THE ILC P2 MARX AND APPLICATION OF THE MARX TOPOLOGY TO FUTURE ACCELERATORS*

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Abstract

The SLAC P2 Marx is under development as the linac klystron modulator for the ILC. This modulator builds upon the success of the P1 Marx, which is currently undergoing lifetime evaluation. While the SLAC P2 Marx's (henceforth, "P2 Marx") target application is the ILC, characteristics of the Marx topology make it equally well-suited for operation at different parameter ranges; for example, increased pulse repetition frequency, increased output current, longer pulse width, etc. Marx parameters such as the number of cells, cell capacitance, and component selection can be optimized for the application.

This paper provides an overview of the P2 Marx development. In addition, the scalability of the Marx topology to other long-pulse parameter ranges is discussed.

SLAC LONG-PULSE MARX TOPOLOGY

SLAC Topology

Stated simply, the Marx topology charges energy storage elements in parallel, and discharges them in series. The output voltage is $N*V_{charge}$ where N is the number of cells. The circuit diagram of the P2 Marx cell is shown in Fig. 1. The design and operation of this cell is more completely detailed elsewhere [1-3]. There are many different variants to the Marx topology, several of which have been adopted to drive a klystron load. Each topology has advantages and disadvantages [4, 5].

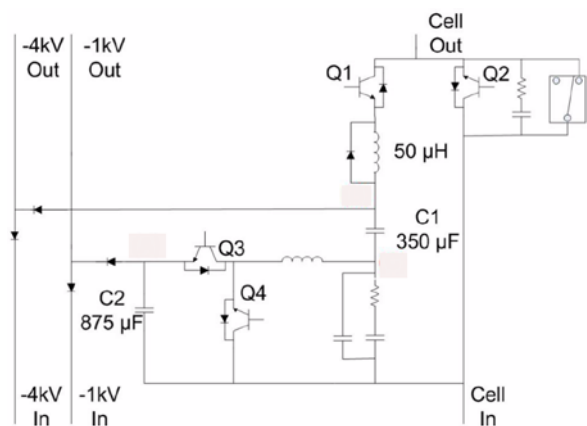In the P2 Marx, all switching is accomplished by solid-state devices. To simplify control and protection, the Marx cell voltage is derived from the blocking voltage of presently available IGBT dies. In addition, the modulator is built with N+2 redundancy. Up to two of the thirty-two cells can fail and the modulator can still provide the full specified output. Regulation is achieved at the cell level; each cell provides a square output pulse. Specifications for the modulator are shown in Table 1.

There are several features of the P2 Marx topology. There is no large output transformer in the modulator. This increasingly is a cost savings as pulse lengths increase. There is active correction of the output. A flat pulse is easily achieved for different impedance loads. The modulator is oil-free, inherently modular in implementation, and is single-sided accessible. This aids in serviceability. There is significant real-time diagnostic access to the transient waveforms within the cells. This enables quick diagnosis of problems and prognostication of future required maintenance.

Table 1: ILC Klystron Modulator Specifications

Output Voltage	120 kV
Output Current	140 A
Pulse Width	1.6 ms
Pulse Repetition Frequency	5 Hz
Voltage Flat-top	+/- 0.5%

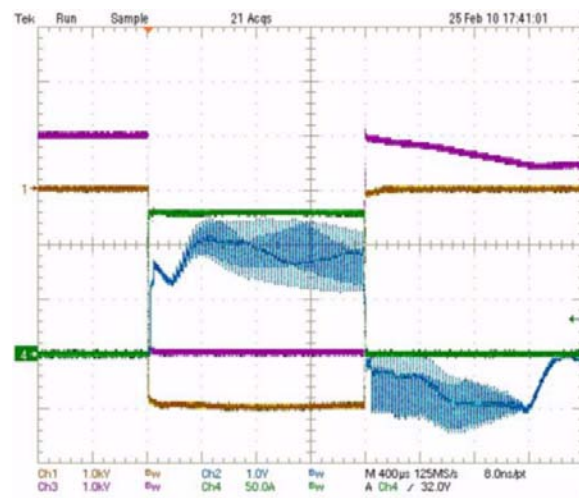Figure 1: Simplified cell schematic.

Figure 2: Single cell test results. (brown) output voltage, (blue) PWM current, (green) output current.

Design Validation

To date, tests have been completed on single and three-cell arrays. The cell design has been finalized and full modulator quantities of all hardware are being fabricated. Cells have been successfully operated at full peak power, nearly full average power (limited until the full modulator is built), and have withstood arc-down testing. Single cell test results are highlighted in Figure 2. Of note is the flat current output of the cell. A separate paper overviews this implementation [6].

