

## AFFORDABLE, SHORT PULSE MARX MODULATOR\*

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### Abstract

Under a U.S. Department of Energy grant, Diversified Technologies, Inc. (DTI) is developing a short pulse, solid-state Marx modulator (Fig. 1). The modulator is designed for high efficiency in the 100 kV to 500 kV range, for currents up to 500 A, pulse lengths of 0.2 to 5.0  $\mu$ s, and risetimes <300 ns. Key objectives of the development effort are modularity and scalability, combined with low cost and ease of manufacture. For short-pulse modulators, this Marx topology provides a means to achieve fast risetimes and flattop control that are not available with hard switch or transformer-coupled topologies.

### INTRODUCTION

Under a DOE SBIR grant and based on research begun under the Next Generation Linear Collider (NLC) program, high energy, short-pulse modulators are being re-examined for the Compact Linear Collider (CLIC) and numerous X-Band accelerator designs. At the very high voltages required for these systems, however, all of the existing designs are based on pulse transformers, which significantly limit their performance and efficiency. There is not a fully optimized, transformerless modulator design capable of meeting the demanding requirements of very high voltage pulses at short pulsewidths.

### BACKGROUND

A Marx generator is a system with energy storage capacitors which are charged in parallel at low voltage and discharged in series to provide high voltage output. This is a legacy idea, practiced for decades using resistor charging networks and spark-gaps for discharge. Constrained by the limits of closing switches, such

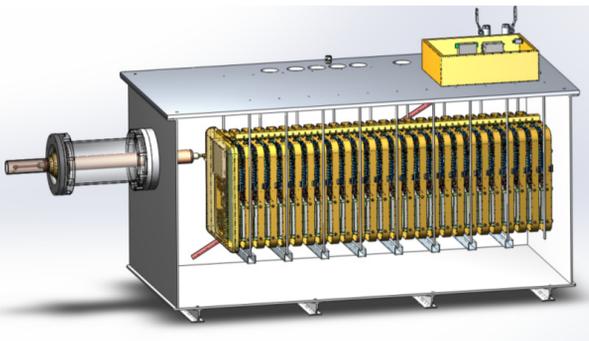


Figure 1: Planned 500 kV Marx modulator with an array of fifty of the plates shown in Figure .

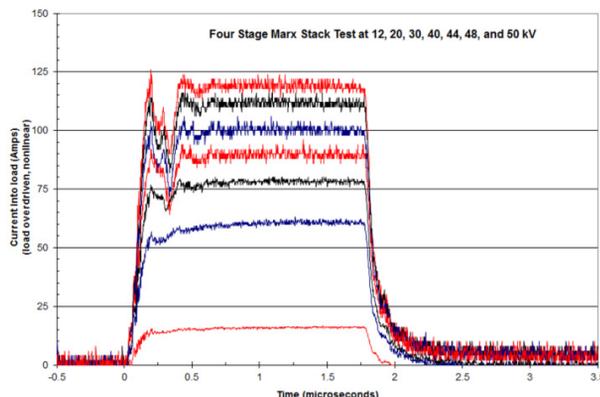


Figure 2: Test pulses of a four-stage Marx bank at 12, 20, 30, 40, 44, 48, and 50 kV. The notch at the beginning of the pulse is the intended result of induced overshoot, which decreases the rise time.

systems required pulse forming networks and crowbars, with their attendant limitations

The Marx topology also enables features which are not common to hard switch modulators. Primary among these is the ability to control each module independently – and thus program the ultimate pulse voltage by choosing the number of modules triggered. The use of a bypass diode rated for full pulse current allows staggering of the modules' turn-on time, and ultimately enables full waveform synthesis in real-time.

### TECHNICAL APPROACH

The Marx topology allows a new degree of freedom unavailable to other architectures – DTI can intentionally underdamp the series snubbing within the pulse circuit. This cannot be done conventionally – the reactive overshoot endangers the load. In a Marx, we can compensate for the overshoot by initially firing only a subset of the switches – thus “sling-shooting” the leading edge faster than otherwise possible. We can tune the number and timing of subsequent module firings to counter the reactive ringing, and hold a flattop pulse to the desired voltage and accuracy (Fig. 2).

Similarly, additional modules may be added to fire sequentially later in the pulse to compensate for capacitor droop. This is a critical enabling technology motivating Marx use for long-pulse accelerators (such as ILC), and yields valuable optimization even for very short-pulse systems. The reduction of capacitor size afforded by this flexibility further reduces parasitic capacitance, and thus reduces equipment size and cost while increasing power efficiency.

\*Work supported by the Department of Energy

## Architecture

The short-pulse modulator under development in this effort is a high peak-power pulse modulator of greater efficiency than presently available, in the 100 kV to 500 kV range, for currents of up to 500 A, pulse lengths of 0.2 to 5.0  $\mu$ s, and risetimes  $<300$  ns. A key objective of the development effort is a design which is modular and scalable, yet low cost, and easy to manufacture and maintain. Recently, DTI significantly reworked its original Marx bank architecture to achieve a low-cost, highly modular, and scalable design without compromising pulse performance.

