MARX BANK TECHNOLOGY FOR THE INTERNATIONAL LINEAR COLLIDER

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Abstract

Diversified Technologies, Inc. (DTI) has developed a high power, solid-state Marx Bank topology for the ILC modulators and power supplies that can deliver equivalent performance and yield acquisition cost savings of 25-50% versus presently proposed alternatives.

In this paper DTI will describe the Marx based technology as it is applied to ILC power systems design, and review recent progress in the engineering of the prototype transmitter being built under a Phase II SBIR from the DOE.

BACKGROUND

In August, 2004, the international science community formally backed the development of a superconducting linear accelerator named the International Linear Collider (ILC). It is expected that the accelerator will employ klystrons operating in the range of 110–135 kV, 120–166 A, and 1.5 ms pulsewidth.

For large accelerator facilities, acquisition cost will be the most significant consideration for an ILC modulator design. The cost of the switching elements (IGBTs, etc.) will be approximately the same in any modulator configuration. The long pulse length of the ILC requires large stored energy, and the cost of the capacitors is thus a consideration in any modulator design. DTI's efforts to reduce acquisition cost, therefore, are focused on power supplies and the energy storage needed to provide millisecond pulses at high power.

Our previous work has shown that a solid-state Marx bank offers the ability to address both of these cost drivers. Directly rectifying medium-voltage power (13.8 kVAC) and stepping it down with a buck regulator provides a very inexpensive power supply[1]. The solid-state Marx design has an inherent capability to arbitrarily switch additional modules onto the modulator output, providing voltage regulation with reduced energy storage. The combination of these factors makes the solid-state Marx bank the optimal approach to constructing ILC modulators and power supplies. We expect our proposed Marx topology to be 25-50% less expensive (in quantity) than any of the presently proposed alternatives.

The long pulsewidth of the ILC requires a large stored energy (about 25 kJ) delivered to the klystron each pulse. This is a significant challenge for any type of pulser which self-exhausts each pulse (i.e. PFN type systems). In addition, there is complexity in tuning a pulse line to +/-0.5% flatness for such a long pulse. Hard switch modulators (including those using pulse transformers) typically require far larger energy storage elements to keep the droop within the flatness tolerance over the pulse duration. The energy storage requirements can be significantly reduced through modifications to hard switch devices such as linear regulation correctors, quasi-resonant bouncers, etc.

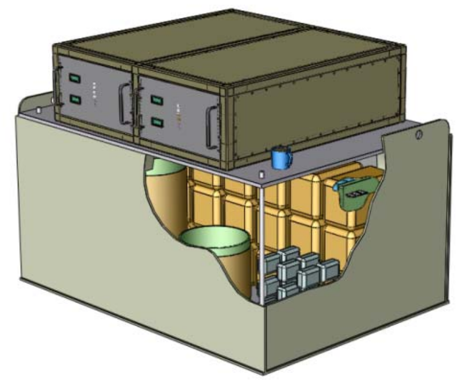

Figure 1. Proposed ILC Marx modulator, nominally delivering 125 kV, 140 A, 1.5 ms, 5 Hz – from a raw 3-phase 13.8 kV input.

The solid-state Marx bank, however, provides a more effective solution to the tradeoff of stored energy versus cost. As we show in following sections, a Marx topology allows some of the energy storage capacitors to be fired with staggered delays, thus maintaining the flattop of the pulse through a series of correction "ratchets".

MARX MODULATOR ADVANTAGES

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 to construct a Marx modulator enables it to open as well as close, thus the capacitors serve as storage capacitors rather than fully exhausting during each pulse. The opening capability of the DTI switches also provides for arc protection of the load. The response time is typically less than 1 μs from the start of the arc until the current is cut off. Such a system requires no 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

[1] M. Gaudreau, J.A. Casey, T. Hawkey, J.M. Mulvaney, M.A. Kempkes *Solid-State DC Power Distribution and Control*, High Voltage Workshop, 1998.

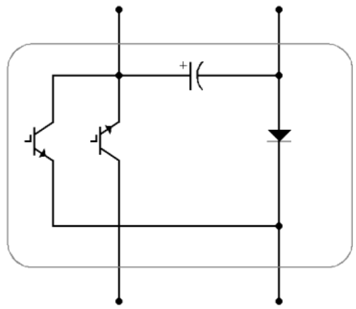

Figure 2. Unit Marx cell, showing pulse switch (at left) and recharge switch (center).

capacitor requires separate switches for charging and for pulsing. The "unit cell" of such a two-switch Marx module is shown in Figure 2.

