ILC MARX MODULATOR DEVELOPMENT PROGRAM STATUS*

C. Burkhart#, A. Benwell, T. Beukers, M. Kemp, R. Larsen, M. Nguyen, J. Olsen, T. Tang
SLAC, Menlo Park, CA 94025, USA

Abstract

A Marx-topology klystron modulator is under development for the International Linear Collider (ILC) project [1]. It is envisioned as a lower cost, smaller footprint, and higher reliability alternative to the present, bouncer-topology, baseline design. The application requires 120 kV (+/-0.5%), 140 A, 1.6 ms pulses at a rate of 5 Hz. The Marx constructs the high voltage pulse by combining, in series, a number of lower voltage cells. The Marx employs solid state elements; IGBTs and diodes, to control the charge, discharge and isolation of the cells. Active compensation of the output is used to achieve the voltage regulation while minimizing the stored energy. The developmental testing of a first generation prototype, P1, has been completed. This modulator has been integrated into a test stand with a 10 MW L-band klystron, where each is undergoing life testing. Development of a second generation prototype, P2, is underway. The P2 is based on the P1 topology but incorporates an alternative cell configuration to increase redundancy and improve availability. Status updates for both prototypes are presented.

INTRODUCTION

The ILC will require 576 Rf stations. Each 10 MW L-band klystron will require a modulator capable of 120 kV, 140 A, 1.6 ms (27 kJ) at a 5 Hz repetition rate. The baseline klystron modulator employs a transformer-based topology. The large size, weight, and cost of this transformer, owing to the long pulse length, have motivated research into alternative topologies that do not employ power magnetics.

DESIGN OVERVIEW

The reliability/availability requirements for ILC systems mandate the use of solid state switching elements to control the klystron modulator output. The Marx topology provides an approach to array solid state switches to the voltage and power levels required for this application. A simplified schematic of the Marx topology selected for the ILC application is shown in Fig. 1. The Marx is composed of cells, which form the basic Power Electronics Building Block (PEBB) [2]. Each cell contains an energy storage capacitor, an IGBT switch to control the discharge of the capacitor (discharge path shown in green), and an inductor to limit dI/dt in the event of a fault. A second IGBT switch and the diodes provide the path to charge the energy storage capacitor, and the auxiliary power supply (both paths shown in red), of all the Marx cells in parallel while isolating these paths during the series discharge of the Marx. A beneficial attribute of this configuration is that cells can be by-passed during discharge (e.g. left cell in Fig. 1), which allows cell turn on to be delayed for pulse shaping, or omitted if the cell has malfunctioned. There are several variations on this topology, however the design illustrated in Fig. 1 is used for both the P1 and P2 designs.

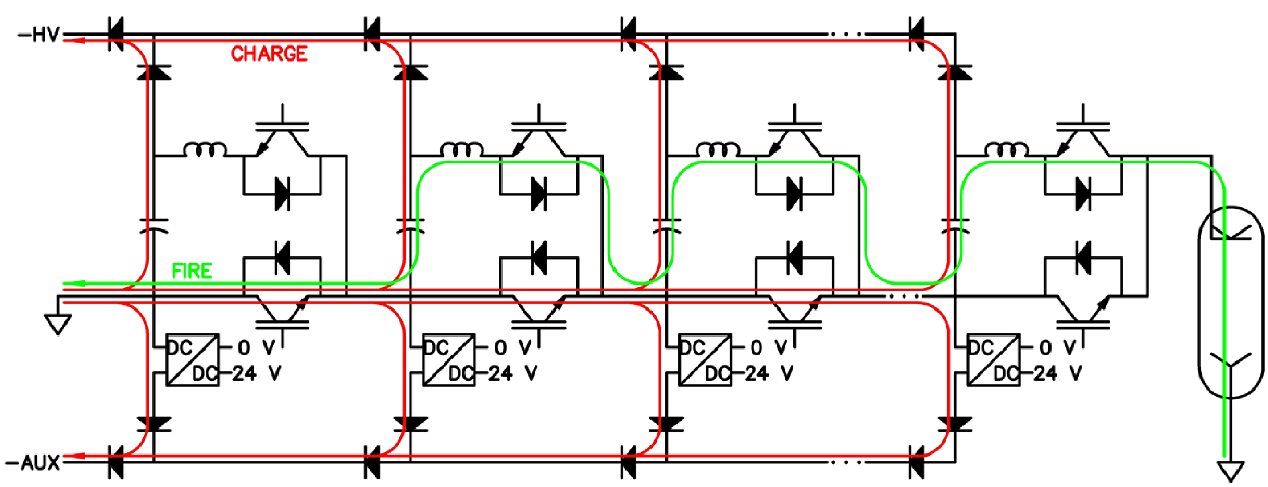

Figure 1: Simplified schematic of the ILC Marx modulator topology (4 cells). The charging current paths are shown in red; HV charging along the upper path, auxiliary along the lower. The discharge current path is shown in green.

