

New Concepts for Pulsed Power Modulators: Implementing a High Voltage Solid-State Marx Modulator

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ABSTRACT

Diversified Technologies Inc. (DTI) developed a Solid-State Marx Modulator under an SBIR program funded by the Department of Energy. The modulator was designed to be a cost effective power source for multi-beam klystrons. The modulator was delivered to the Stanford Linear Accelerator Center (SLAC) and will be used as a test platform for ILC class klystrons.

Index Terms — Pulsed power; modulator; Marx; solid-state; accelerators; klystrons; high voltage

1 INTRODUCTION

The International Linear Collider (ILC) program is expected to require up to 650 pulse modulators, each of which will nominally provide at 120 kV, 120 A, 1.5 millisecond, 5 Hz cathode pulses for the multi-beam klystrons (MBKs). The objective of this SBIR was to build a full-scale Marx bank pulse modulator for the ILC, and deliver it to the Stanford Linear Accelerator Center (SLAC) for evaluation. The Marx bank modulator demonstrates a new technology for compact and economic ILC class performance.

2 MARX MODULATOR DESIGN

The defining characteristic of the ILC klystron is its (relatively) long pulse width. The long duration of the pulse requires a large stored energy regardless of modulator technology. The raw specification requires about 25 kJ delivered to the klystron each pulse. This is significant for any type of pulser which self-exhausts each pulse (i.e. PFN type systems), in addition to the complexity of tuning a pulse line to +/- 0.5% flatness for such a long pulse. Hard switch modulators (including those using pulse transformers) typically require far larger energy storage elements to keep the droop within the flatness tolerance over the pulse duration. The energy storage requirements can be significantly reduced through modifications to hard switch devices – linear regulation correctors, quasi-resonant bouncers, etc. We have concluded the solid-state Marx bank provides a more effective solution to the tradeoff of stored energy versus cost. The Marx topology allows some of the energy storage capacitors to be fired with staggered delays – thus maintaining the flatness of the pulse through a series of correction “ratchets”.

The basic theory of the Marx modulator design is to charge an array of capacitors in parallel (at low to medium voltage), and then erect these capacitors in series to achieve a high-voltage output. The “parallel” charging of the capacitors can be accomplished in a number of ways. For a very low duty cycle, resistive isolation can suffice. Similarly, for short pulses, inductive isolation is ideal. For the long pulses required of the ILC, these are not suitable. Instead, each capacitor requires two separate switches – one for charging, and one for pulsing. Four “unit cells” of such a two-switch Marx module are shown during the charging state in Figure 1A. Pulsing the switches stacks the cells into a series array as shown in Figure 1B.

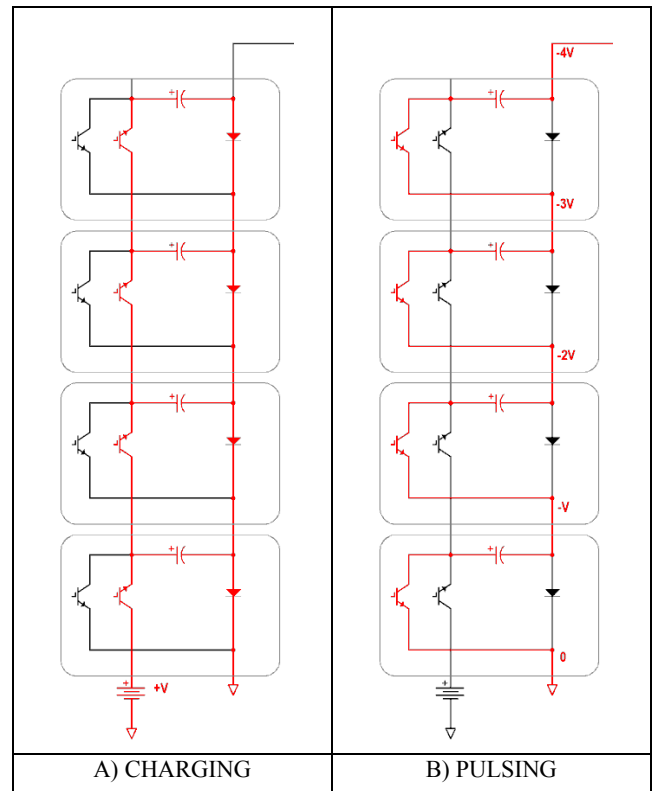


Figure 1. The DTI Marx Bank Topology.

