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Design of a Marx-Topology Shaped-Pulse Modulator for FNAL *

M.A. Kemp[ξ], T. Beukers
SLAC National Accelerator Laboratory
Menlo Park, CA, USA

T. Butler
Fermi National Accelerator Laboratory
Batavia, IL, USA

Abstract

Fermi National Accelerator Laboratory is undergoing an effort to upgrade the 201 MHz Proton Source system. One subset of this upgrade is addressing the triode modulator reliability and performance issues. SLAC National Accelerator Laboratory proposes a Marx-topology modulator to replace the existing system. This paper presents the system design of this modulator, the SLAC F1 Marx.

I. INTRODUCTION AND MOTIVATION

The Proton Source Task Force Report was authored at Fermi National Accelerator Laboratory (FNAL) in 2010. The charge was to address the feasibility of operating the FNAL pre-injector, linac, and booster for another 15 years. It was deemed possible, but several upgrades were necessary [1].

One system requiring upgrade is the 201 MHZ triode-based RF power source. The modulator driving the triode has reliability, obsolescence, and performance issues. It uses series-pass regulator vacuum tubes to provide pulsed voltage to the anode of a triode amplifier. A multifaceted waveform is generated including long rise and fall times, a high dv/dt step during the middle of the pulse, and a precise flat top. The shape of this waveform changes from pulse to pulse as it is part of the RF feedback system. Some of the features of this waveform are shown in Fig. 1. Approximate desired characteristics of the triode modulator are given in Tab. 1.

Table 1. Characteristics of the FNAL triode modulator.

Max. Voltage	35 kV
Max. Current	300 A
Total Pulse Width	300 µs
Pulse Repetition Frequency	15 Hz

One potential topology to produce the shaped-pulse needed for the triode application is the Marx bank. This modulator topology has many advantages for high power applications [2]. It also has been utilized for its ability to stagger turn-on and off cells to produce varying-shaped pulses. In the case of the SLAC P1 Marx, staggered turn-on of cells are used to produce a flat waveform. The delayed cells counteract the effect of capacitor droop during long pulses [3]. In the SLAC P2 Marx, instead of delayed turn-on and turn-off of the cells, a buck converter is placed in series with each Marx capacitor. The output of this buck converter is a ramp-up which adds with the drooping capacitance to yield a flat output for each cell [4]. The buck converter is driven by a closed-loop control system which feeds the buck converter with a pulse width modulated (PWM) signal. This has resulted in very accurate and controllable outputs [5].

To fulfill the needs of the FNAL triode modulator, a Marx-topology solution is proposed: the SLAC F1 Marx (F1 Marx). A driving principle is to re-use as much of the

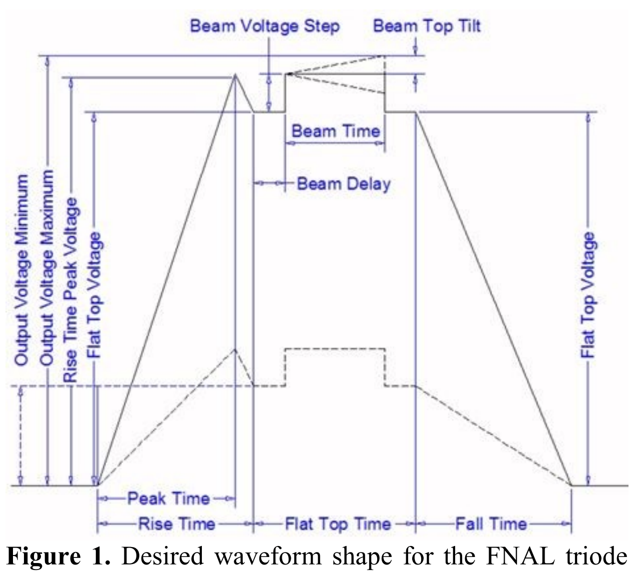

Figure 1. Desired waveform shape for the FNAL triode modulator.

