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ILC-CLASS MARX MODULATOR AT KEK*

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Abstract

In October 2013, Diversified Technologies, Inc. (DTI) successfully installed and began operation of a 120 kV, 120 A, 1.7 ms Marx modulator for the High Energy Accelerator Research Organization in Japan (KEK).

INTRODUCTION

Originally conceived, designed, and built under a DOE SBIR grant to support SLAC (which was completed in 2010), the Marx bank modulator (Fig. 1) demonstrates a new technology for compact and economic ILC-class performance (long pulse, high voltage). The design meets or exceeds all performance requirements for ILC, does so in a more compact form factor than other known technologies, and will be more economic than other technologies.

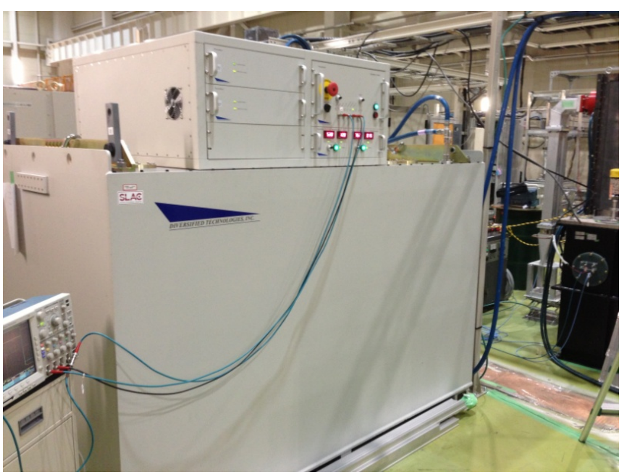

Figure 1: DTI's ILC-Class Marx Modulator in tank, installed and tested at KEK in Japan in October 2013.

CONCEPT

The basic concept of a Marx modulator is that it charges an array of capacitors in parallel at low voltage, then erects them in series to form a high-voltage discharge. Using DTI's solid-state switches (instead of traditional spark gaps or SCRs) to construct a Marx modulator enables it to open and close, thereby allowing the capacitors to store energy between pulses, rather than fully exhausting each time the system is discharged. The opening capability of the DTI switches also provides for arc protection of the load, opening in less than a microsecond after detection of a transient (precisely as occurs in a DTI direct-switch system). This means that solid-state Marx systems do not require crowbar protection to protect the load against arcs.

The parallel charging of the capacitors can be accomplished in a number of ways. For a very low duty cycle, resistive isolation can suffice. Similarly, for short pulses, inductive isolation is ideal. For the long pulses required of ILC, these are not suitable. Instead, each capacitor requires two separate switches – one for charging, and one for pulsing.

SOLID-STATE SWITCHING

One key element of DTI design is the patented ability to construct robust series-array circuits from individual transistors – effectively extending at will the voltage capabilities of today's high performance power transistors.

The speed of a solid-state array allows complete removal of stored energy from the load in less than one microsecond after detection of a fault, effectively eliminating the possibility of arc damage and removing the need for crowbar circuits.

It is important to note that the gross quantity of switching silicon is relatively constant for applications such as ILC and at KEK. The advantages of the Marx topology lie not in reducing the cost of the HV switches, but in allowing flexibility of the system design in order to optimize secondary characteristics. We find that this flexibility is particularly powerful for the ILC-class specifications – substantially reducing the volume and cost of a high-reliability transmitter.

TOPOLOGY

We have taken advantage of the flexibility of this approach to design a system which optimizes the power efficiency and economy of the solid-state switches. There are four distinct components to the Marx modulator. These are:

- A power-entry buck regulator, which takes unregulated DC power from an outdoor transformer/rectifier, and regulates the prime power to about 6-7 kV DC,

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- A bank of 20 highly efficient "core" switch modules, which erect the leading edge of the pulse to a voltage of 20x the prime DC feed,
- A low-power buck regulator, which steps the 6-7 kV DC feed down to 900 V max for trimming,
- A bank of 16 "corrector" switch modules at 900 V, which fire at staggered intervals to regain the pulse voltage as the prime capacitor bank droops.

The motivation for the Marx switch for ILC was strictly due to long pulse width, as the ability to stagger timing of switching elements enables incremental correction of droop within the pulse. Our design focuses on this capability, significantly lowering the size of the stored energy capacitor bank.

SYSTEM INTEGRATION

The Marx Modulator is installed in an oil tank with a 53" × 88" footprint, and 52" in height. Controls reside in an oil free "doghouse" on the tank top, which holds two 6U standard rack drawers in height, by two racks in width. The interior of the tank is quite dense; the core modules comprise one entire face of the modulator interior, and the correctors and both buck regulators the other face (Fig. 2).

Figure 2: The ILC/KEK Marx system, showing the 20 core modules which comprise half the tank volume. Each module used fourteen series 500 V 4700 μF electrolytic capacitors for an effective module storage of 335 μF at 7 kV. Over 80% of the volume of the core modules is used by these capacitors.

At the far end of the tank, an output snubbing circuit is included, which is no different than similar snubs used in hard switch modulators. This consists of a small inductor to limit dI/dt in the case of a load arc, along with a freewheeling diode and damping resistor across the inductor. Diagnostics of output voltage and current are also included in the tank on the output section.

INSTALLATION AT KEK

Following shipment from SLAC, the ILC-class Marx modulator was successfully installed at KEK in late October, 2013. Initial tests were run at approximately 120 kV and 80 A over 1.5 ms. A representative pulse is seen below (Fig. 3).

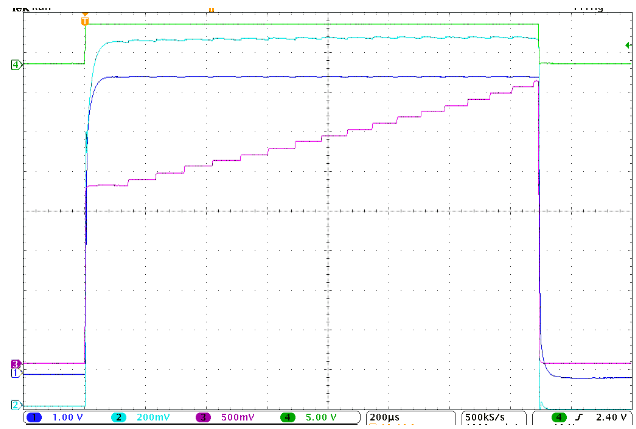

Figure 3: Pulse from the ILC Marx following installation at KEK. Pulse is 1.5 ms, 114 kV, 74 A. Ch1 (Blue): Voltage, 15 kV/div. Ch2 (Cyan): Current, 8 A/div. Ch3 (Magenta): Analog address, each step represents an additional corrector being added. When tuned, the steps are evenly spaced. Note the start is a 20x step. Ch4 (Green): Command.

SUMMARY

Based on this SBIR design, it is now possible to refine the ILC Marx design for greater affordability and ease of construction in production systems. This design is ideal for a wide range of long pulse (ms and higher) accelerator applications, and for similar requirements in radars, materials processing, and other applications. The elimination of separate power supplies provides a significant simplification of the ILC Marx design, as well as a reduction in overall system size and cost. Finally, the high level of pulse control afforded by the Marx design provides the operators of these systems with the unprecedented ability to tailor the pulse rise time and flattop to achieve optimal RF performance for future accelerator systems.

The ILC Marx Modulator topology has performed as designed. It promises to be a reliable, high performance, and economical solution to the needs of long-pulse modulators.