MARX BANK TECHNOLOGY FOR ACCELERATORS AND COLLIDERS

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Abstract

Diversified Technologies, Inc. (DTI) has developed high power, solid-state Marx Bank modulators for a range of accelerator and collider designs. We estimate the Marx topology can deliver equivalent performance to conventional solid state modulator designs, while reducing system acquisition costs by 25-50%.

In this paper DTI will describe the application of Marx based technology to two different designs, built under two separate DOE Phase II SBIR grants: a long-pulse ILC focused design (140 kV, 160 A, 1.5 ms), and a short-pulse design (500 kV, 265 A, 3 µs). These designs span the known requirements for future accelerator modulators. For the ILC design, the primary challenge is minimizing the overall size and cost of the storage capacitors in the modulator. For the short-pulse design, the primary challenge is high speed operation, to limit the energy lost in the pulse rise-time while providing a very tight (+/- 3%) voltage flattop. Each design demands unique choices in components and controls, including the use of electrolytic capacitors in the ILC Marx design.

INTRODUCTION

In the last decade, advances in high voltage, solid state switches have enabled a new class of Marx modulators, using "opening switch" technology for the basic building blocks. Three key advances are enabled by using this class of switches. First, the switches may open under fault conditions with sub-microsecond response, minimizing the energy discharged into a load arc, and the need for arc protection crowbars. Second, the capacitors may be sized for an arbitrarily small droop during the pulse duration, eliminating the need for pulse forming circuitry. Last, the triggering of the individual stages may be staggered, with the non-triggered stages bypassed via a diode, allowing programmable waveform synthesis within a single high voltage pulse.

We are nearing completion of two Marx development projects funded under the U.S. Dept. of Energy SBIR program. Although both of these projects are inspired by advanced accelerator requirements, the detailed engineering requirements of each are quite different.

COMMONALITIES TO MARX MODULATORS

The Marx cell is fundamentally composed of an energy storage capacitor and a pulse switch, with a bypass diode spanning them both (Figure 1). When the pulse switch is closed, the capacitor is added in series to the circuit, erecting the high voltage pulse. If the switch remains open, but other cells are closed (and pulse current is flowing), the bypass diode is pulled into conduction and the cell contributes nothing to the series voltage.

This choice – to fire or not to fire the pulse switch – is the key to synthesizing a desired waveform during the pulse. The usual application is to compensate for capacitor droop by firing additional cells as the voltage falls. We can also use such waveform synthesis to actively compensate for transient effects, such as leading edge ringing due to parasitic capacitance.

Between pulses, the energy storage capacitors must be recharged. At very low repetition rates, this charge can be dribbled in with high impedance resistance or high inductance daisy-chain wiring, which carries little current during the erection of the pulse. For short pulse durations, a common-mode choke topology can be used, with differential leads to recharge the capacitors at low impedance, while providing common-mode impedance during the pulse. This technique becomes impractical for long pulse durations, however, as the choke core becomes prohibitively large to avoid saturation. Instead, the technique of choice for long pulses is to use a second string of high voltage switches to supply a charging chain, firing these switches with gating complementary to the pulse switches (Figure 1).

Diversified Technologies has over a decade of experience building series arrays of IGBTs that act as single high voltage switching elements, and are sufficiently robust to use as hard switches in systems over 100 kV. These arrays are ideal for sizing the individual cells of a Marx modulator to optimize the overall system performance. The use of such series arrays can yield further advantage – since IGBTs generally fail short, a properly sized system can lose a single IGBT and
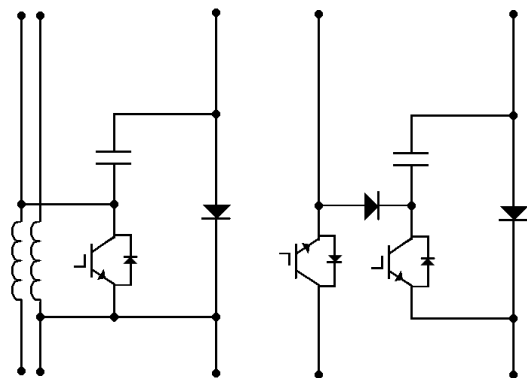

Figure 1: (left) A single Marx cell, recharged via common mode choke, is suitable for short pulses. (right) Long pulses require prohibitively large choke cores, thus recharge is better served via a second switch.

continue to operate at full specification. In order to achieve this capability, there must be a reasonable number (at least five or six) of series IGBTs comprising each cell. Failure of the modulator thus requires double failures within a single cell.