Effect on Mains

A primary interest during the P2 Marx development is the proof of the modulator concept. Because it was not a focus of development, commercial off the shelf DC power supplies were chosen to recharge the Marx. In the future, further effort is needed to optimize the DC power supply with respect to efficiency, cost, and power factor correction.

A concern for long-pulse, low rep rate modulators is ensuring constant power draw from the mains. This is typically achieved by building up energy over the long period of time between pulses for discharge during the pulse. The power supply/modulator must be designed to both store this energy between pulses, and also draw from the mains appropriate current during the pulse. In long pulse, low duty cycle systems, this increases the complexity of the power converter.

IEEE 519 is the recommended standard for handling harmonics in electric power systems at the point of coupling to the utility. At certain power levels, excessive harmonics injected into the power system can result in fines. At the facility level, excessive current harmonics injected into the line can result in equipment malfunction.

Figure 3 shows three (of many) potential arrangements of the modulator in a full system. Scheme (a) has a single DC supply per modulator. An advantage of this arrangement is that modulator-generated harmonics are not injected onto the facility mains. Scheme (b) has multiple modulators driven by a single supply. This is
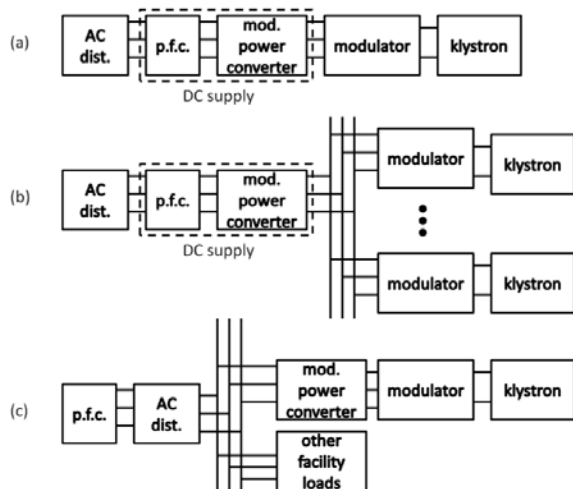

Figure 3: Three schemes for interfacing the modulator with the AC distribution.

likely a more economical option than (a), but removes flexibility in that each modulator produces the same voltage output. Scheme (c) has the feed for the modulator DC supply co-mingled with other facility loads. This is the most cost-effective solution, but results in injected harmonics into other facility loads.

SCALING TO ADDITIONAL PARAMETER RANGES

The P2 Marx is being developed for the ILC klystron modulator application. Attributes of the topology also make it viable for other parameter ranges. Certainly, changes in modulator specifications require a critical re-examination of the modulator topology and the design tradeoffs used. However, as a starting point to explore future potential applications, this section presents some issues in scaling.

Table II displays the parameters used in evaluating longer-pulse operation. As shown, klystron beam voltage and perveance are assumed constant for all configurations. Such klystrons are not yet commercially available, but are included for the sake of the following calculations. In this analysis, the topology is assumed identical to the P2 topology. To achieve long pulse operation, the energy storage capacitance is increased. Various other components also are altered to account for the higher average power operation. There are other methods to adapt the topology to longer pulse operation, but just this straightforward method is presented here.

Table 2: Three options for scaling.

	A (P2)	B	C
Output Voltage	120 kV	120kV	120kV
Output Current	140 A	140 A	140 A
Pulse Width	1.6ms	5 ms	25 ms
Pulse Repetition Frequency	5 Hz	5 Hz	1 Hz
Average Power	134kW	420 kW	420 kW

Cost

One issue with scaling is the difference in cost of the long pulse options compared to the P2 Marx. The distribution of materials and services (M&S) costs for the three options are shown in Fig. 4. Board level assembly costs are included in this distribution. Assembly of cells and the enclosure are not. In addition, no economy-of-scale is assumed. Numbers utilized for the P2 Marx are from purchases made in 2010 and 2011 for the prototype.

As shown in Fig. 4a, the three largest components of the modulator cost are the DC power supplies, the power semiconductors, and non gate drive controls. Mentioned above, during future development, the DC supplies can likely be further optimized with respect to cost. When scaling to larger average power versions of the modulator, many costs do not increase. For example, controls, gate

drives, snubbers, and cabling do not substantially increase in cost.