The ability to stagger the timing of switching elements, and thus to incrementally correct for droop, is the motivation for using a Marx switch for ILC. Our design focuses on this capability, significantly lowering the size of the stored energy capacitor bank. At less than 150 kV, the mechanical configuration of the switch is not critical. We are designing a rectangular array of modules for ease of maintenance and compactness, as is standard for DTI oil immersed systems.

Ultimately, the design of the ILC Marx modulator will be driven by cost optimization. Although there is clearly an advantage to reducing the capacitor bank to a "practical" size, at some point the additional complexity of a very intricate correction system exceeds the incremental savings – capacitors, after all, are relatively inexpensive.

During our development efforts, we have used the flexibility of the Marx topology to reduce the total cost further than we had originally planned. The selection of lower voltage modules and reliability inherent in *"N+1"* redundant systems enabled us to consider the use of electrolytic capacitors, which would normally not be considered feasible for high-voltage system designs.

FLATTOP CORRECTION ARCHITECTURE

The diode bypass, shown in Figure 2, allows us to delay the turn-on time of any number of Marx modules. When bypassed, a Marx module adds no voltage to the output, but passes full current easily through the diode. It is this capability which reduces the size of the energy storage capacitor bank – when the bank drops to the minimum voltage allowed by the flattop specification, we turn on an additional module, which ratchets the voltage up by that module's voltage. The tradeoff is that additional Marx modules are required.

The size of this increment is determined by the flattop requirements. Our ±0.5% specification translates to roughly ±600 V, or a 1200 V span. We have designed in margin by choosing to ratchet in 900 V increments. Figure 3 shows the tradeoff between the size of the core capacitor bank and the number of additional switch modules that must be added to achieve flattop for the full pulse duration. A practical capacitor bank size gives significant droop over the long 1.5 ms pulse of the ILC.

It is possible to design all switching elements to have the same voltage (900 V). This would require, however, a very large number of switching elements. In addition, the recharge currents would be very large (as the modules are recharged in parallel). Instead, we will use a number of "core" modules to produce the 120 kV output voltage, albeit with significant droop. We then add a number of 900 V "correction" modules to cancel the droop of the core capacitor bank. Both the core and correction modules will have the structure of the unit cell Figure 2 – only the values of the components differ.

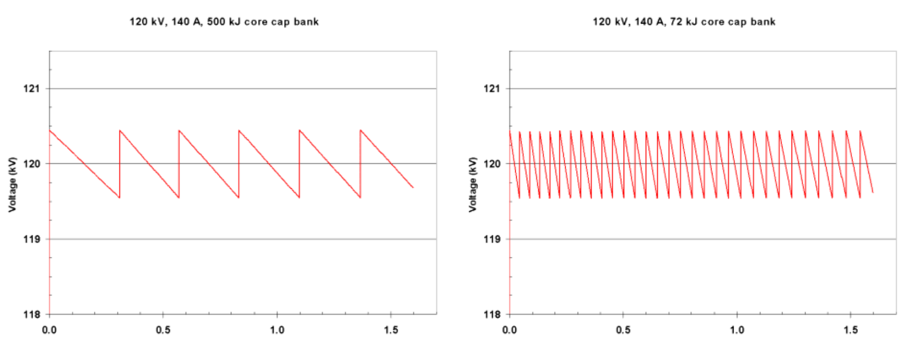

Figure 3. (left) A very large capacitor bank has a low droop rate, and needs few correction pulses. (right) A smaller capacitor bank droops quickly, so many more correction steps are required.

Although the voltage increment of the correction modules is determined by the flattop specification, we are free to choose an arbitrary voltage for the core modules[2]. Our recent shift towards a compact and economical

[2] Our ability to choose an arbitrary switching voltage for the core modules is enabled by DTI's patented series IGBT technology, which utilizes series arrays of IGBTs to make high performance, high-reliability pulse switches to arbitrary voltages.

system using electrolytic capacitors has found an optimum design point which differs from that for film capacitors.

