SOLID-STATE PULSED POWER SYSTEMS FOR THE NEXT LINEAR COLLIDER

Marcel P.J. Gaudreau, Jeffrey A. Casey, Ian Roth, Timothy Hawkey, Michael Kempkes, J. Michael Mulvaney; Diversified Technologies Inc. 35 Wiggins Ave. Bedford, MA USA

Abstract

Diversified Technologies, Inc. has received Phase II SBIR grants from the DOE for the application of solid-state switching to the Next Generation Linear Collider. Under the first of these, DTI delivered a hybrid modulator to SLAC in October 2002 for assessment. The modulator uses a solid-state series IGBT switch and a conventional pulse transformer to cathode pulse two klystrons at 500 kV, 530 A, with tight voltage regulation and pulse flattop.

During this effort, the pulse transformer was determined to be an obstacle to increased modulator performance. A second grant was received to develop a low impedance toroidal pulse transformer, to operate efficiently in the hybrid modulator. Under a third grant, DTI investigated transformerless options for solid state switching, and tested a scale prototype of a 500 kV Marx switch for improved efficiency.

This paper describes results from the hybrid modulator and Marx switch development efforts.

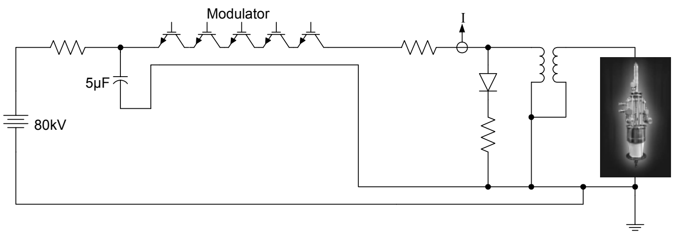

Figure 1: NLC Hybrid modulator schematic. The solid state switch pulses 3500 A at 80 kV to drive two 500 kV 265 A klystrons.

1 INTRODUCTION

Diversified Technologies, Inc. (DTI) has over a decade of experience in developing high voltage pulsed power systems using solid-state technology. DTI has obtained multiple SBIR grants from the Department of Energy to support the modulator development efforts for the Next Linear Collider (NLC). The NLC will require ~1600 klystrons, with a power load of over 120 MW. The goal of these efforts is to develop modulator technology capable of reducing the operating costs associated with the NLC and other large RF systems.

DTI's solid-state modulators are built from series stacks of IGBTs, configured for very high voltage standoff, and operated as single ideal SPST switches. These switches can open quickly (< 1 µs) under normal or even fault load currents, eliminating crowbar circuits and providing a high degree of load protection.

The near-ideal properties of solid-state switches make them well suited to remedy the inefficiencies of conventional line modulators. The challenging specifications of NLC klystron operation have required additional switch development through these programs.

2 HYBRID MODULATOR

A "hybrid modulator" uses a storage capacitor, a solid-state switch and a pulse transformer (Figure 1). The switch provides a high current pulse (~ 3500 A) into the pulse transformer at approximately 80 kV. The load on the secondary of the transformer is two parallel NLC klystrons, operating at 500 kV with a combined load of 1.5 µP (530 A), for 3 µs flattops of +/- 3%.

The resulting system is shown in Figure 2. The pulse transformer is in the foreground, and the solid state switch in the background. Controls are above the switch. The entire assembly is constructed to drop into a dual oil tank for cooling and insulation. Auxiliary systems are included for core bias and dual filament control. The full system was tested at DTI, and shipped to SLAC for further testing and for support of the klystron development efforts (Figure 3) in Fall 2002.

Figure 2: Hybrid modulator assembly, ready for immersion in oil.

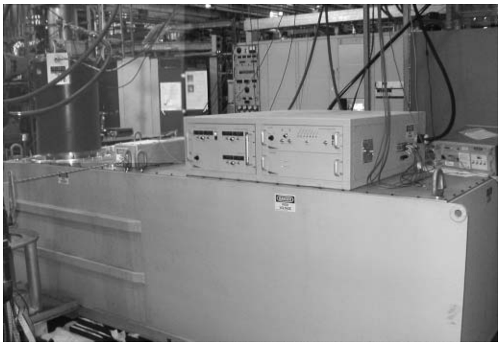

Figure 3: Hybrid Modulator in tank at SLAC, with a SLAC 5045 klystron in a load socket.

The critical performance constraint on the hybrid modulator is primary circuit inductance, to meet the high primary current and fast risetime desired, at the relatively low primary voltage. The switch accounted for this problem by assembly on a distributed transmission line. These transmission line characteristics, together with the product of the transformer primary leakage inductance and secondary parasitic capacitance, determine the pulse risetime.