At a 5-ms pulse and higher average power, the DC supply becomes a larger proportion of total cost. Storage capacitors become the third most expensive component. At 25-ms, the storage capacitors are the second most expensive component. The 5-ms option is ~2.2x the cost of the P2 Marx while the 25-ms option is ~3.4x the cost of the P2 Marx.

In the P2 topology, the majority of energy storage is distributed at the cell level. A small DC link at the power supply level is needed ensure continuity in current draw from the mains during the pulse. Other topologies may instead have a much larger DC link at the power supply. In this case, cells are compensated during the pulse through a transformer [4].
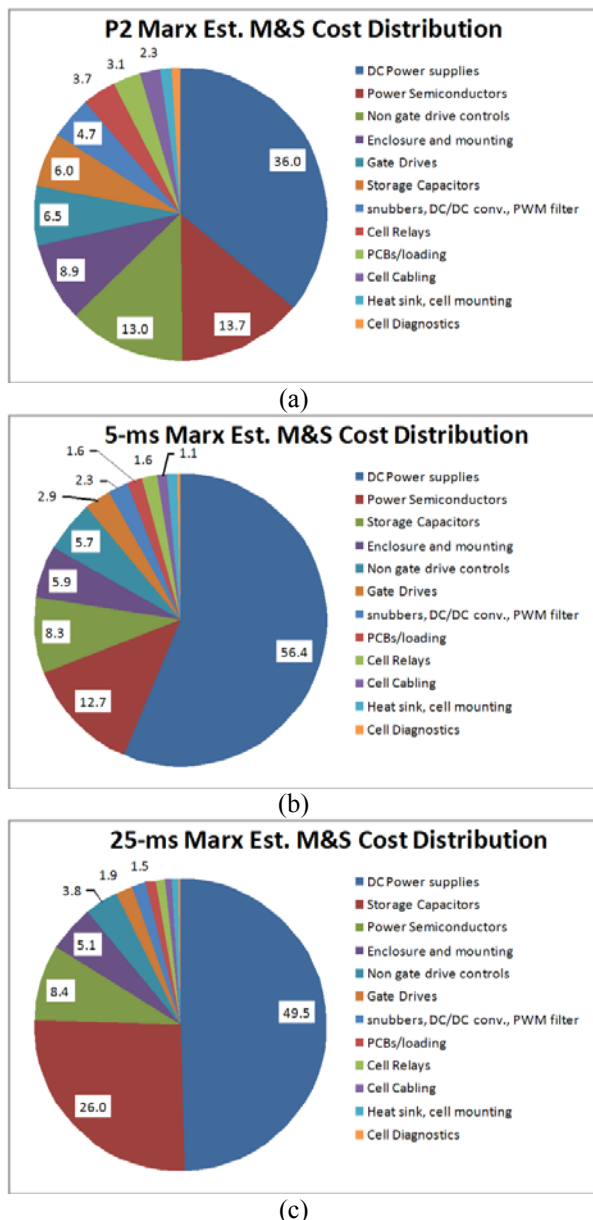
(a)

(b)

(c)

Figure 4: Estimates of modulator M&S cost distribution.

Size

The long-pulse, higher average power modulators require a larger footprint to handle the increased capacitor volume as well as increased air-duct volume. Figure 5 shows the overall modulator layout of the P2 Marx. The modulator size is determined by the cell volume and the space utilized for high-voltage insulation. Component spacing requirements to handle high voltage effects to not substantially increase with increased average power. Therefore, modulator volume does not increase linearly with increased average power. Table 3 summarizes the calculated relative size increases as well as the calculated proportion of volume taken-up by capacitors.
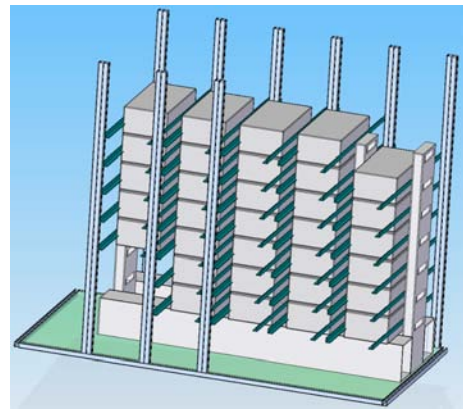
Figure 5. Rendering of SLAC P2 Marx. Some components are omitted for clarity.

Table 3: Three options used for scaling.

	A(P2)	B	C
Relative Size	1.0	1.4	2.8
Capacitor Volume/Total Volume	.03	.06	.15

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