The advantage of the Marx modulator architecture for an ILC class transmitter lies in a couple of simple effects:

- The flattop correction capability of ratcheting in additional modules allows us to reduce the size of the core capacitor bank, drastically reducing cost and size
- The erection of high-voltage from multiple stages of intermediate (~5 - 10kV) allows us to supply prime power (125 kW) at a voltage and current which enables the cheapest and most reliable supply architecture (a buck regulator).

Early in the design of the ILC Marx system, we assumed that the optimum system would use conventional film capacitors for energy storage. The technology development which drove the initial study was entirely based on realization of the Marx topology for a long pulse/large stored energy system, where the subsequent switching in of additional Marx modules would maintain the flattop with a practically sized capacitor bank.

During the Phase I effort, we began to study the possibility of using electrolytic capacitors. The advantages of this are simple – lower cost and higher energy density. The disadvantages are the necessity of balancing a series array of capacitors to achieve high voltage, and considerations of failure mode and lifetime. We now believe that the concerns of reliability can be suitably remediated through careful design, component selection, and engineered graceful degradation – and we are fully embracing an electrolytic capacitor design for assessment within the Phase II program.

The key to increased reliability is the use of *"N+1"* redundant design for the most at-risk elements. This allows for graceful degradation, where a single failure is noted and flagged for the next maintenance interval, but does not impair the ability of the modulator to operate to full specification. A modulator failure is thus defined as a case where two failures have occurred – not just in the same modulator, but *in the same sub-unit* of a single modulator. This gives us enormous gain in the reliability of the system overall.

Electrolytic Capacitors

The favorable characteristics of electrolytic capacitors are small volume and low cost. High quality electrolytic capacitors are typically 600-800 mJ/cc fully packaged, compared to 100-200 mJ/cc for fully packaged film capacitors – a factor of about 5X in energy density. Electrolytic costs are typically $90-$130/kJ, while film capacitors can range from $100-$200/kJ. DTI experiments have shown that clean Shell Diala-X transformer oil does not affect the operation of electrolytic capacitors. The system will require proper circulation and filtration of the oil, together with sufficient modularization to prevent a local insulation failure or capacitor blowup from taking down the whole system. The Marx design lends itself to

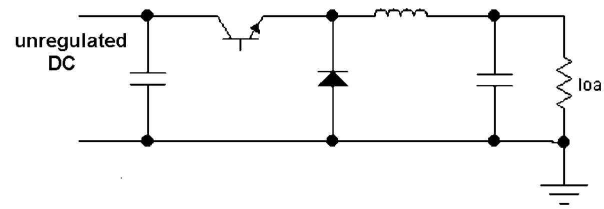

Figure 4. The basic architecture of a switching buck regulator, or DC-DC down-converter, shows the series switch, the freewheeling diode, and the filter inductor.

this modular design, and the use of electrolytic capacitors will significantly reduce the size and cost of this design for the ILC.

DC Power Supplies

For the ILC system, we propose to use two buck regulators. The first must supply the entire ~125 kW power feed at about 7-10 kV. The raw power for this will be isolated, rectified 13.8 kV three-phase mains. At the ILC facility, eight transmitters can be supplied by a modest 1 MW pad mounted T\R set. The second buck regulator is floating at the top of the stack of core modules, and steps the 7-10 kV core recharge down to 900V to supply recharge to the correction modules. This second unit need only supply 10-20 kW. Both of these systems will be fairly small, and fit in the main modulator tank along with the switching modules – the power input is thus raw 13.8 kV from the mains, which passes through an isolation transformer and a set of contactors.

We have examined alternative schemes for providing regulated power to the Marx, including conventional inverter/transformer/rectifier supplies and self-regulation within the Marx stack[3] – but none can compete with the economy and simplicity of the two buck scheme we propose.

CURRENT STATUS AND PLANS

At the present time, (approximately 8 months into the 24 month Phase II SBIR schedule), DTI has completed the detailed circuit design, and released the circuit boards and other components for fabrication and purchasing.

Construction of the full ILC Marx modulator will begin in Fall 2007, and full testing will begin in the Spring of 2008. The completed unit will be delivered to a DOE-designated laboratory in the summer of 2008 for further testing, and assessment against other ILC modulator designs.

[3] In this scheme, we use unregulated DC to recharge the Marx modulator, but locally regulate the voltage within each Marx module. This is accomplished by opening the recharge switch in each module when the voltage reaches the desired setpoint. Although attractive for some applications, the additional control infrastructure makes this uneconomical for ILC.