* Work supported by the U.S. Department of Energy under contract DE-AC02-76SF00515
# burkhart@slac.stanford.edu

P1-Marx Modulator

The details of the P1 Marx design and operational behavior have been presented elsewhere [3]. The P1 has 16 cells, each charged to 11 kV. Eleven cells are initially triggered to produce the full output voltage. As the 50 µF energy storage capacitors discharge, the output voltage drops. Without compensation, the voltage will droop ~40% over the duration of the pulse, as seen in Fig. 2 (green waveform). The capacitors would have to be increased to >2 mF per cell to maintain the required output voltage regulation. This would substantially increase the modulator size and cost.

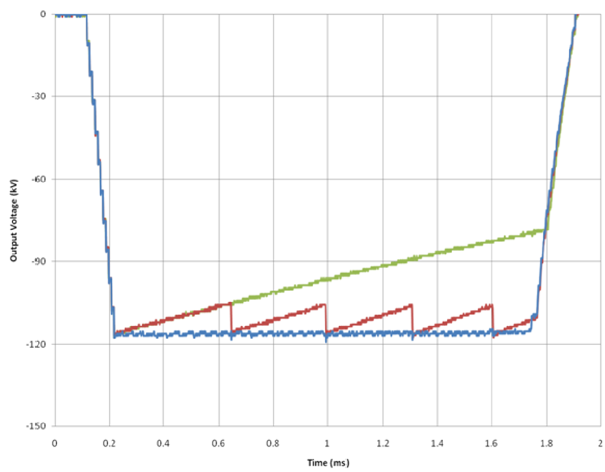

Figure 2: Marx output voltage waveform; without droop compensation (green), with delay cell compensation only (red), and with vernier regulation (blue).

Instead, a two-stage, vernier, active compensation scheme is employed to regulate the output voltage. Once the output voltage decreases by 11 kV, ~0.35 ms after the start of the pulse, an additional cell is triggered to restore the output to 120 kV. This proceeds sequentially through the remaining five cells to provide coarse, ±5%, pulse flattening. Applying only this first stage regulation generates the saw-tooth waveform shown in Fig. 2 (red waveform). To further regulate the output to ±0.5%, a second, "vernier," Marx [4] is connected in series with the main Marx. The topology of the vernier Marx is similar to the main Marx, however each of the 16 cells is charged to 1.2 kV. These are fired sequentially to generate a stair-step waveform, which adds to the main Marx to maintain an approximately constant output voltage. Each time a delayed main cell is added, the vernier Marx will open (cell output goes to zero) and the process repeats. The fully regulated P1 Marx output is also shown in Fig. 2 (blue waveform).

The developmental testing of the P1 has been completed and the modulator has been integration into a 10 MW L-band Rf test station. The integrated operation time to date, operating 24/7, is nearly 2000 hours. The time history of the operation with the Toshiba MBK generating 10 MW of Rf power, approximately 1500 hours (60 days), is shown in Fig. 3. The remainder of the

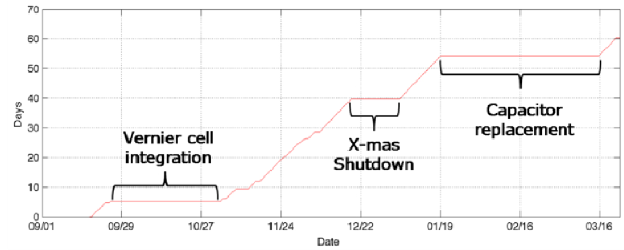

Figure 3: Operational history of the P1-Marx life test.

operation has been with a test load. There have been three significant interruptions in the testing, first to integrate the vernier Marx into the system, and then during a holiday closure of the lab. The only significant maintenance downtime to date was to replace the energy storage capacitors. These failed prematurely due to improper voltage grading between the series capacitors. This has been corrected and life testing of the modulator and klystron continues.

P2-Marx Modulator

The P2 Marx builds on the experience gained during development of the P1. The major changes are: (1) the cell voltage is decreased to 4 kV, (2) the number of cells is increased to 32, and (3) droop compensation is integrated into each cell. These changes improve the system redundancy and improve diagnostic/prognostic access to key cell elements. In combination, these improvements will result in higher system availability.

Reducing the cell voltage eliminates the need to array IGBTs within a cell (each P1 switch is a 5 series by 3 parallel IGBT array). This simplifies the cell design and allows diagnostic access to each IGBT and driver to evaluate switch performance, which is not possible in the P1. The improved diagnostic access enhances the hierarchical control system [5] ability to detect degradation of the switch and driver and take corrective action prior to a catastrophic failure.

A pulse width modulated, PWM, regulated voltage source, the shaded portion of the schematic shown in Fig. 4, is added in series with the energy storage capacitor to compensate for the capacitor voltage droop and maintain a constant cell voltage throughout the pulse.