SHORT PULSE HIGH VOLTAGE MARX MODULATOR

We recently completed a solid state Marx Modulator originally designed for the Next Linear Collider (NLC). After the 2004 decision to back a "cold" machine (the superconducting International Linear Collider, or ILC), this project was orphaned, and later redirected to support the Yale Magnicon development – at similar voltage and pulsewidth (500 kV, 1.5 us), but less current.

The charging topology for the short pulse Marx was naturally chosen to be a common-mode choke scheme. In addition to carrying the two-in-hand conductors for charging the capacitors, this choke carried two additional conductors – one with +400V for local housekeeping power, and one to carry a continuous current for core reset. This last winding comprised fewer turns per coil relative to the common return lead, thus a continuous current feed through the stack biased all cores to offset magnetization current.

The system for NLC was originally designed to be air-insulated, to minimize the effects of parasitic capacitance. In addition, the arrangement of the modules was used to "self-shield" the overall system as much as practical, to further reduce parasitic capacitance. For the Yale Magnicon, power efficiency was no longer critical, but compactness (to meet the existing facility constraints) became essential. As a result, we redesigned the system layout for a highly compact, oil-immersed system.

Our optimization calculations settled on a 12.5 kV cell size for this system, which we implemented with a single 0.6 µF capacitor and a six-stage series switch (Figure 2). Each cell was powered via the common-mode choke, and triggered via fiber-optics. An additional optical feed from each cell reported diagnostic information to ground-based controls.

SPICE models for a 500 kV pulse with a 0.625 µP load, 270 pF load capacitance, and 50 cells showed that we could maintain better than +/-1% flatness of the pulse. We included a small amount of *LR* compensation within each module, yet intentionally underdamped this compensation to decrease risetime. We then eliminated the ringing by firing only 44 stages initially, with several more timed to cancel the ring-up, and the remainder spaced out for the duration of the pulse to cancel capacitor droop. SPICE model runs with a wide variety of load and parasitic changes showed that the authority of the waveform synthesis through timing changes was sufficient to maintain a flat pulse over all reasonable conditions.

The physical layout of the cells included significant Faraday shielding (Figure 2), to protect the control logic, diagnostics, internal power, and gate drives from
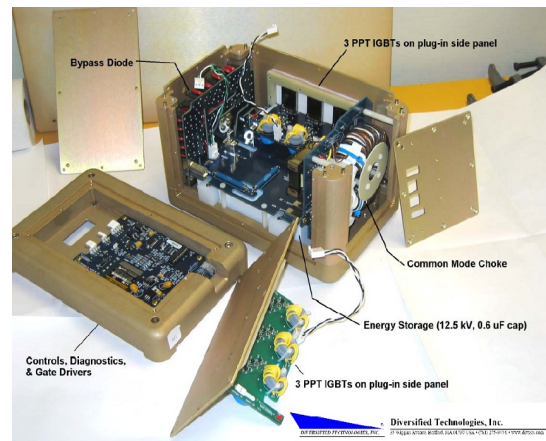

Figure 2: Exploded photograph of a single cell for the short-pulse Marx modulator. This cell has 0.6 uF energy storage, 12.5 kV switching, housekeeping and diagnostics, mounted in a tight Faraday shield.

Figure 3: Nine cells of the short-pulse Marx mounted in a rack for system testing.

transients as other modules are pulsed. We have completed the design, and assembled 9 stages into one rack (Figure 3). With this assembly, we were able to test the controls and pulse output at about 20% voltage (Figure 4). The programmatic delays and scope redirections, as well as the unforeseen expense in machining the Faraday enclosures, precluded completing the full system under the SBIR budget. Completion of the modulator awaits further funding.