## Gate Drives

The relatively high per-module voltage (10-12.5 kV) precludes the use of single IGBTs within each module – thus series switch technology is an enabling feature for this system. For most high voltage modulators, all IGBTs pulse in unison, and a single ground based control system provides both motive power and timing control to all of the “floating” or “high-side” gate drives at the various successive stages. In a solid-state Marx modulator, the topology is quite different. The central ground-based control must determine which subset of modules are fired at any time, thus the “command on” signal changes from a single-bit control pulse into an effective address for each individual module.

For this effort, we took the opportunity to redesign the gate drives with a different topology. Instead of the magnetically coupled gate pulses, we have chosen a more robust gate drive with independent magnetically coupled power and optically coupled gate triggers. This is a far more “brute force” approach, usually reserved for larger high voltage systems, but has the advantage that there is no asynchronous refresh, thus no opportunity for jitter.

## Overall Topology

The physical layout of the Marx system has similarly undergone changes compared to our earlier work. In this effort, we revisited the ideal of a flat-pack design, where each module is a thin “pancake”. Thus, the system-to-ground capacitance from each module is that of a thin segment of a coaxial capacitor. The large area of each “pancake” is exposed only to modules immediately above and below in the stack. Since the parasitic energy is proportional to  $V^2$ , rather than linear in  $V$ , we believe the new design will have better than a 10% parasitic capacitance reduction (hence faster risetime) than the prior approach, and far fewer mechanical components.

The co-location of devices inherent in the flat-pack design requires that all the shielding take place either within the multiple layers of the circuit board, or within shielding cans soldered onto the board. A peripheral corona shield minimizes voltage gradients between the Marx bank and the tank walls, as well as directing the parasitic charge into an appropriately stiff driven portion of the system circuitry.

Table 1: Yale Marx Design Parameters

Pulse Voltage	500 kV
Pulse Current	250 A
Pulse Width	1.8 $\mu$ s
Repetition Rate	20 Hz
Module Voltage	12.5 kV
Module Capacitance	0.6 $\mu$ F
# Modules for Base Pulse	40
Total # Modules in System	48-50
Expected Risetime	300 ns
Heater Voltage	24VDC
Heater Current	21A
Insulation	oil

## Design Benefits

**Reduced module costs** - Through the use of PC board trace shielding and RF cans in sensitive areas of the circuit, we were able to co-locate controls directly on the board within reasonable proximity to pulsed current sections of the same board. By exposing the IGBTs directly to the oil, we can cool the devices effectively while eliminating machined parts and hardware, further reducing the module parts count, associated materials, and assembly costs. Since the flat-pack design significantly reduces voltage gradients from module to module within the Marx bank, the only significant need for corona and field reduction geometry is at the interface between the



Figure 3: Stack of four connected modules viewed on edge. Fifty of these modules are shown connected in Figure.

Marx bank stack and the walls of the tank. We anticipate more than a four-fold reduction in module mechanical costs, with the potential for additional reductions in manufacturing costs, compared to earlier designs.

**Simpler Interconnect** - Each module in the redesigned Marx bank plugs directly into the two adjacent modules (Fig. 3). We oriented the connectors and offset the board components and corona shields to allow any individual module to be added or removed from the stack, much like a book on a shelf, without any significant disassembly of support structures or disruption of the rest of the Marx bank. Since all module electrical connections and buswork are integral to the modules, only the fiber-optic control line (and optional fiber-optic monitor) needs to be externally connected. The first module in the stack plugs into a connector supplying charging HV, core bias current, auxiliary housekeeping power, and ground. A connector on the final module is connected to the Marx output coaxial cable, and includes a loopback for the common-mode choke bias current.

**Scalability** - The flat-pack Marx design is inherently modular and scalable, as additional plates may be added for a wide range of voltages. Whether at 100 or 500 kV, a Marx bank can use the same modules. The primary impact of additional plates is an increase in the charging current at the first plate, since it carries the current for all subsequent plates as well. Stray capacitance is also greatest at higher voltages, assuming constant spacing to the tank.

### Prototype Testing

During testing of the prototype bank, we ran all four gates synchronously for a 1.5  $\mu\text{s}$  pulse, with a 10 kV pre-charge into the system, resulting in a 40 kV output. The prototype modules performed flawlessly into high voltage, with none of the chatter or jitter that would otherwise be associated with gate drives impacted by noise coupling at high voltage. We then demonstrated the pulse-staggering capability of the Marx design by delaying the successive modules by 0, 0.5, 1.0, and 1.5  $\mu\text{s}$  on a 2.3  $\mu\text{s}$  pulse with a 7.5 kV pre-charge (Fig. 4). The distributed effect of the snubbing RL networks is clearly apparent here, with the fractional overshoot visible as each successive stage turns on into the high impedance load.



Figure 4: Four modules operated in staggered pulse mode, showing the individual control of each module.

### Status/Plans/Conclusion

DTI has completed the redesign of the short-pulse Marx modulator and demonstrated multiple modules working both synchronously and in staggered operation. DTI is building and testing the complete 500 kV modulator, and will install it at the Yale University Beam Physics Laboratory for operation with Yale's Magnicon amplifier.

In Phase III, DTI will extend this design to future short-pulse, high voltage modulators for the next generation of planned accelerators, as well as transition this design to industrial / medical accelerators. We believe that the same combination of modular, low cost elements demonstrated in this Phase II effort will allow solid-state modulators to finally reach a price level that will supplant traditional (but low cost) thyatron / PFN designs currently used in these systems.