Prototype Development Progress Toward a 500 kV Solid State Marx Modulator*

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Abstract— **Recent advances in IGBT and SiC technology have made possible a range of solid-state modulator concepts that were unthinkable a decade ago. Power densities and speeds of pulsed-power circuits have increased dramatically due to the commercial introduction of fast, multi-kilovolt IGBT silicon and SiC diodes featured in PCB-style packages.**

A solid-state modulator concept that stands to benefit considerably from recent IGBT and SiC breakthroughs is the Marx configuration -- where an array of stacked modules generates high-voltage output pulses directly from a low voltage DC supply. The Marx scheme avoids the large, inefficient and costly magnetic cores inherent in standard modulator designs, resulting in a considerably simpler, cheaper and more compact mechanical solution. The main disadvantage to this approach is that the individual cells in a Marx bank must float at high voltages during the pulse, complicating the distribution of power and timing signals.

This paper examines in closer detail the practical advantages and pitfalls of a solid-state Marx configuration, and explores a design approach with emphasis on performance, wall-plug efficiency, cost of manufacture, availability and ease of service. The paper presents electrical diagrams, mechanical CAD layout and preliminary prototype test data.

I.   INTRODUCTION

Several interesting proposals [1] [2] [3] [4] for solid-state Marx bank modulators have emerged in recent years. Richter-Sand et al [3] have demonstrated a long-pulse 30 cell, 30kV 400A Marx bank that operates at 7.5kW average power with sub-microsecond edge speeds. Casey et al [4] have demonstrated a 5 cell, 50kV design, capable of edge speeds better than 100nS at 24kV and 210A output.

To date, most solid-state Marx research has focused on switching performance and the control of parasitic components within the assembly. However, strategies for optimizing scalability, throughput, efficiency, cost and reliability have yet to be fully explored in the published works. These practical issues will ultimately become of vital concern in evaluating the large-scale feasibility of the Marx bank approach.

II.   DESIGN CONSIDERATIONS

The basic Marx circuit suggested by [3] and [4] is shown in Figure 1. Each Marx 'cell' consists of an energy storage capacitor, an IGBT switch, a free-wheeling diode and a common-mode inductive isolator that distributes the DC

prime power to the next cell. An arbitrary number of cells are stacked to obtain the desired output voltage at the load. The input to output voltage transformation ratio is simply equal to the total number of cells.
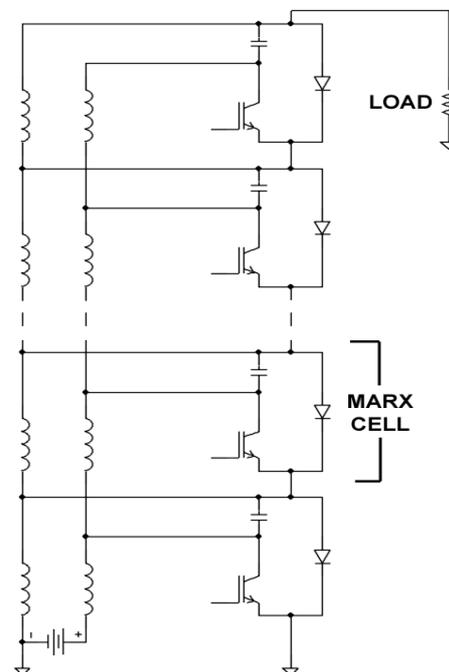
Fig. 1. Basic IGBT Marx Design.

A.   Scaling Limitations

There must be an ultimate limit to the number of cells in a practical Marx design. Several factors come into play here:

1) Current inrush from increasing stray capacitance.
2) Excessive DC charging current in the lower isolators.
3) Lower efficiency as the output impedance increases.
4) Decreasing reliability as the number of cells increases.

B.   Single-point Failure Risks

The probability of critical component failure increases directly with the number of cells. In the basic design scheme of Figure 1, the failure of any single IGBT or capacitor will fail the entire modulator by shorting out the input DC power. These critical single-point failures must be eliminated in any practical design with large numbers of cells. The transmission scheme for vital control data and timing fiducials must also be massively parallel in nature, to avoid single-point control-induced failures.