LONG PULSE (ILC) MARX MODULATOR

Our second Marx project was directed towards the ILC, with specifications of 140 kV, 160 A, 1.5 ms, and 5 Hz. Unlike the short pulse system, which gravitated towards Marx topology to attain high speed and avoid 500 kV DC infrastructure, we found that the ILC modulator engineering was completely dominated by the long pulse, and the very large delivered energy per pulse.
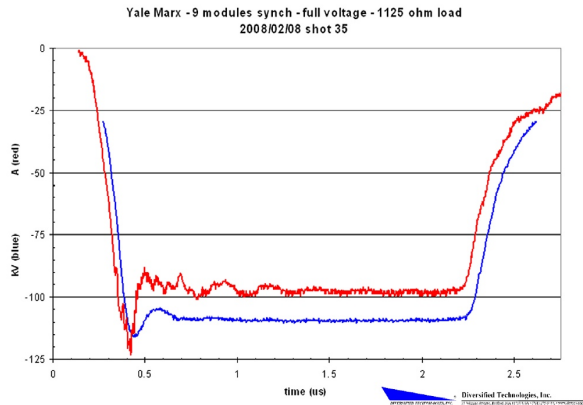
Figure 4: A test pulse of the nine-stage (20%) short pulse Marx has initial charging voltage of 12.5 kV, resulting in 110 kV into 1125 ohms. (Lower/blue: voltage in kV; upper/red: current in amps).

A simple hard switch – or a Marx modulator with simultaneous firing of all cells – would need an energy storage capacitor bank of ~ 1.5 MJ to maintain the specified 1% flattop. This is prohibitive, for reasons of physical size as well as cost. Our preference for a Marx topology is motivated primarily by its capability for waveform synthesis, which allows us to reduce the capacitor bank nearly 10x without sacrificing the 1% flattop specification.

The key to achieving this without unwieldy requirements of high charging currents is to use a dual cell approach. We chose a 6-7 kV cell size for the core cells – each with 8.2 kJ of series electrolytic capacitors and a six stage IGBT switch for pulsing. A second identical switch is used for the charging circuit, eliminating the need for a common mode choke. All of the core modules are fired simultaneously to erect the initial pulse voltage, with high reliability ensured by the *N+1* redundant design.

A hot deck at the top of the core module stack houses a small buck regulator, which steps the 6-7 kV charging supply down to 900VDC. This is passed to the next array of modules, which correct the pulse waveform in 900V steps, ensuring that the 1% pulse flatness specifications are met. No synthesis is necessary for transients – only for droop remediation. We can merely stack the modules in an oil tank, as we do for conventional hard switch modulators at similar voltages (Figure 5).

This project is nearing completion. The corrector modules are completed and tested, and the core modules are in assembly and testing (Figure 6). Full-width pulses have been obtained at partial voltage (Figure 7), and assembly of the tank is complete. Delivery of the full specification system to a DOE laboratory is planned in early 2009.

Figure 5: The ILC Modulator is presently being assembled into a compact unit, for immersion in a 7' x 5.5' oil tank, with controls on top and coax cable pulse output.
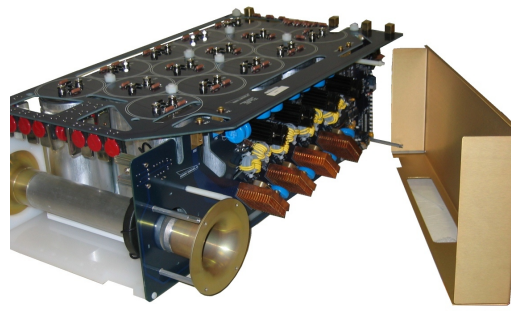

Figure 6: Photo of a long pulse "core" module shows the 8.2 kJ electrolytic capacitor bank and the two four-stage 7kV IGBT switch arrays.
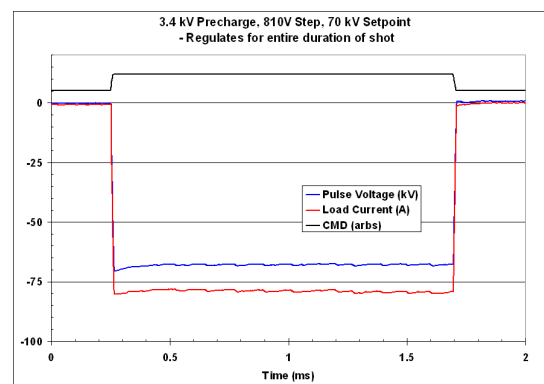

Figure 7: Full 1.5 ms pulse with corrector regulation atop the main high voltage pulse (70 kV into 900 Ohms). The main pulse is constructed through 20 core modules at 3.4 kV each; with the correctors charged to 810 V (+/- 0.6% regulation).

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