SOLID-STATE PULSED POWER SYSTEMS FOR THE NEXT LINEAR COLLIDER

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

Abstract

The Next Generation Linear Collider (NLC) represents a significant challenge for high voltage modulator technology. It will require pulse modulators capable of driving over 1600 NLC klystrons at 500 kV, approximately 265 A, with 3.2 microsecond pulses at 180 Hz with strict tolerances for flattop and voltage regulation.

Given the large number of modulators required, certain life cycle costs, in addition to those for acquisition of components, will be significant factors in the NLC’s affordability.

1 INTRODUCTION

In 1999, Diversified Technologies, Inc. (DTI) was awarded two Phase II Small Business Innovative Research (SBIR) grants from the Department of Energy to assess the cost benefits that solid-state modulators could realize through improved efficiency, reliability, and maintainability.

Generally, a solid-state modulator is a large series stack of FETs or IGBTs, configured for very high voltage standoff, and operated as a single ideal SPST switch. More importantly, the switches may be arbitrarily closed or opened quickly, thus providing sub-microsecond removal of stored energy from the load during an arc.

The assessment is focused on three modulator configurations: a "hybrid modulator”, using a solid-state switch and a pulse transformer, and two transformerless designs, one based on a 500 kV hard switch, and a second based on solid-state Marx Bank. Each of these is discussed below.

2 HYBRID MODULATOR

A "hybrid modulator”, uses a solid-state switch and a pulse transformer (shown in the schematic in Figure 1). It will provide high current pulses into a pulse transformer at approximately 80 kV; allowing use of the identical power supplies being developed for the baseline thyratron/PFN modulator. The switching is done at high voltage, using IGBTs in series, at medium voltage (50 – 150 kV) and current. The key to effective design of the hybrid is careful attention to inductance in the primary circuit – implied by the very high primary currents and lower primary voltages, and fast risetimes required.

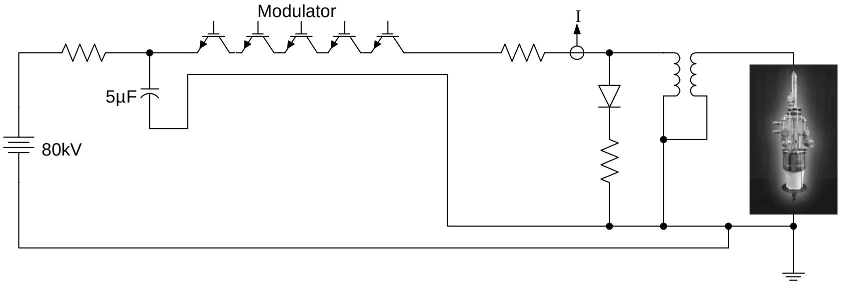

Figure 1. NLC Hybrid modulator schematic

The hybrid modulator is currently in testing at DTI. It has three major components: an 80 kV, 100 kW switching power supply, an 80 kV, 3500 A solid-state switch (Figure 2), and a 6.5:1 pulse transformer. It will be

Figure 2. Hybrid modulator. Solid-state Switch (80 kV, 3500 A peak). Pulse transformer in foreground**.**

contained in its own oil tank. The solid-state switch itself is the key to this architecture. Figure 3 shows one of the 24 individual switch modules that comprise this switch. When all 24 modules are connected in series, they provide the required 80 kV, 3200 A pulses at the primary of the pulse transformer.

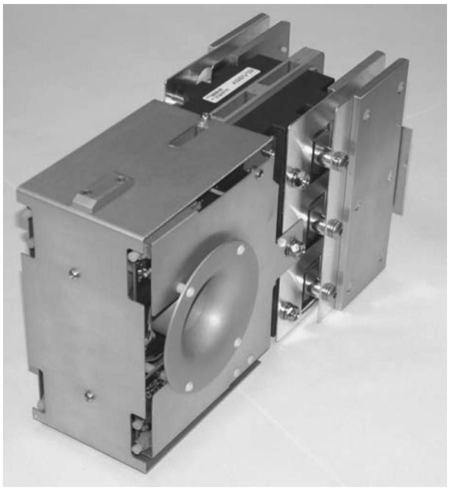

Figure 3. Dual IGBT Switch Module for the Hybrid Modulator (3.5 kV, 5000 A Peak)

A second oil tank contains the pulse transformer, built by Stangenes Industries to DTI's specifications, and sockets for the two NLC klystrons. The two tanks are electrically connected through a low impedance bus.

