – both in the avoided cost of thyratrons as well as the labor in replacing and adjusting them.

DTI recently completed the construction and test of this solid-state thyratron replacement under a Phase II SBIR from the Department of Energy, Fig. 1.

Figure 1: DTI solid-state replacement for the L-4888 thyratron used at SLAC. The switch, which operates at 48 kV and 6.3 kA, fits in the same location as the legacy thyratron assembly.

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-WEPMF063

Our objective was to make a solid-state thyratron replacement that would provide equivalent or better performance, much higher reliability (at least a 20-year lifetime, compared to a thyratron's one-to-two-year lifetime) and would sell for ~3x the cost of a thyratron, or approximately \$40k. This would allow the SLAC to transition to the solid-state thyratron replacement with minimal incremental cost over replacing thyratrons.

We were successful in building a solid-state switch which could reliably function as a thyratron replacement. The unit directly replaces the thyratrons currently being used at SLAC's LINAC Coherent Light Source (LCLS), in a tank that fits into the existing thyratron cabinet, providing a true form-fit-function replacement path. We tested the switch at the full operating specifications: 48 kV, 6.3 kA, and 1 µs risetime, see Fig. 2. We also demonstrated a peak-to-peak pulse jitter of 1.5 ns, which is five times lower than is typical for thyratrons. This lower jitter would improve the performance of the LCLS beam. The predicted reliability is more than 80 years.

DESIGN

The switch developed under this SBIR uses IGBTs, which have a fast risetime and can carry substantial currents. Other possible solid-state devices are thyristors and FETs. Thyristors can carry higher currents, but when the current rises quickly (as it does at SLAC), it tends to concentrate in a small region, which can cause a short. FETs, the other alternative, switch rapidly, but cannot carry as much current as IGBTs. We considered 22 different IGBTs for the switch. Once the device was selected, 60 devices were connected in series, and tested to demonstrate series operation and ruggedness to arcs at a current of 250 A. The tests were:

- Resistive load, inductance corresponding to normal operation. This test demonstrated that the voltages share evenly in a series stack. It also showed that the current rises to its peak value in under 2 µs, as required.
- Arc inductance corresponding to a klystron arc. We performed 300 tests with the switch stack, which corresponds to the number of klystron arcs the switch would experience in 20 years of operation. Based on other DTI work, the IGBTs are expected to survive many more arcs; our IGBT switches are routinely used for klystron conditioning.
- Arc inductance corresponding to a cable short. There were 10 tests for the switch stack. This is more than the number of cable shorts the switch would see in 20 years of operation.

With this performance demonstrated, we designed the circuit board ("switch plate") used in the switch, see Figure 3. The plate has 2 groups of IGBTs, each with 8 devices in parallel and 20 devices in series.

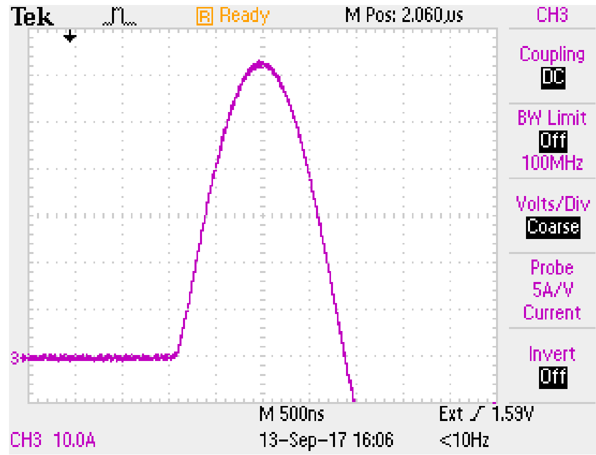

Figure 2: Switch test at full operating current, 6.2 kA, and pulsewidth for the SLC modulator. 1 kA/div (not 10 A, as listed). Sweep speed 500 ns/div.

The current per device is 200 A. At this current, and the 6 µs pulse width and 120 Hz frequency at SLAC, the IGBTs dissipate only 1 W per device. At this power, the IGBTs do not need heat sinks and can be closely packed.

Since there are 3840 devices in the switch assembly, the total power dissipation is 3840 W. To remove this power, there is an oil-circulation pump and an oil-to-water heat exchanger, which are located in the oil above the switch stack, which is standard practice at DTI.

One issue which took considerable engineering effort was ensuring that the current was shared equally between the parallel IGBTs, see Fig. 4. This current sharing is critical in the event of a fault. It was impacted by a number of parameters. Some, such as distance between rows and resistance were obvious, but others, such as the gate drive loop design, required considerable analysis and attention to identify and optimize. Thermal images of the final switch assemblies show that we were successful in balancing the current sharing between parallel devices, Fig. 4 and 5.

The IGBTs are gated on and off by pulses coupled by ferrite toroids. The drive wires pass through the center of the toroids, with 60 kV solid insulation to prevent breakdown between the drive and the high voltage on the switch.