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ξ email: mkemp@slac.stanford.edu

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already-developed hardware as possible. However, rather than produce a flat top as with the ILC P2 Marx klystron modulator, the F1 Marx cells produce an "arbitrary waveform" utilizing a combination of staggered turn-on and turn-off of the cells as well as the PWM-driven buck converter inherent in each cell.

II. THE F1 MARX

A. System Description

The overall layout of the F1 Marx is shown in Fig. 2. The power flows from the 480VAC mains to a AC/DC converter. This power supply system produces three DC bus voltages: 1kV, 4kV, and a second 4kV voltage. These feed a Marx modulator which contains ten "main" cells and five "vernier" cells. The modulator feeds the anode of the triode. Similar to the P2 Marx, master control is accomplished with a centralized application manager.

The cell layout of the modulator is depicted in Fig. 3. All fifteen cells are fed the common 1kV bus. One 4kV bus is fed to the five vernier cells while the second 4kV bus is fed to the ten main cells.

The simplified cell schematic is shown in Fig. 4. This layout is identical to the P2 Marx except for different values of the PWM filter, the snubbers, and the di/dt limiting inductor. These are modified in order to properly handle the specific transient characteristics of the desired waveform.

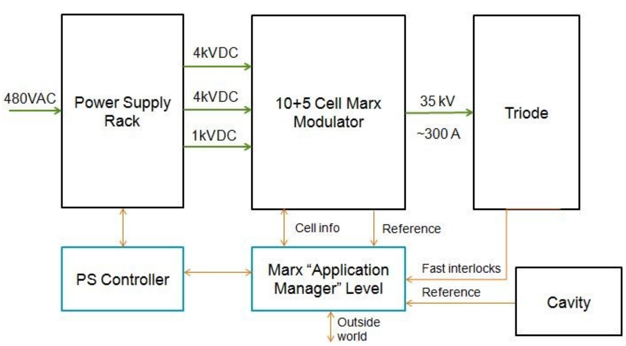


Figure 2. System diagram for the F1 Marx modulator.

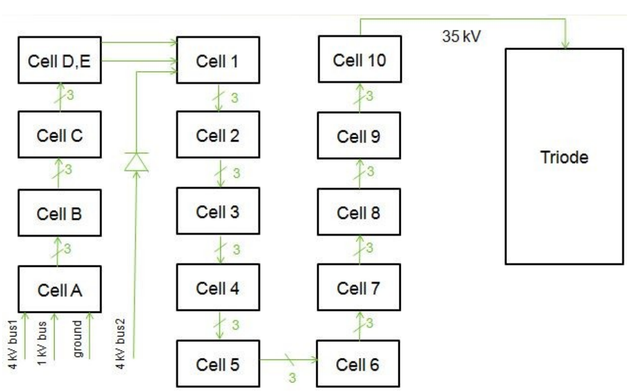


Figure 3. Modulator block diagram for the F1 modulator. The "vernier" cells are denoted by letters (A-E) and the "main" cells are denoted by numbers (1-10).

Articulation of all the desired characteristics of the transient waveform are outside the scope of this paper, but some of the key features will be mentioned. One parameter is the "beam step." This is shown as the beam time in Fig. 1. This is an abrupt step in the waveform that corresponds to when the proton beam enters the cavity. When there is no beam present during the pulse, no beam step occurs. The vernier cells have the role of producing the waveform which corresponds to the beam step. The main cells produce the waveform corresponding to everything else.

Cells affect the output waveform in two ways. First, they can produce abrupt steps when they turn on or turn off. Second, they can produce slower ramp-up, ramp-down, or other characteristics by varying the output from their integral buck converters.

