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 (Figure 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 μs, and risetimes <300 ns. Key objectives of the development effort are modularity and scalablity, 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 simply not available with hard switch or transformer-coupled topologies. In this paper, DTI will describe the new design and provide an update on progress.

INTRODUCTION

The high energy physics community continues to plan the next generation of particle accelerators. These accelerators will require large numbers of RF cavities, producing field gradients undreamt of a dozen years ago. The modulators that will drive the klystrons for these new accelerators must meet pulse risetimes, flatness, and repeatability beyond the current state-of-the-art. Overlaid on these technical specifications are increasing demands for reliability and up-time, which far surpass the norm for high voltage electronics. Fortunately, solid-state modulators, with proven architectures for a wide range of pulse characteristics, are available to meet future demands.

High energy, short pulse modulators are the next frontier. Based on research begun under the Next Generation Linear Collider (NLC) program, modulators of this type are being re-examined for the Compact Linear Collider (CLIC) and numerous X-Band accelerator designs. There is not, however, a fully optimized, transformerless modulator design capable of meeting the demanding requirements of very high voltage pulses at short pulsewidths.

Solid-state Marx modulators have gained preferred status alongside alternative modulator topologies. For example, the hybrid modulator, consisting of a solid-state switch with pulse transformer, achieves better performance than conventional thyratron/PFN designs, but has significant risetime and flattop limitations compared to the Marx architecture. Alternative designs, with multiple primary switches driving a pulse transformer with series-connected secondaries, have similar pulse performance limitations. The Marx topology, however, provides a means to achieve astounding short-pulse risetimes and flattop control that are simply not available with hard switch or hybrid topologies. The basic proof of principle of solid-state Marx architectures has been demonstrated by several organizations, including DTI. Deployable solutions for high voltage, short pulse accelerators have not previously been available, however, DTI believes that this flat-pack design will provide the required performance and reliability at a cost that is competitive with existing technologies.

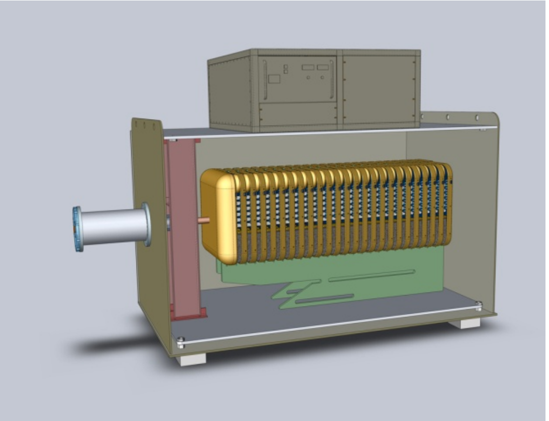

Figure 1: Planned 500 kV Marx modulator with an array of fifty of the plates shown in Figure 3.

ARCHITECTURE

The short-pulse modulator 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 us, 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.

DTI’s previous prototype experiments quickly showed that a design which optimized risetime incurred very high *dI/dt* throughout the switching circuitry – and thus required extreme attention to detail to eliminate induced currents in nearby logic, gate drives, and diagnostics circuitry. In addition, the very high system voltage incurred significant capacitive pickup on the higher stages on pulse leading and trailing edges. These burdens were remediated by careful circuit design and layout and precise mechanical Faraday shielding. The design makes use of both filter and snubbing elements to protect the sensitive sub-circuits. It also includes careful routing and layout in order to guarantee that such inductive pickup as exists does not drive parasitic secondary currents in harmful areas.

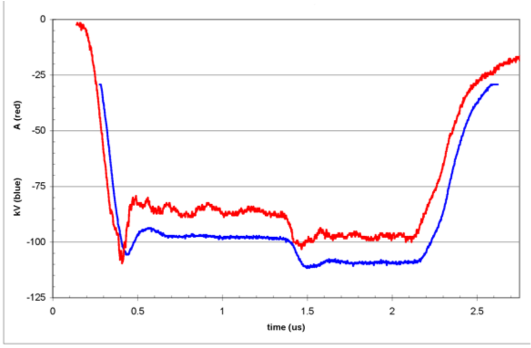

Figure 2: Test pulse of a 100 kV Marx system with eight modules pulsed synchronously, and the ninth stepped on at mid- pulse. This test is at full voltage (12.5 kV pre-charge) into a 1125 Ohm load. Red (upper) trace is pulse current in Amps, Blue (lower) trace is pulse voltage in kV.

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. Over the last decade, DTI has developed a number of proprietary technologies for gate drives, each one accompanied by various constraints, advantages, and disadvantages. 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.

Benefits of the Design

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.

Simpler Interconnect - Each module in the redesigned Marx bank plugs directly into the two adjacent modules. (Figure 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

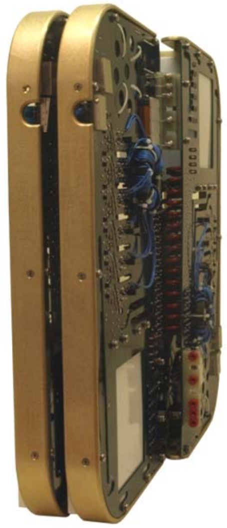

Figure 3: Stack of four connected modules viewed on edge. Fifty of these modules are shown connected in Figure 1.

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 μs 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 μs on a 2.3 μs pulse with a 7.5 kV pre-charge (Figure 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/CONCLUSIONS

DTI has completed the redesign of the short pulse Marx modulator and demonstrated multiple modules working both synchronously and in staggered operation. In Phase II of this effort, DTI will build and test a complete 500 kV modulator, and install it at the Yale University Beam Physics Laboratory for operation with Yale’s Magnicon amplifier.