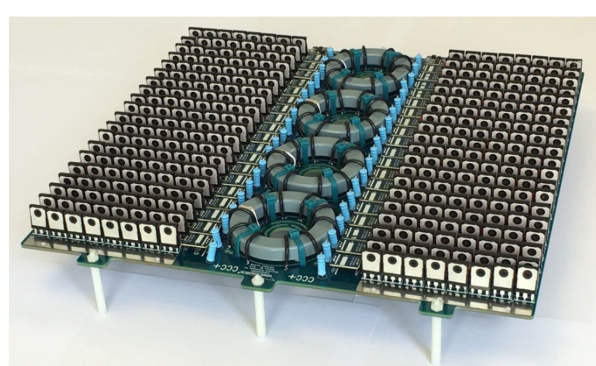

Figure 3: One of ten switch modules, with 384 IGBTs and four toroids for gate drive coupling.

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-WEPMF063

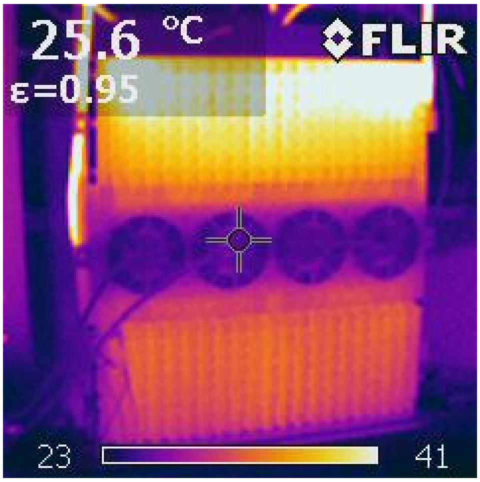

Figure 4: Thermal imaging showing uneven current sharing between rows of IGBTs in a circuit board.

An additional 0.5 inches of oil separates the ferrite secondary winding at high voltage and the solid insulated trigger wire at ground potential. The wires are connected in pairs to minimize the inductance effects of the drive loop.

The complete switch assembly is designed to fit within the 22” wide × 22” deep × 37” high dimensions of the modulator tank. The switch has 120 rows of devices in series. This is 20% more than the minimum required, so multiple devices must fail before the switch shorts. Note that IGBTs always fail short, allowing a series-string with margin to maintain full functionality until such a time as the margin is exceeded (“graceful degradation”).

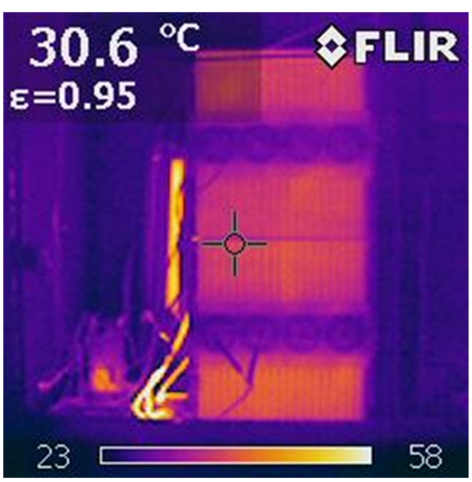

Figure 5: Thermal image showing uniform current distribution in the switch, with circuit boards stacked two high.

FUTURE PLANS

We were successful in meeting our technical objectives for this effort. The final switch was tested at both nominal and fault conditions, and proved reliable over the full range of operation and faults. It fit within the mechanical envelope of the existing thyratron assembly (see Figure 6) and had a very long predicted lifetime (over 80 years by analysis).

Unfortunately, the final design was more complex, and required significantly more devices for reliable operation, than initially expected. The cost of the IGBTs alone approached the target price for the entire unit. As a result, this switch would be significantly higher in price than a thyratron – even in quantity. While this would provide a savings to SLAC over the anticipated life of the LCLS, the up-front investment would be much higher than originally expected, and the payback longer than acceptable from a budget perspective.

We do believe that, on a long-term basis, the solid-state approach would provide a lower overall life cycle cost, but the cost of each unit would require a significant upfront investment from SLAC during the transition. The primary limiting factor to the switch cost is determined by the *dI/dt* capability of IGBTs, which is improving with each new generation of devices. This should make subsequent versions of this switch much less expensive.

Although this specific switch is not destined for installation at LCLS in the near-term, the switch assembly is commercially available, and can be tailored to the requirements of other legacy systems still using thyratron pulse-forming network pulse modulators.

ACKNOWLEDGEMENTS

The authors wish to thank SLAC for their collaboration on this project, which was funded under DOE Grant DE-SC0011292.

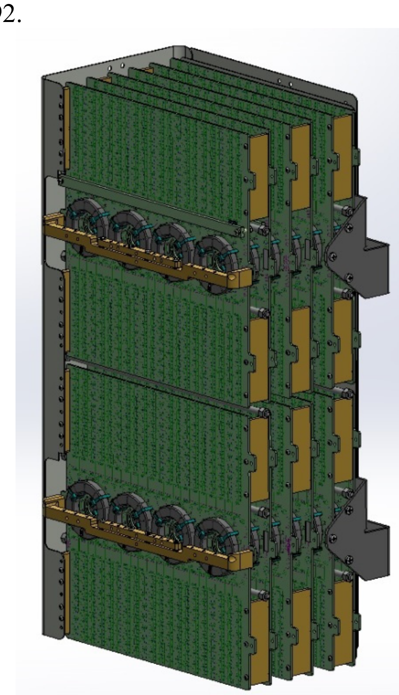

Figure 6: Unpopulated switch assembly with 10 of the switch modules shown in Figure 3.