B. Control Algorithm

For the square-pulse P2 Marx, the closed-loop algorithm uses a DC level as a reference. Utilizing a feed-forward scheme, each cell adjusts its PWM timings on subsequent pulses until a very flat waveform is achieved. For the F1 Marx, this algorithm is not viable. For example, a slow overall ramp up and down of the output voltage is required. This is achieved by staggering the turn on and off of the cells. Each cell has a varying amount of droop and may actually be required to ramp up or down during the duration of the pulse. Therefore, each cell will have a different output waveform characteristic. Handling the cell outputs on an individual basis is likely overly burdensome and not necessary. Only the sum total is relevant.

The proposed correction algorithm uses the central "application manager" to control the PWM timings. In addition, every main cell is given the same PWM timing and every vernier cell is given the same PWM timings. This is claimed to be one of the simplest ways to control this complex system.

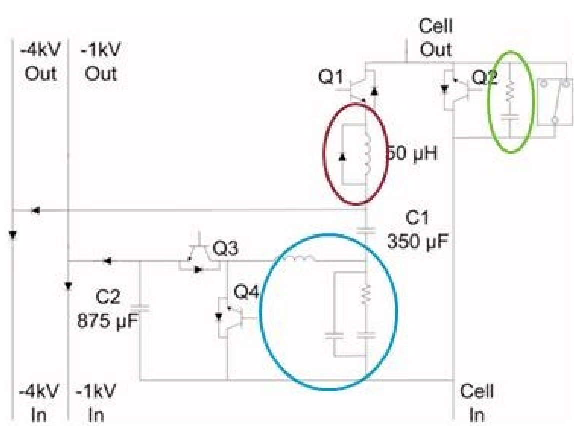


Figure 4. Simple schematic for one SLAC P2 Marx cell. This cell is slightly altered for the F1 Marx by adjusting the PWM filter (blue circle) and the two snubbers (green and brown circles)

III. SIMULATION

To evaluate if the proposed architecture and control algorithm fulfills the requirements of the Fermi system, a circuit simulation was run. A full modulator model was built up within PSpice. For each of the switching elements in the model, the on/off timings were read in from a text file. This includes the PWM waveforms and the overall cell switching times.

Matlab was utilized to generate the switch timings. A desired waveform shape was entered into the script. The default switch timings were output to text files, and PSpice was run by Matlab. The Matlab script then read in the PSpice results and compared them to the desired waveform. An error waveform was calculated, the switch timings were adjusted, and the process repeated. This was done until convergence. A screen capture of the Matlab GUI which was used with this script is shown in Fig. 5.

A typical result from the circuit simulation is shown in Fig. 6. As shown, the slow rise and fall of the waveform is achieved. In addition, the fast vernier cell-driven beam step is also produced. In this case, a ramping-up is programmed in during the beam step.

Fig. 7 shows individual cell voltages during the pulse. Also shown is the PWM driving waveform that is common to all of the cells. The cell voltages in Fig. 7 are the same cell waveforms that were used to produce the overall output waveform shown in Fig. 6. As shown, the actual cell waveforms contain features such as overshoot and ripple. However, when the cells are added together in the Marx topology, they produce the desired waveform. In particular, the modulator voltage from ~100µs to ~150µs in Fig. 6 needs to be very flat. No individual waveform in Fig. 7 is flat during that time. However, the sum produces very little ripple.

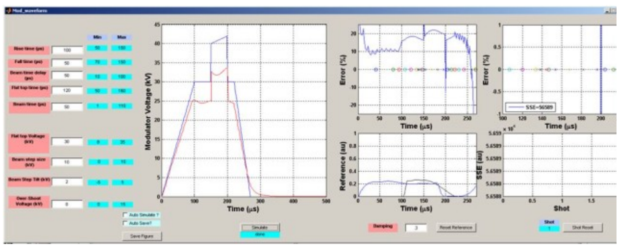


Figure 5. Screen capture of the Matlab gui used to test the control algorithm.