A) Highlights the recharging currents – when the charging switches are on, the capacitors are effectively in parallel, and quickly charge through the diodes.

B) Highlights the pulse current when the pulse switches close.

By using solid state switches, the capacitors serve as energy storage units, rather than fully discharging during each pulse (as they would in a conventional Marx bank with spark gaps). The opening capability of the DTI switches also provides arc protection of the load, exactly as would a hard-switch. This system, therefore, does not require additional crowbar circuitry to protect the load against arcs. The solid-state Marx architecture provides system flexibility; it has an inherent capability to arbitrarily switch additional modules onto the modulator output, providing voltage regulation with reduced energy storage.

We have taken advantage of this flexibility to design a system topology to optimize the power efficiency and economy of the solid-state switches. As shown in Figure 2, there are four distinct components to the Marx Modulator. These are:

- A power-entry buck regulator, which takes unregulated DC power from an outdoor transformer/rectifier, and regulates the prime power to about 6-7 kV DC,
- A bank of 20 highly efficient “core” switch modules, which erect the leading edge of the pulse to a voltage of 20x the prime DC feed,
- A low-power buck regulator, which steps the 6-7 kV DC feed down to 900V max for trimming,
- A bank of 16 “corrector” switch modules, which fire at staggered intervals to regain the pulse voltage as the prime capacitor bank droops.

The solid-state Marx topology offers all the advantages of solid-state switching, plus it provides self-regulation of the pulse voltage, eliminating the need for a separate power supply.

A key issue to address for the ILC Marx transmitter design was the system parameterization. Our Phase I prototype demonstration showed that the circuit elements performed at or above expectations. Our challenge in Phase II was to optimize this modulator so that it met the technical specifications while being manufacturable at affordable cost, simultaneously meeting the reliability and maintainability

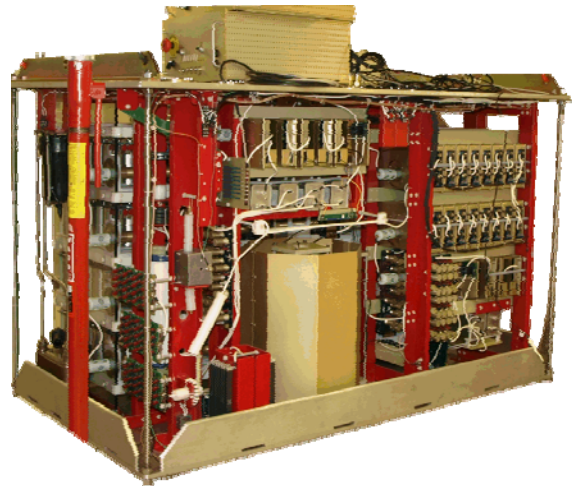


Figure 3. Marx Modulator Outside of the Oil Tank. This unit is 89” long by 53.5” wide by 77.5” tall.

challenges for ILC subsystems.

Within the constraints of the ILC performance and reliability specifications, we undertook (in Phase I) a detailed costing study to evaluate the tradeoffs of total stored energy capacitor bank size, including the effect on number of core and corrector modules, type of IGBTs required, number of switch module overhead circuits, overall tank size, etc.

In both cases – film and electrolytic capacitors – there is a “sweet spot” which yields the minimum total system cost as a function of base core capacitor bank size (base measured in kJ of stored energy). Qualitatively speaking, the cost increases for smaller bank size due to the quickly increasing need for more corrector modules, with the additional infrastructure required by the additional switches. Similarly, the cost increases for a larger bank size, albeit more slowly, due to the physically larger footprint of the tank and other hardware, as well as the base cost of the capacitor bank itself. The results of the study determined that optimal total energy storage would be at about 100 kJ, which was taken into account when designing the modulator.

A picture of the unit is shown in Figure 3. The entire modulator is placed in oil (although air cooling is also possible). The controls are in a “doghouse” on the lid and the entire assembly lifts from the tank should it need to be serviced. This allows clean and easy access to the modulator.