Preliminary tests at DTI show that fast risetime has been achieved. Figure 4 shows the voltage waveform of a test pulse into a 990 Ω load at DTI. Note the overshoot and the ripple – both effects of the difference between the test (resistive) load and the design (perveance) load.

Initial tests at SLAC were performed using a single 5045 klystron, but with the cathode operated in temperature limited mode to mimic the effective 1.5 μP of the NLC design load. Figure 5 shows a nominal pulse at 421 kV cathode voltage. Additional inductance was added to the primary circuit for initial operation, as a safety factor for load-arcs. Note the slower risetime than in Figure 4. The full assembly also includes a small two stage tuned *LC* circuit, with about 10 kV of authority, which flattens out the capacitor droop during the pulse. The resulting flattop is better than +/- 0.5%, well within the +/- 3.0% specification.

The most challenging aspect of the hybrid modulator is arc protection. DTI's solid-state switches sense

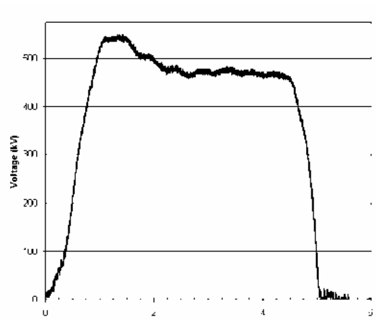

Figure 4: Fast pulse data at 500 kV, into a 990Ω load.

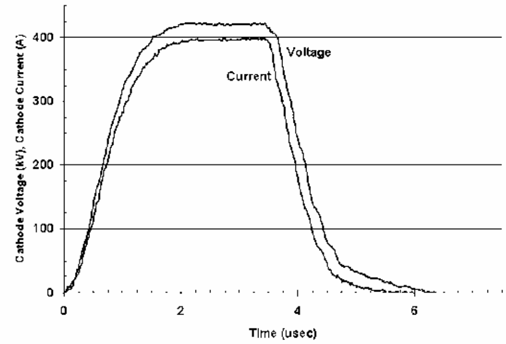

Figure 5: Hybrid modulator operation at SLAC. Load is 5045 klystron, with the cathode operated in temperature limited mode for an effective 1.5 μP load.

overcurrent conditions, which then command all the series switches to shut off. The response time of this event is approximately 750 ns. For the hybrid modulator, high current and high speed operation place a very large demand on the capability of the solid-state switch to open under large fault loads. The NLC hybrid switch is rated for 10 kA opening. Figure 6 shows a typical arc of the overdriven 5045 klystron during testing at SLAC. The upper trace shows the cathode voltage, which collapses

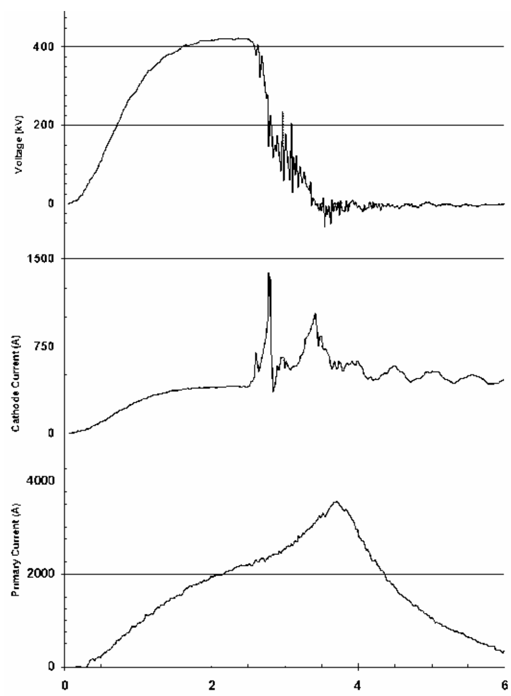

Figure 6: Hybrid modulator with a load arc at 420 kV. The load (5045 klystron) arcs at about 2.5 μs. The switch safely opens under full *fault* primary currents. The lag time is about 1 μs between arc occurrence and switch opening. (Primary current shown at reduced bandwidth.)