C. Design Robustness

For applications that require long run-times between scheduled maintenance, the modulator must be able to seamlessly 'work around' component failures as they occur during normal operation. In a practical Marx design this requires keeping a certain number of spare cells in 'standby' mode, which the modulator could bring online as needed. The number of spare cells would depend on the length of the desired run-time and the overall reliability of the cells.

III.   DESIGN OPTIMIZATIONS

The design example for this paper is a solid-state 500kV, 550A Marx modulator, operating at 120PPS. Given that the highest voltage IGBT silicon currently available is 6500V, an IGBT-based design will obviously require a large number of cells. It is possible to construct larger voltage cells by using multiple IGBTs in series within each cell. However this scheme does not ultimately reduce the total number of IGBTs or HV diodes required, and introduces the risk of over-voltage damage to the slowest IGBT within each cell. MOVs or snubbers across each IGBT can reduce this risk, but at increased component expense and switching loss. Using a higher cell count avoids this risk entirely, allows the use of lower DC input voltages, and provides finer control resolution of the output waveform.

The proposed IGBT Marx topology is shown below.
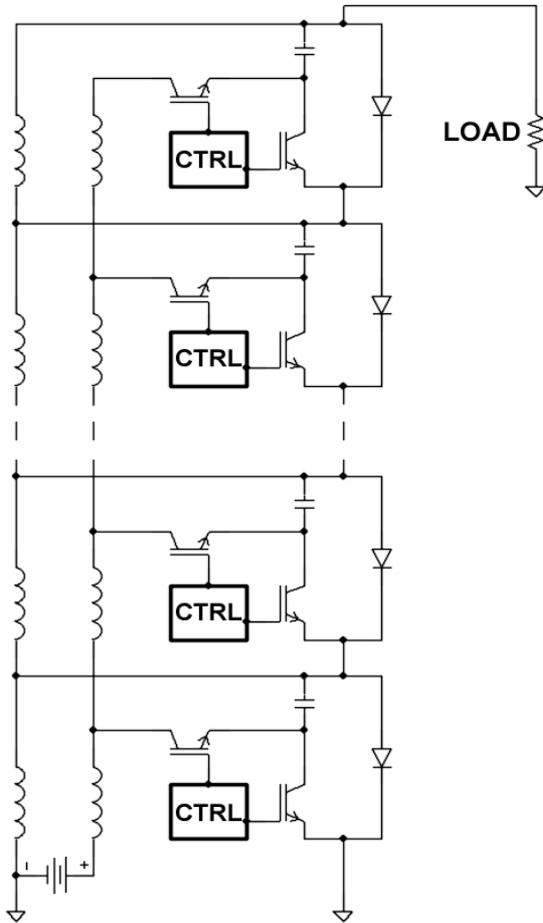
Fig. 2. Proposed Design with HV Control.

A. Mitigating Single-point Failures

Failures of any IGBT or capacitor in the basic Marx design of Fig. 1 will fail the entire modulator. These single-point risks are mitigated by adding a simplified high-side IGBT buck regulator to each cell, as shown in Figure 2. This regulator serves three vital functions:

1) Control of inrush currents during modulator startup.
2) Local regulation of the cell operating voltage.
3) Isolation of the cell from the main DC charging path, in the event of a cell failure.

Failure of the free-wheeling diodes is not critical, as the diodes invariably fail shorted, and can continue to carry the full modulator current. The cell control module associated with the shorted diodes will disable that cell, upon detecting the resulting overcurrent in its IGBT.

The local cell control module receives timing fiducials and control data from the central controller through an RF wideband link using inexpensive off-the-shelf 2.4GHz telecom chipsets. Each cell communicates directly with the central modulator controller, avoiding the potential single-point failures of a daisy-chained or optically-coupled communications link. The local cell control circuit also performs corrections of timing skew introduced by each IGBT and gate driver, allowing the cells to be synchronized to within a few nS without the need for hand-tweaking.