DTI will complete in-plant testing of the hybrid modulator in June 2002, after which it will be delivered to SLAC for full scale testing.

3 TRANSFORMERLESS SWITCHES

In pursuit of higher overall power efficiency, we are studying two alternate topologies that eliminate the transformer, and its associated ~5-10% core and magnetization losses. The net result of a 10% efficiency increase translates to $15k to $30k in electricity costs per klystron over the NLC system lifetime of 10 years. While this is a small savings for each klystron, it represents a significant savings when applied to all 1,600 klystrons anticipated in the NLC. The prime disadvantage of transformerless systems is that silicon switches must experience the full 500kV of the load.

DTI's solid-state switch modules are typically powered via an inverter supply, coupled with a single turn primary transformer. The HV standoff and parasitic capacitance preclude using this technique at 500kV. Instead, both transformerless systems utilize a patented technique for powering the gate drive and diagnostic circuits (for each switch stage) directly off of the HV line itself.

3.1 500 kV Hard Switch.

In the hybrid modulator, minimizing overall inductance is the key to fast risetimes and high efficiency. The key to high efficiency without a pulse transformer is minimizing parasitic capacitance (Figure 4). During DTI's development of this approach, the major challenges of directly switching 500 kV have been overcome. Modeling results show that >90% efficiency is possible for a design optimized to power eight klystrons in parallel. This is only possible for very carefully configured switch assemblies however – the net ten year power cost to NLC of additional stray capacitance on each modulator is $140k/pF!

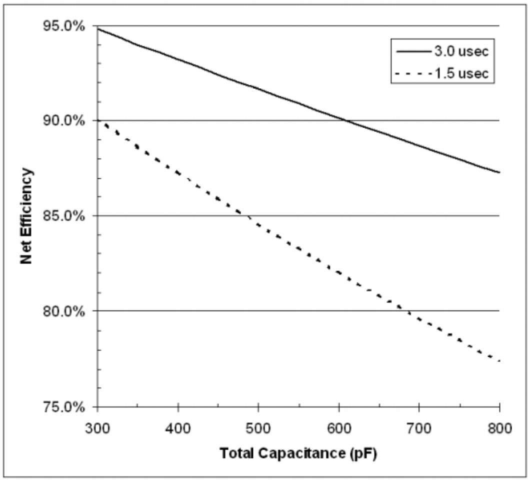

Figure 4. Efficiency versus capacitance

3.2 Marx Bank

The third architecture being investigated is a Marx Bank system, first proposed for NLC application by A. Krasnykh et al [3]. Similarly to the hard switch, the Marx bank uses no pulse transformer, instead supplying additional silicon to switch to full voltage. The prime advantage of the Marx bank architecture over the hard switch is the elimination of the 500kV DC standoff problem from the system engineering. This must be offset by the requirement of repetitively elevating the larger physical bulk of the energy storage capacitors to pulse voltage and back, thus the higher parasitic capacitance penalty that must be paid. The challenge to the Marx design is thus to devise a configuration which takes advantage of the lower system DC voltages to minimize the effects of the parasitic capacitance.

