Marx Bank Technology for Accelerators and Colliders

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

In this paper DTI will describe the application of Marx based technology to two different designs: 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. This paper will review recent progress in the development and testing of both prototype Marx designs, built under two separate DOE Phase II SBIR grants.

1. Introduction

The Marx architecture – a means of charging capacitors in parallel and discharging in series – has long been used to generate high voltage pulses without the need for DC supplies and switches at equivalent high voltages. Traditionally, these are constructed with spark gaps or other "closing switches", which then exhaust the energy storage capacitors each pulse – necessitating the addition of pulse forming networks to deliver high fidelity waveforms.

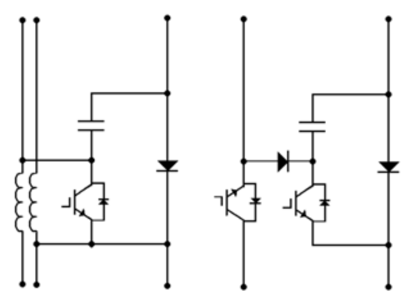

Fig. 1. (left) A single Marx cell, recharged via common mode choke, is suitable for short pulses. (right) Long pulses require prohibitively large choke cores, thus recharge is better served via a second switch.

In the last decade, the advances of 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, eliminating the full energy discharge into a load arc, or 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. Marx modulators can be used for both short and long pulse systems, but the designs for each vary considerably.

Fig. 2. Nine cells of the short-pulse Marx mounted in a rack for system testing.

2. 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 (Fig. 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, the bypass diode is pulled into conduction and the cell contributes nothing to the series voltage. Optimal closing of each Marx cell is key to synthesizing the 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.

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. There are, however, better options. 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. Instead, the technique of choice for long pulses is to use a second string of high voltage switches to supply a charging chain, and fire these switches with gating complementary to the pulse switches (Fig. 1).

Diversified Technologies has over a decade of experience building series arrays of IGBTs that act as single 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 component constraints.

3. Short pulse high voltage Marx modulator

DTI recently completed a solid state Marx Modulator originally intended for the Next Linear Collider (NLC). The NLC requirements were a 1.5 μs pulse (at 120 Hz) of 500 kV and 530 A to drive two X-band klystrons for a "warm" accelerator topology.

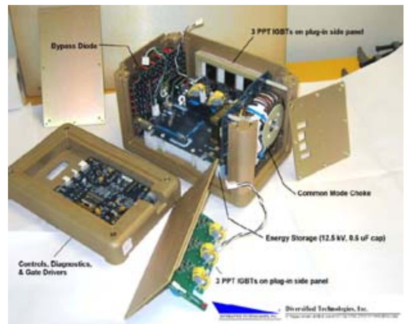

Fig. 3. Exploded photograph of a single cell for the short-pulse Marx modulator. This cell has 0.6 μF energy storage, 12.5 kV switching, housekeeping and diagnostics, mounted in a tight Faraday shield.

The charging topology for the short pulse Marx was chosen to be a common-mode choke scheme. 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 (Fig. 3). Each cell was powered via the common-mode choke HV and housekeeping power, 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.

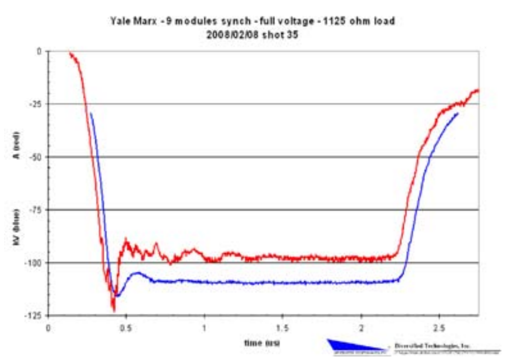

Fig. 4. A test pulse of the nine-stage (20%) short pulse Marx has initial charging voltage of 12.5 kV, resulting in 110 kV into 1125 ohms. (Lower/blue: voltage in kV; upper/red: current in amps).

The physical layout of the cells included significant Faraday shielding (Fig. 3). Logic, diagnostics, power, and gate drives were within a double-shielded inner enclosure, while the IGBTs were mounted against the enclosure walls for heat sinking. The system was designed to use a number of "racks" of cells. Each rack, of 9 or 16 cells, was pre-wired and dressed, then slid into place and interconnected (Fig. 2). This arrangement eased maintenance access to all cells.

We have completed the design, and assembled 9 stages into one rack. With this assembly, we were able to test the controls and pulse output at about 20% voltage (Fig. 4). Completion of the modulator presently awaits further funding.

4. 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.

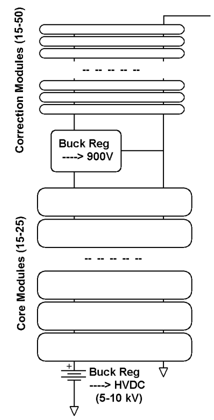

Fig. 5. The topology of the ILC Marx modulator includes a dual voltage scheme to efficiently pulse to high voltage, yet regulate the flat top pulse with small steps.

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. Our preference for a Marx topology is motivated primarily by its capability for waveform synthesis, which allows us to reduce the capacitor bank nearly ten times 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 (Fig. 5). 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. This project is nearing completion (Fig. 6). The system is currently in final test, with delivery to a DOE laboratory anticipated in 2009.

Fig. 6. Long pulse ILC Marx modulator in final stages of completion at DTI.

Acknowledgement

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