B. Electric Field Control

Assuming a 500kV risetime of 250nS, electric field movements can reach speeds of 2MV/uS. Even a stray capacity to ground of 1pF would experience a 2A current. It is critical not only to minimize the stray capacitance of the cell structures to ground, but to shield the local cell control electronics from these fast electric fields as well.

In order to shield the individual cells and to simplify the overall mechanical design, the Marx bank is arranged into 32 individually shielded blocks, as illustrated in Figure 3.
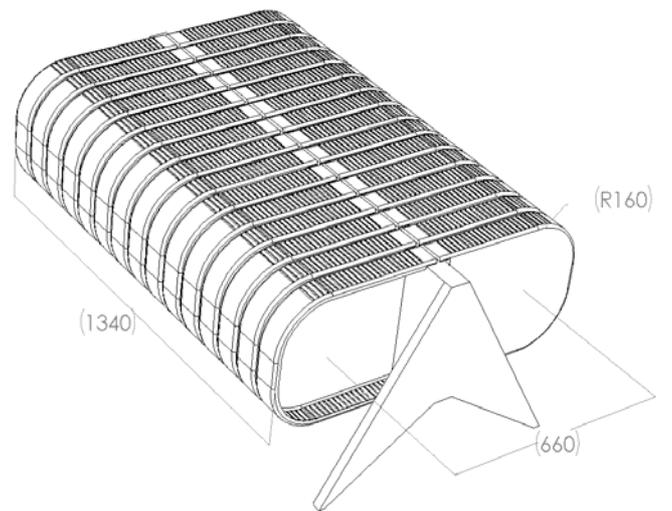
Fig. 3. Proposed Marx Modulator Stack. Dimensions in mm.

The stack lies horizontally as shown, with a backbone that runs through the center of the stack. The backbone structure supports the 32 blocks, and provides simple

electrical interconnectivity from block to block. The individual block assemblies weigh about 21kg each, and can be removed from the top for servicing. The first 30 blocks closest to ground contain 12 Marx cells each, integrated onto a single G-10 PC board. The two blocks closest to the klystrons are reserved for klystron utilities, pumps and diagnostics. In addition to the 48VDC present on the backbone, the HVDC can be switch-mode converted down to suitable voltages and currents for klystron filament use. The entire modulator is immersed in standard transformer oil, which supports the electric fields and transfers waste heat from the cells to a single water heat-exchanger.

The outer aluminum casing of each block structure is radiused to minimize the electric field on the outer surface, and is electrically connected to the center of the 12 Marx cells contained within. Capacitively induced currents incurred by the shield drain directly to the high current path, and appear as an increase in the risetime surge current. Each block shield contributes about 5pF to the overall capacitive load, although only the upper 30% or so of the blocks store any appreciable energy. The total stored energy in the stray stack capacitance to ground at 500kV is about 5J, and the two klystron cathodes contribute approximately 25J total.

Each block generates 18kV total from its 12 cells. The 18kV is arranged symmetrically around the shield potential, so that internally the cells never experience a voltage excursion of greater than 9kV. Each cell control module has electrostatic shielding around critical timing components.

C. Block-level Integration

The cell layout inside the block attempts to minimize volume and current path inductance, while allowing enough space for the free passage of oil through the block. The internal arrangement of the block is shown in Figure 4.
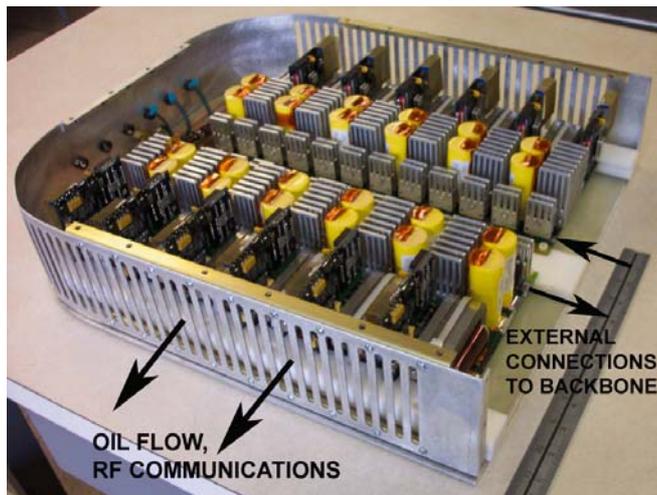
Fig. 4. Prototype block assembly containing 12 Marx cells.

