AFFORDABLE SHORT PULSE MARX MODULATOR *

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Abstract

Under a U.S. Department of Energy grant, Diversified Technologies, Inc. (DTI) has developed a short pulse, solid-state Marx modulator. The modulator is designed for high efficiency in the 100 kV to 500 kV range, for currents up to 250 A, pulse lengths of 0.2 to 5.0 µs, 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.

I. INTRODUCTION

Under a DOE SBIR grant and based on research begun under the Next Generation Linear Collider (NLC) program, Diversified Technologies, Inc. (DTI) has developed a short pulse, solid-state Marx modulator relevant to the Compact Linear Collider (CLIC) and numerous X-Band accelerator designs (Figure 1). The modulator is designed for high efficiency in the 100 kV to 500 kV range, for currents up to 250 A, pulse lengths of 0.2 to 5.0 µs, and risetimes <300 ns (Table 1). This fully optimized, transformer-less modulator design is capable of meeting the demanding requirements of very high voltage pulses at short pulsewidths.

Table 1. Yale Marx Design Parameters

Pulse Voltage	500 kV
Pulse Current	250 A
Pulse Width	1.8 us
Repetition Rate	20 Hz
Module Voltage	12.5 kV
Module Capacitance	0.6 µF
# Modules for Base Pulse	40
Total # Modules in System	48 – 50
Expected Risetime	300 ns
Heater Voltage	24 VDC
Heater Current	21 A
Insulation	Oil

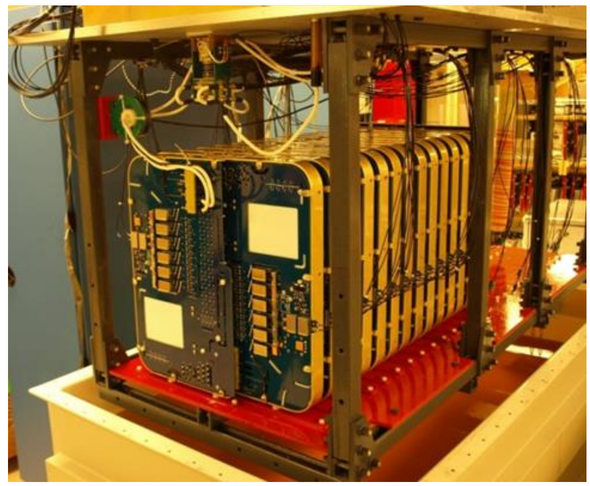

Figure 1. The Yale Marx 500 kV modulator charges many stages in parallel at low voltage, then discharges in series at high voltage. Each 12.5 kV, 250 A “flat pack” module is identical, providing for low fabrication and assembly cost.

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 (Figure 2). 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 systems required pulse forming networks and crowbars, with their attendant limitations.

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-shotting” the leading edge faster than otherwise possible. We can tune the number and timing of subsequent module firings to

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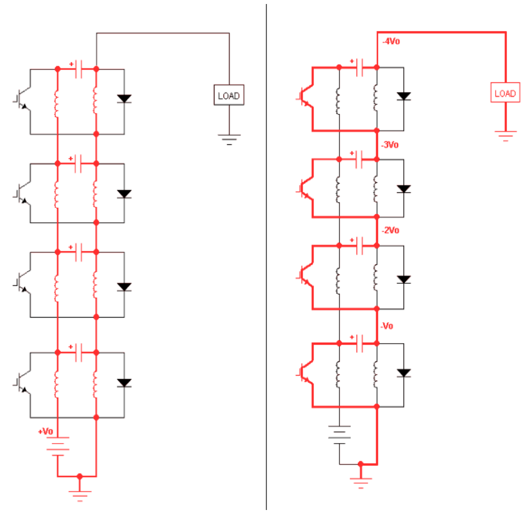

Figure 2. Marx bank theory; current flow shown in red. During charging (left), capacitors are charged in parallel at low to medium voltage. During the pulse (right), capacitors are erected in series to achieve high voltage output.

counter the reactive ringing, and hold a flattop pulse to the desired voltage and accuracy.

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.

II. 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 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.

III. SIMPLER INTERCONNECT

Each module in the redesigned Marx bank plugs directly into the two adjacent modules. 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.

IV. 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.

V. TESTING

During preliminary testing, we ran controls tests to demonstrate pulse shaping via staggered module turn-on. Figure 4 is a screen shot from a test conducted at 60% full voltage (280 kV, 185 A) into a resistive load at DTI. The gray trace shows the voltage output when 30 modules, each at 9.5 kV, are turned on at once. After the peak voltage is reached, the pulse quickly droops. The green trace however shows that a flattop pulse is achieved in the case where 21 modules are turned on during the base pulse and the turn-on of the 9 remaining modules are delayed.

DTI recently completed full testing of a stack of 48 plates to 500 kV into a resistive load (Figure 3) with a pulse rise time of 1 μs. Flattop performance will be much improved into the perveance load given by the magnicon. The unit has been shipped and is awaiting installation at the Yale University Beam Physics Laboratory. DTI expects to assist with integration and final testing with Yale’s magnicon.

VI. FUTURE PLANS

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) thyratron / PFN designs currently used in these systems.

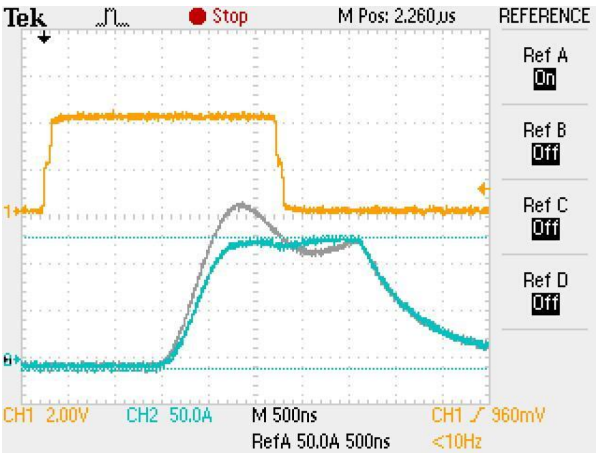

Figure 4. Module control tests at 60% full voltage (280 kV, 30 modules at 9.5 kV) into a resistive load. Gray trace is voltage when 30 modules are turned on at once. Green trace is voltage when 21 modules are turned on at once and the remaining 9 modules have delayed turn-on.

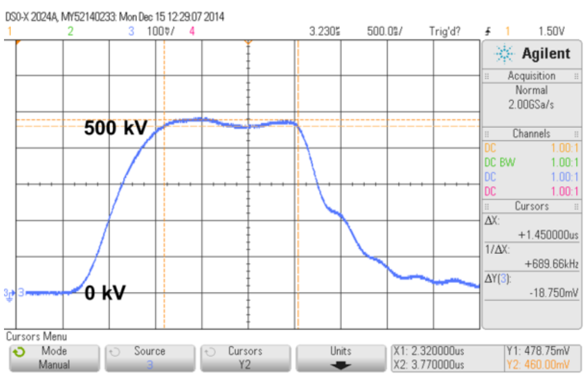

Figure 3. Output pulse voltage with 48 plates, showing 500 kV with staggered plate switching to optimize flat top. 106.2 kV/div, 500 ns/div.