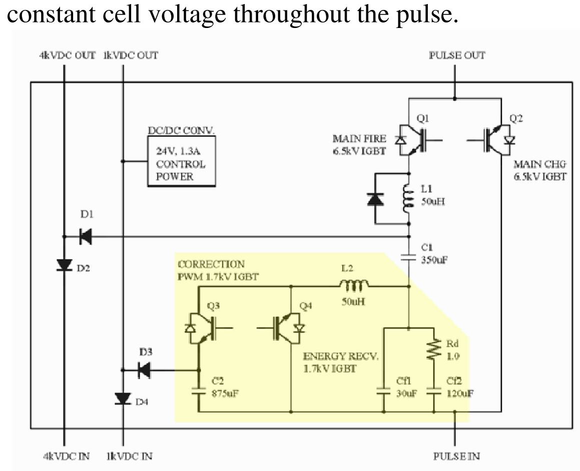

Figure 4: Simplified schematic of the P2-Marx cell.

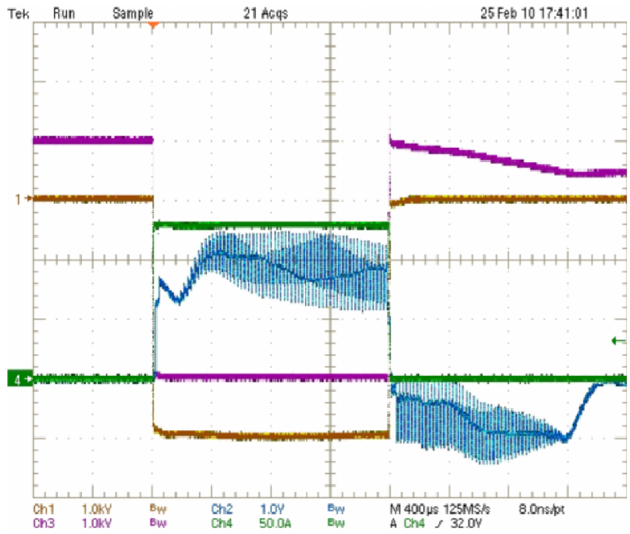

Figure 5: P2 cell output voltage regulation with a resistive load, load voltage (Ch1), PWM filter inductor (L2) current (Ch2), main switch (Q1) voltage (Ch3), and load current (Ch4).

This regulation approach is illustrated in Fig. 5, obtained while operating a single cell with a resistive load. The PWM switch operates at 40 kHz as the pulse width is varied such that the current through the filter inductor ramps the voltage on the filter capacitor Cf1 as C1 discharges and the sum of the two voltages remains constant. The results shown were achieved under open-loop control, which produces some perturbations on the output that will be eliminated when closed-loop operation is implemented. Incorporating the voltage regulation into each cell, all cells are then identical (unlike the P1), and provides true redundancy. With 32 cells, N+2 redundancy is achieved, which will promote high system availability. The specifics of the cell design, and life and availability estimates, have been presented previously [6]. A conceptual design of the P2 is shown in Fig. 6. Each of the 32 cells slide into the support structure and can be easily removed for service. In addition to physical support, this structure provides the electrical interconnection between cells, flow channels for air cooling, and field shaping elements to control the electrostatic fields. The field shaping elements are essential to achieving a compact modulator. The maximum electric fields within the enclosure are less than 18 kV/cm. The enclosure is 2.6 m long, 1.4 m deep, by 2.2 m tall, approximately 20% smaller than the P1.

The prototype cell testing is nearing completion. Fabrication and testing of the complete modulator will take place in 2011.

CONCLUSIONS

A Marx-topology modulator has been successfully developed to meet the ILC klystron modulator requirements. The first generation prototype, P1 Marx, is undergoing life testing at SLAC. A second generation prototype, P2 Marx, with an increased service life is under development.

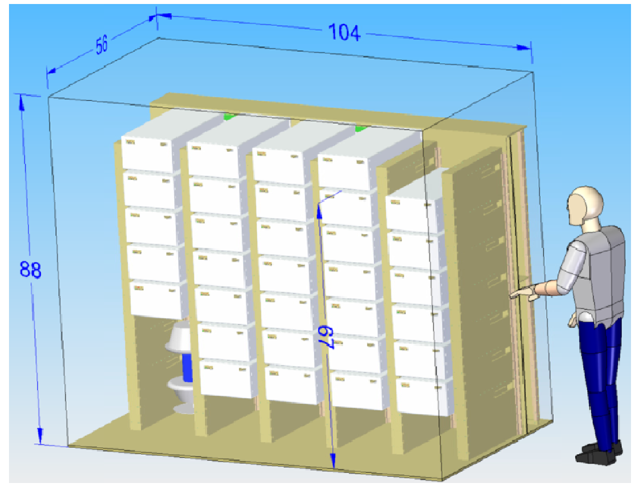

Figure 6: Conceptual design of the P2-Marx.

ACKNOWLEDGMENT

The authors wish to acknowledge the significant contributions of D. Anderson, C. Brooksby (LLNL), R. Cassel, E. Cook (LLNL), K. Macken, G. Leyh, D. Moreno, P. Shen, and A. Viceral to the SLAC Marx development program.

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