The 12 Marx cells are arranged in two rows of six, with the free-wheeling diodes placed closest to the central plane. The FWDs have the shorter heatsinks, and the IGBTs use the larger ones between the capacitors. The aluminum outer case connects electrically to the midpoint of the string, near the left-hand side of the block assembly. The control module of each cell faces towards the outside, allowing the 2.4GHz antenna an aperture through the vertical slots in the shielding. The block attaches mechanically and electrically to the support backbone along the right-hand edge.

D. Marx Cell Design

Each cell consists of an IGBT, energy storage capacitor, free-wheeling diode, inductive isolator and a cell control module, arranged as shown in Figure 5.
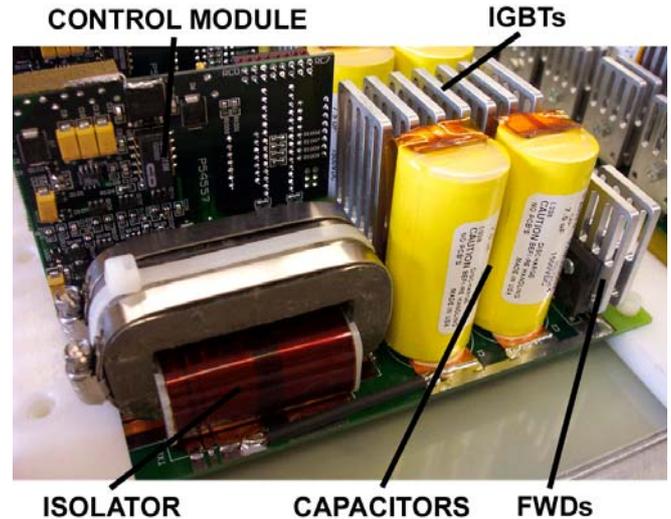
Fig. 5. A Marx Cell.

All of the components including the inductive isolator are designed for surface-mount assembly. The IGBTs and FWDs come in standard flat plastic cases, which stack easily with interspersed heatsink plates. The cell control module mounts vertically to the main board, and contains the DC regulators, timing circuitry, PIC microcontroller, IGBT gate drivers and charging regulator.

IV. PROTOTYPE TESTING AND EVALUATION

Performance evaluation of the prototype 12-cell Marx block will include the following tests:

- Control module stability under high dV/dt conditions
- Effects of capacitive load surge currents on IGBTs
- Waveform efficiency at 18kV, 550A
- Thermal performance at a full rep-rate of 120Hz
- Effects of high dV/dt electric fields on outside of case
- Effects of hard short-circuits, using triggered sparkgap

A. dV/dt effects on control module stability

As shown in Figure 4, each cell control module is in close proximity to the aluminum case. The electric field between the control module and the case can change at speeds up to 180kV/uS for cells at the ends of the block rows. Initial tests revealed field-induced timing skew errors as high as 200nS at full operating voltage with no shielding. Adding a simple electrostatic shield around the timing circuitry appears to have solved this problem.

B. Effects of capacitive surge currents

Capacitance in the klystron load and the stray capacity of the bank itself will shunt a substantial amount of current to ground as the voltage rises. This initial surge current is in addition to the normal load current and must be supported by the IGBTs, energy storage capacitors and FWDs in each cell. Simulations of the electric field energies and lumped-circuit parameters predict peak IGBT surge currents of about 1000A, leveling out to the nominal 550A within about 150nS. For the single-block test we added a 5000pF capacitive load in parallel to the 32ohm resistive load to simulate the 30-block capacitive load of 166pF. The actual resultant surge current was about 850A x 200nS, owing to the current-limiting action of the IGBTs. No irregular circuit performance or overheating was observed in repetitive pulsed operation.