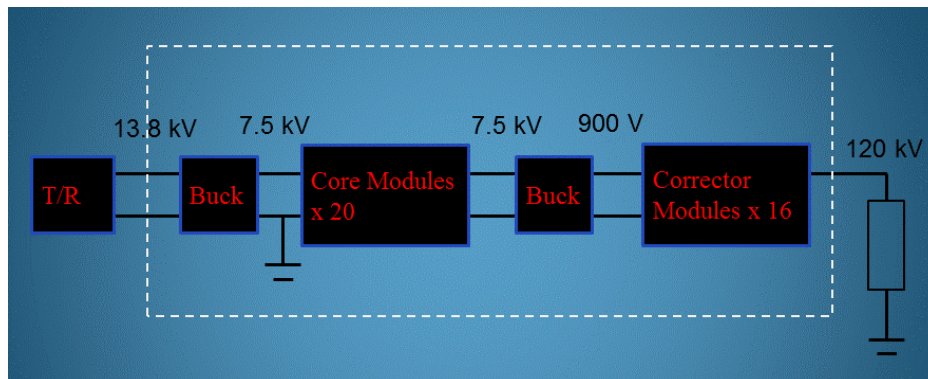


Figure 2. Marx Modulator block diagram.

3 SYSTEM PERFORMANCE

A scope trace of a full specification pulse into a resistive load is shown in Figure 4. Ch. 3 shows the incremental firing of the corrector modules, which are turned on after the pulse begins to droop. The output pulse meets the $\pm 0.5\%$ flattop requirements of the ILC, as shown in Ch. 2.

For large accelerator facilities, the key criteria for selecting a modulator architecture and optimizing its design, is overall cost. Two expensive components of a hard switch modulator are the regulated power supply, and the large energy storage capacitor bank. A Marx bank offers the ability to address both of these cost drivers. The design of the Marx modulator significantly reduces the stored energy requirement. In addition, this same ability to directly regulate output voltage eliminates the need for an external, regulated DC power supply. This enables the modulator to be powered by directly rectifying medium voltage AC power (e.g., 13.8 kVAC). This provides a very inexpensive power supply, based on low cost, utility grade components.

4 CONCLUSION

The Marx Modulator has met all design goals, demonstrating its intended capability for ILC class accelerators. It meets the performance requirements for the ILC, does so in a more compact form factor than other known designs, and is more economical than other technologies. DTI estimates that this class of modulator can be built for $\sim \$300k$ (in ILC quantity), with essentially no additional cost for a power supply. The combination of these factors makes the solid-state Marx bank the optimal approach to constructing ILC modulators and power supplies. Operation of this unit at SLAC will provide additional insight into potential operating refinements, as well as the inherent reliability and performance of the Marx design in combination with prototype ILC klystrons. Figure 5 shows the completed unit.

Based on this SBIR design, it is now possible to refine the ILC Marx design for greater affordability and ease of construction in production systems, for a wide range of long pulse (millisecond plus) accelerator applications, and similar requirements in radars, materials processing, and other applications. The elimination of separate power supplies provides significant simplification of the modulator design, as well as a reduction in overall system size (footprint) and cost. Finally, the high level of pulse control afforded by the Marx design provides the operators of these systems with the unprecedented ability to tailor the pulse risetime and flattop to achieve optimal RF performance for future accelerator systems.

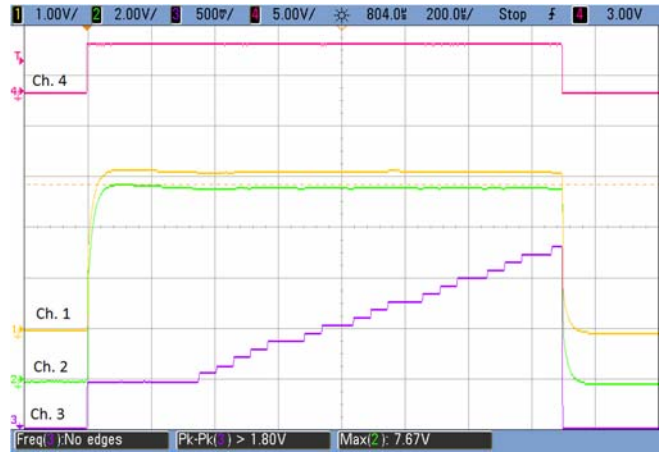


Figure 4. ILC Marx Full-Scale Test Pulse into Resistive Load: 120 kV, 120 A, 1.5 milliseconds. Ch. 1 (Yellow): Load Current at 40 A/V. Ch. 2 (Green): Load Voltage at 16 kV/V. Ch. 3 (Purple): Address Monitor (shows incremental module firing). Ch. 4 (Pink): Command Logic Signal.



Figure 5. Tanked unit delivered to SLAC.