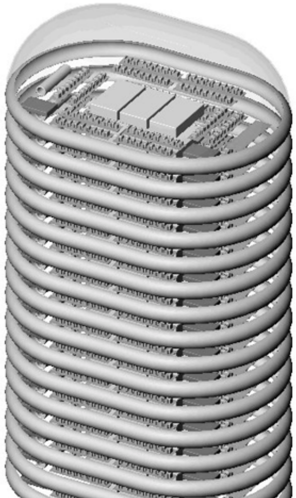

Figure 5 Marx bank concept 3' x 5' x 10'

Our modeling has shown that a stack of thin, hoop-like assemblies serves this purpose well. Figure 5 shows the modulator: air insulated, 16 decks of 32kV per deck, for overall dimensions of about 3’x5’x10’. The use of very flat high energy density energy storage capacitors is key to its success. The key parasitic capacitance (that between each stage and ground) is drastically reduced at the expense of the less-important stage-to-stage capacitance. Parametric surveys show that the overall system performance is best optimized around 25-35kV per stage, high enough to retain rugged redundancy within each high voltage switch assembly and keep recharge currents low, yet low enough to make the *intra-module* parasitic capacitances negligible. These results show that 90% efficiency appears attainable.

The key advantage of the Marx system over the hybrid modulator is a faster risetime, higher efficiency, and a flatter pulse. The tradeoff for this is a higher equipment cost, perhaps 20%-40% higher ultimately.

4 SUMMARY

DTI has developed multiple, solid-state modulator topologies which will meet the NLC requirements. The major distinctions between them relate to construction cost, operating cost (primarily measured by modulator efficiency), and technological risk. In our efforts across these topologies, our objective has been to minimize total life cycle cost.

The Hybrid Modulator, designed for a two klystron load, is low risk, supports easy maintenance, and represents a relatively mature solid-state architecture. It is currently estimated to be the lowest manufacturing cost, but also has lowest efficiency of these three architectures (about 80% - still significantly higher than a conventional line-type modulator). This design is essentially complete, and full-scale construction is underway at DTI. The Hybrid Modulator prototype delivery to SLAC is scheduled at the end of 2001.

The hard-switch system drives eight klystrons. It has the highest efficiency (90%) and good pulse shape, but also has the highest risk and a complicated mechanical structure.

The Marx bank drives one or two klystrons. The risk is low to moderate, maintenance is easy, and the efficiency is high (nearly 90%). The pulse shape is clean, and the life cycle cost may be better than that of the Hybrid Modulator.

Both the hard switch and Marx bank alternatives are scalable up to 1 MV for future high-energy physics systems.

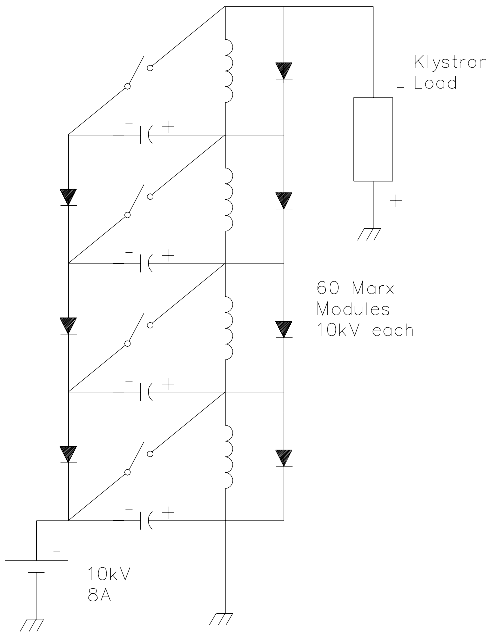

Figure 6. Marx modulator schematic

5 REFERENCES

[1] Marcel P.J. Gaudreau, Jeffrey A. Casey, J. Michael Mulvaney, Michael A. Kempkes, “Solid-state Modulator for Klystron / Gyrotron Conditioning, Testing, and Operation,” Conference Record of the 2000 Twenty-Fourth International Power Modulator Symposium, pp.125-8.

[2] Marcel P.J. Gaudreau, Jeffrey A. Casey, J. Michael Mulvaney, Michael A. Kempkes, “Modulator Development for the Next Generation Linear Collider,” **PPPSC 2001**

[3] A. Krasnykh, R. Akre, S. Gold, and R. Koontz, “A Solid-state Marx Type Modulator for Driving a TWT,” ibid, pp. 209-211.

6 ACKNOWLEDGEMENTS

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