C. Waveform efficiency at 18kV, 550A output

When driving a load with a non-linear response such as a klystron, it is important to shape the contour of the output voltage waveform so the klystron can use as much of the pulse energy as possible. Since the NLC klystrons are normally operated in the space-charge limited regime, the klystron beam current I_b is proportional to the beam voltage V_b to the 3/2 power. The instantaneous beam power is therefore proportional to $V_b^{5/2}$. The waveform efficiency is calculated by plotting the waveform of $V_b^{5/2}$, and placing the largest possible rectangle under the waveform with the required pulse width. The calculated efficiency is then simply the area of the rectangle divided by the total area under the $V_b^{5/2}$ waveform.

Figure 6 below shows the output voltage and current waveforms of the single block operating at 18kV and 550A, into a 32ohm resistive load immersed in water. Figure 7 shows the calculated waveform efficiency based on the voltage waveform $V_b^{5/2}$. The $V_b^{5/2}$ waveform and the usable area are both multiplied by a constant of 6e-7 in order to plot them on the same graph as Vb for comparison.
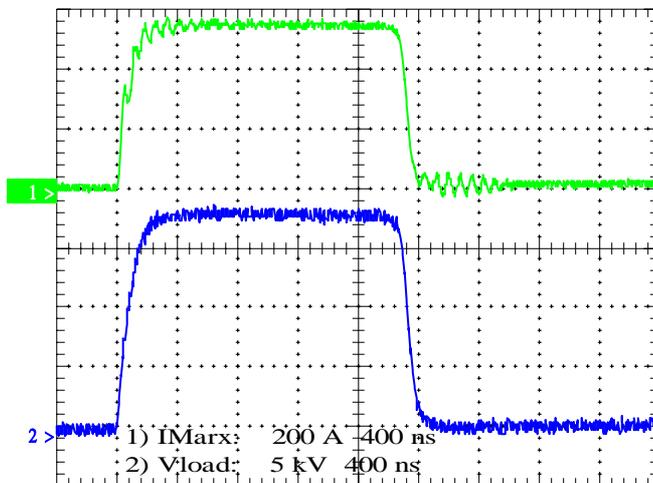
Fig. 6. Prototype output voltage and current waveforms.
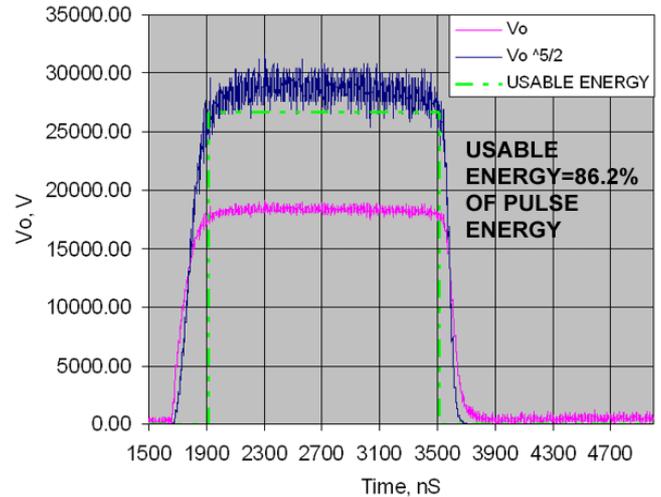
Fig. 7. Waveform efficiency.

V. CONCLUSION

To determine the feasibility of the Marx approach, there are several critical parameters that still need to be explored:

- Thermal performance at 120Hz operation
- Effects of high dV/dt electric fields on block shielding
- Effects of hard short-circuits, using triggered sparkgap
- Overall modulator efficiency
- Overall modulator MTBF, MTTR and availability
- Production costs

The first three tests can be performed at the single-block level. The other tests will be performed on a complete 30-block prototype modulator.

At this early stage there appears to be no fundamental limits preventing a solid-state Marx design from providing 500kV, 550A service to two klystrons with nominal load capacitance. Further test results will be presented at the PESC04 conference poster session, and in future papers.

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