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P1-Marx Modulator for the ILC

T. Beukers, C. Burkhart*, M. Kemp, R. Larsen, M. Nguyen, J. Olsen, T. Tang
SLAC National Accelerator Laboratory
Menlo Park, CA 94025 USA
*burkhart@slac.stanford.edu

***Abstract*—A first generation prototype, P1, Marx-topology klystron modulator has been developed at the SLAC National Accelerator Laboratory 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 P1-Marx has been integrated into a test stand with a 10 MW L-band klystron, where each is undergoing life testing. A review of the P1-Marx design and its operational history in the L-band test stand are presented.**

Keywords-klystron modulator; high level radio frequency system

I. 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.

II. 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 Figure 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.

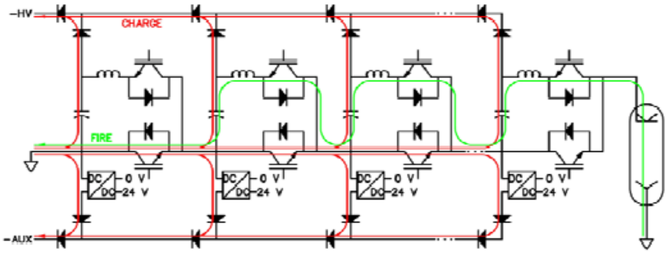

Figure 1: Simplified schematic of the ILC Marx modulator topology (4 cells). The charging current paths are shown in red; HV charging along the upper path, auxiliary along the lower. The discharge current path is shown in green.

III. DEVELOPMENTAL DETAILS

The P1 has sixteen 11 kV cells. The cell structure is shown schematically in Figures 2. To control the charge voltage, which exceeds the capacity of commercial solid-state switches, an array of five series modules is employed. The same module, see the Figure 3 schematic, is used in both the fire and charging stacks. Eleven cells are initially triggered to produce the full output voltage. For further details of the P1 Marx design and operational behavior please see references [3-6].

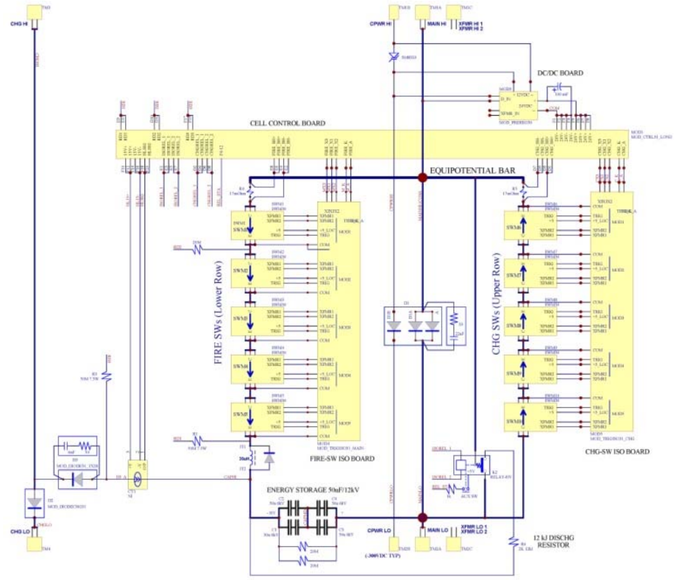

Figure 2: Schematic diagram of the P1-Marx modulator cell.

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 Figure 4

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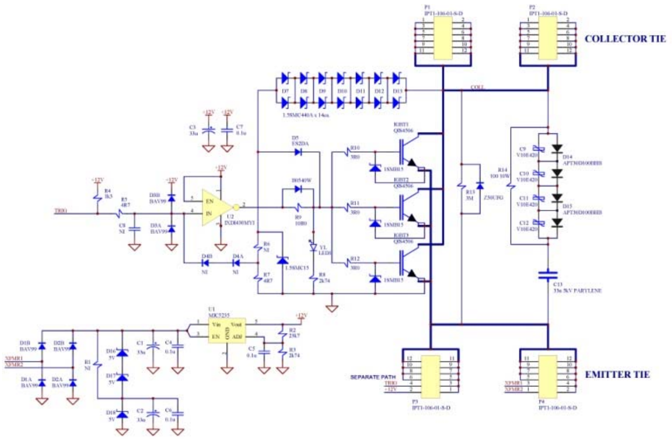

Figure 3: Schematic diagram of the P1-Marx switch module.

(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. Instead, a two-stage, vernier, active compensation scheme is employed to regulate the output voltage. Approximately 0.35 ms after the start of the pulse the output voltage of the initial 11 cells has decreased by 11 kV and 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. 4 (red waveform). To further regulate the output to ±0.5%, a second, "vernier," Marx [6] 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 Figure 4 (blue waveform).

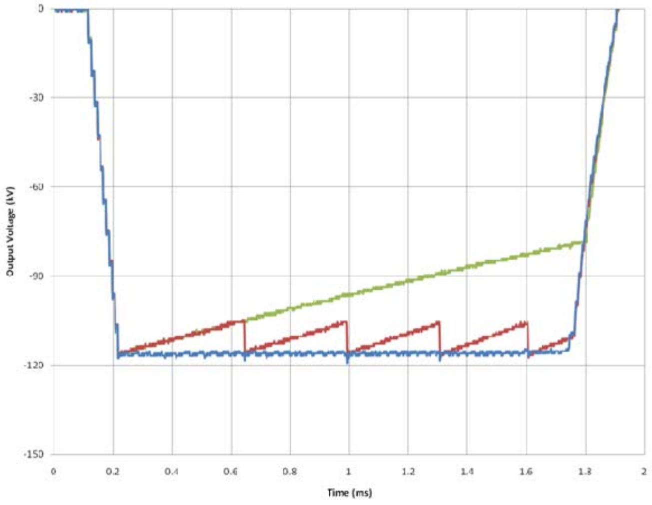

Figure 4: Marx output voltage waveform; without droop compensation (green), with delay cell compensation only (red), and with vernier regulation (blue).

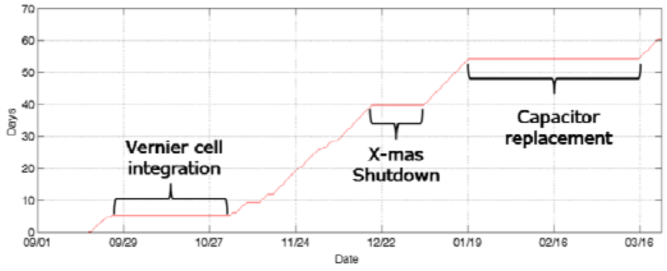

Figure 5: Operational history of the P1-Marx life test.

IV. OPERATIONAL TESTING

Once the developmental testing of the P1 was completed, the modulator was 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 Figure 5. The remainder of the 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 extensive life testing of the modulator and klystron continues.

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