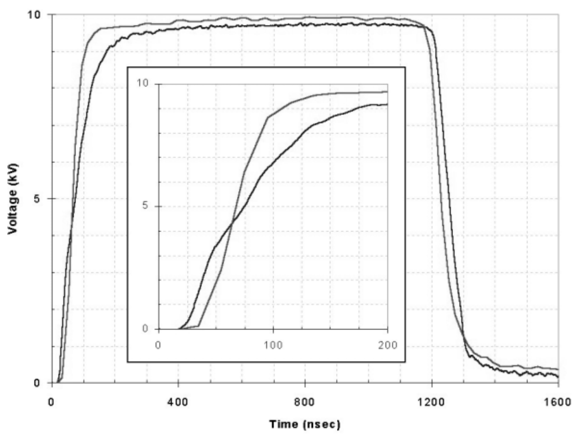

Figure 7: Single cell Marx switch risetime tests show very high speed. Both shots at 10 kV. Faster one into 59 ohms, slower one into 21 ohms.

from 421 kV at the arc. The middle trace shows the cathode current. There is a sharp spike of current as the parasitic capacitance of the pulse transformer discharges into the cathode, followed by a slower current rise as the primary circuit begins to deliver additional current. The lowest trace shows the primary current, which opens at a bit under 4 kA, about 1 μs after the arc is detected (this signal is processed through a reduced bandwidth amplifier).

A large part of the speed limitation in the primary circuit, aside from the inserted "safety inductance" (which will be reduced as testing continues), is due to the pulse transformer. Presently, this is a conventional Stangenes transformer (quadrifilar, slanted basket, with a Lord winding). Under a separate SBIR, we are developing an improved pulse transformer of toroidal geometry (based on work originally proposed by Kazarezov, [1]) for integration into the hybrid modulator at a later date.

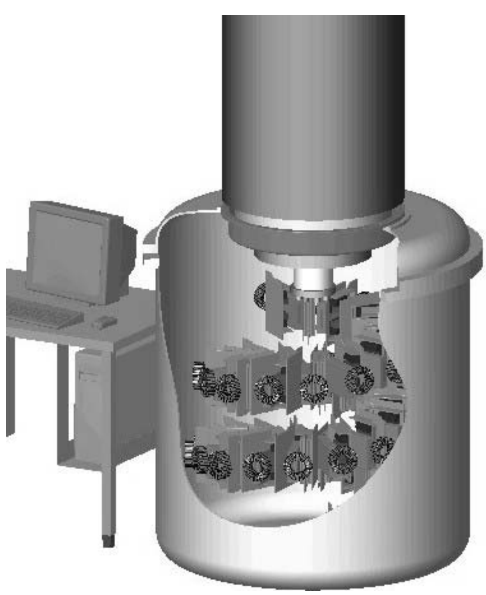

Figure 8: Proposed 500 kV "desk size" 250 A modulator.

3 TRANSFORMERLESS ARCHITECTURE

In parallel SBIR efforts, DTI is improving the overall power efficiency and performance by eliminating the pulse transformer altogether – motivated by a 5-10% net energy savings. Originally, two topologies were examined: a hard switch with a 500 kVDC supply, and a Marx switch [2]. Design studies and scale experiments have led us to concentrate on the Marx for further development.

A solid state Marx switch is somewhat different than conventional Marx switches fired by thyristors or spark gaps because the capacitors do *not* fully discharge during a pulse. Instead, the opening capabilities of the IGBT series switches are used, so that the intra-stage capacitors act as filters, and are only shallowly discharged. A very fast risetime and very high quality flattop can be delivered this way. The critical cost & performance requirement for the Marx switch is parasitic capacitance – analogous to the role of primary inductance in the hybrid modulator.

A scaled (50 kV, full current) Marx switch of five stages was built, and is presently undergoing final assessment at DTI. Figure 7 shows a single stage pulse, demonstrating the very fast risetime of the configuration. Design studies suggest that a full specification Marx switch for a single klystron (500 kV 265 A) will be "desktop" size as shown in Figure 8.

4 SUMMARY

We have a continuing advanced solid-state modulator development program to support the NLC efforts. These pulse power systems will improve performance and reduce operating costs of the NLC when built, and are presently aiding in the klystron development efforts as well. Several advanced technologies are under development, and one system – the hybrid modulator – has been delivered to SLAC for further assessment and use in klystron development and testing.

5 REFERENCES

[1] Kazarezov, et.al., "Pulse Transformer for the NLC Klystron".

[2] A. Krasnykh, R. Akre, S. Gold, and R. Koontz, "A Solid-state Marx Type Modulator for Driving a TWT," 24th International Power Modulator Symposium, 2000, Norfolk VA, USA. "Analyses for Klystron Modulator Approaches for NLC", International Linac Conference, Monterey CA, USA

This work has been supported by DOE SBIR grants (DE-FG02-99ER82775 and DE-FG02-99ER82776). We appreciate the assistance of our colleagues at the Stanford Linear Accelerator Center.