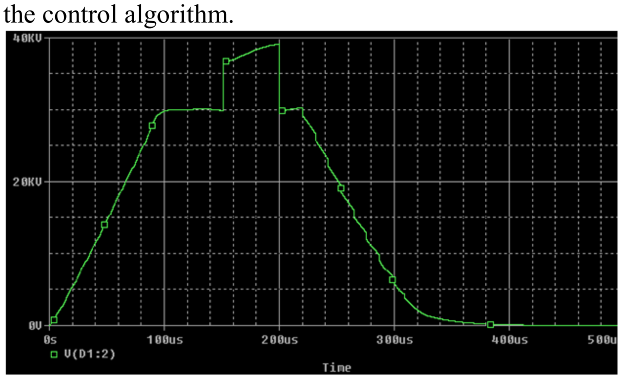


Figure 6. Typical circuit simulation result for the output voltage of the F1 Marx.

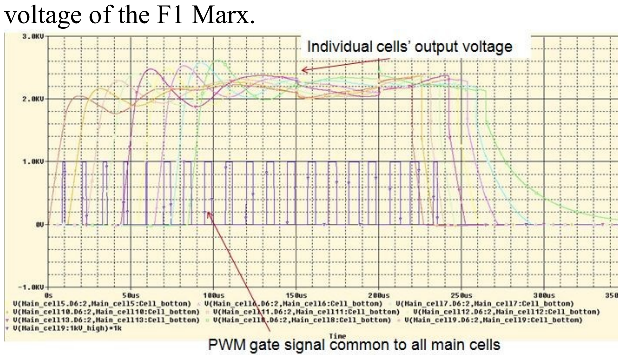


Figure 7. Simulated individual "main" cell voltages along with the common PWM signal. The sum of these

IV. EXPERIMENTS

Prior to prototyping a full-scale modulator, it was desired to test two cells into a resistive load. In this way, critical performance parameters can be verified at minimal cost. Two P2 Marx cells were modified with different values of snubbers, different di/dt limiting inductor values, and a higher PWM frequency.

One critical parameter is the fast rising edge of the modulator pulse during the rise-time of the beam step. To test this, one cell was turned on, and after 10's of µs, a vernier cell was turned on. In this way, the vernier cell turns on into a "current source" generated by the already-on first cell. As shown in Fig. 8, the dv/dt of the single cell is approximately 3.2 kV/µs. The specification for the beam step is for 15 kV/µs. It is hypothesized that this slew rate will add with the inclusion of additional cells. Circuit simulations confirm this claim, so confidence is gained that the full-scale system will meet specifications.

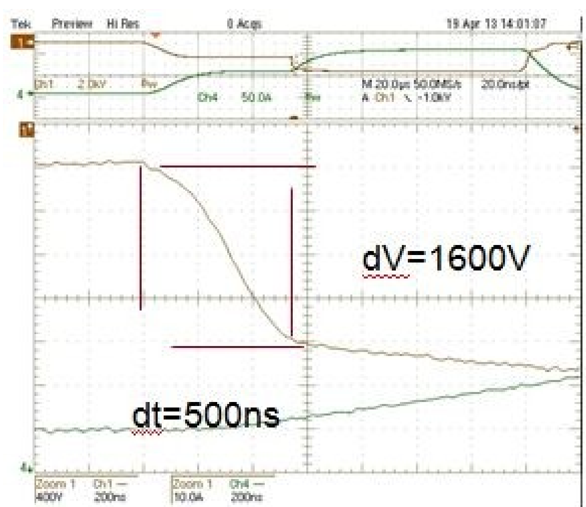
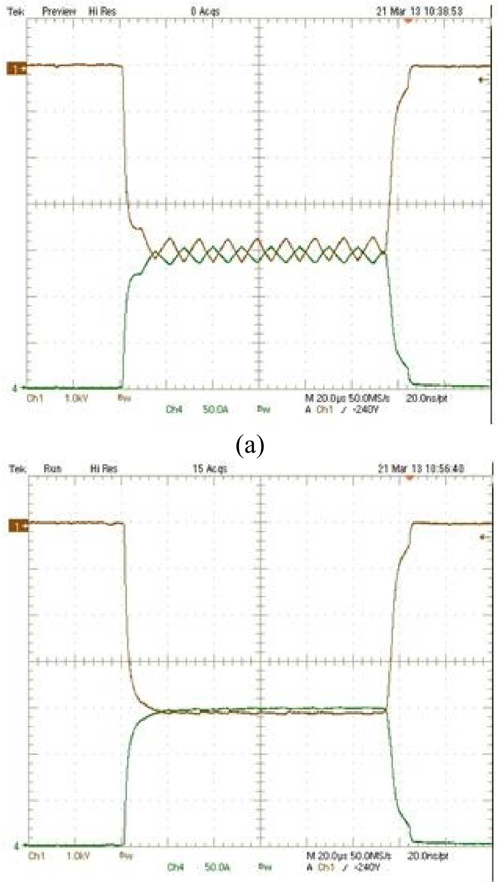


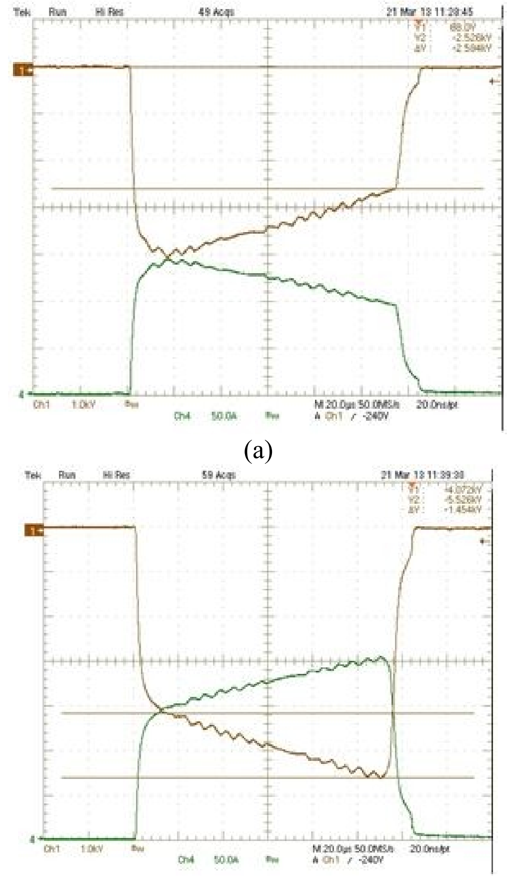
Figure 8. Single "vernier" cell turn-on voltage. Measured dv/dt is 3.2 kV/µs.



(a)

(b)

Figure 9. Two cell tests into a resistive load. These tests illustrate the difference if the PWM timings are (a) in phase and (b) out of phase.



(a)

(b)

Figure 10. Measured waveforms showing the ability of the vernier cells to (a) ramp down and (b) ramp up.

In a second test, two cells were turned on at the same time, but the phase-shift of the PWM timing relative to each other was altered. As shown in Fig. 9, the top traces are the output voltage and current with the cells in-phase with each other, the bottom plot is with the cells out of phase. The ripple is dramatically reduced as the interleaved cell outputs cancel the effective output ripple. Finally, in Fig. 10, the ability of two cells to either ramp up or ramp down is demonstrated.

V. CONCLUSION

Simulations and two-cell experimental results have been presented for the proposed triode modulator, the F1 Marx. This modulator has the advantage of producing a wide range of output voltage shapes while substantially re-using the hardware from the ILC P2 Marx. As funding allows, potential next steps include modeling the control loop of the modulator with the actual feedback signals from the existing system as well as full scale modulator prototyping.

VI. REFERENCES

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