SOLID-STATE MODULATORS FOR THE INTERNATIONAL LINEAR COLLIDER

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Abstract

Diversified Technologies, Inc. (DTI) has designed several solid-state architectures suitable for use in the International Linear Collider (ILC) modulators, including a transformer-coupled design, a hard switch, and a solid-state Marx bank. Transformer-coupled modulators for ILC have already been demonstrated by Fermilab and DESY. This paper describes DTI's ongoing development of solid state, transformerless modulators for the ILC, including Marx Bank (Figure 1) and hard switch modulator configurations under separate DOE SBIR grants.

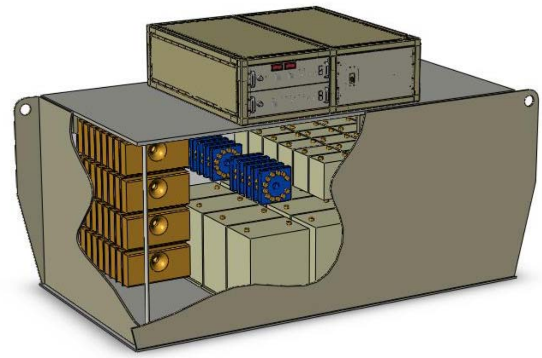

Figure 1. Conceptual drawing of an ILC Marx Modulator, nominally delivering 125 kV, 140 A, 1.5 ms, 5 Hz – from a raw 3-phase 13.8 kV input.

BACKGROUND

In August 2004, the international science community agreed to back a superconducting linear accelerator as the world's next major physics facility. Named the International Linear Collider, or ILC, the machine builds directly on the designs of its two predecessors, the Next Generation Linear Collider (NLC), a warm machine, and Tesla, a superconducting (or cold) machine.

The ILC klystrons are expected to be similar to the Tesla klystrons, with the final design in the range of 110–150 kV, 120–166 A, and 1.5 ms pulses of ± 0.5% flatness. The defining characteristic of the ILC klystron modulators is the relatively long (1.5 ms) pulse width, which requires 25 kJ delivered every pulse, and the resultant large stored energy required to deliver this energy without significant cathode voltage droop. Other requirements (voltage, current, risetime, pulse flatness) present no particular difficulty for existing DTI modulator technologies.

COMMON CONSIDERATIONS

Stored energy capacitors are normally a minor design consideration in any of these variants of hard-switch modulators. A brute force approach of *any* of the three modulator architectures (transformer coupled, Marx, hard switch), however, must use an energy storage bank on the order of 1.5 MJ to keep the droop within a 1% range. DTI's efforts in ILC modulator design have, therefore, been focused on variants of droop correction circuitry – trading off increased modulator complexity against reduction in the size of the energy storage bank. Two architectures – an incrementally correcting Marx switch and an actively bounced hard switch – appear to be easily configured for such corrections.

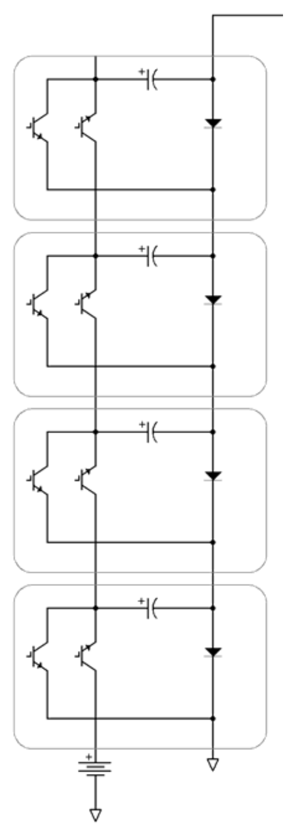

Figure 2.Four Stage Solid State Marx Bank Modulator (with switched recharge).

For each of these architectures, our goal was to reduce the size of the energy storage bank drastically without materially increasing the cost or complexity of the modulator. A goal of under 100 kJ stored energy was targeted, as an energy storage bank of this size has both cost and volume of the same order as the solid state switch – hence, further reductions yield diminishing returns.

The cost (in size, dollars, and reliability) of supplementary systems used to reduce the energy storage bank must be weighed against the benefits. The high voltage solid-state switches for either architecture are extremely robust and well proven in both commercial and military use – a significant dent in this performance is not acceptable. The tenfold reduction in energy storage will result in a "raw droop" of over 12kV (10x that acceptable) to be removed. We have considered and dismissed linear series-pass regulation of the delivered pulse voltage, as the additional power and cooling costs exceed those of the corrective schemes discussed below.

INCREMENTALLY CORRECTED MARX MODULATOR

A Marx Bank Modulator is an array of capacitors charged in parallel (at low voltage), then switched in series to form a high voltage discharge (Figure 2). This has the advantage of requiring DC power at a voltage much lower than that delivered to the load – indeed there is no DC present at load voltage anywhere in the system.

Traditional Marx modulators use "closing" switches (i.e. SCRs or spark gaps) to make the series connection and erect the HV stack of capacitors – thus the stored charge must be fully exhausted and replenished each pulse, and a pulse forming network is required to shape the output. A solid state Marx modulator uses IGBTs or FETs which can open under load, thus the capacitor stack becomes a filter/storage bank analogous to that of a solid state hard switch modulator.

The Marx architecture is a convenient way of using devices with intrinsic limits of a few kV to erect very large pulses. Unfortunately, the cost and efficiency of the system suffer if the unit voltage is *too* low – the repeated overhead at each stage, and the ohmic losses of the higher current recharge, make this option unattractive for voltages beyond 40-60 kV. Using DTI's series IGBT technology to assemble single modules of higher unit voltage avoids this issue. This does not affect the *overall* size of the energy storage bank, but significantly affects the size, number, and complexity of the switching modules – and allows for greater optimization of the complete design.

Recharge of the capacitors in parallel during the interpulse period can be accomplished by one of several means, each of which has advantages for certain classes of performance.

- A chain of resistors is the simplest recharge scheme, but is limited to only very low duty cycle and power,
- A diode / inductor network allows average current to recharge while blocking HV discharge during the pulse, but is limited to low duty cycle and short pulse,

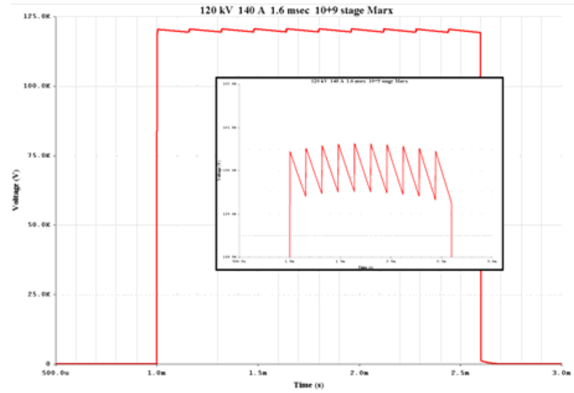

Figure 3. Staggered module switching to compensate for capacitor droop during the pulse.

- A common-mode choke scheme recharges faster and thus works at higher duty cycle, but is still limited to short pulse,
- A second bank of switches (Figure 2) can be used for arbitrary duty cycle and power, but at higher cost and complexity.

Any of these schemes can be configured to fire the switches independently. Any section which is not turned on is bypassed by a diode – thus the pulse voltage is simply lower by the potential of that stage. It is this capability that we use to correct for the droop of the reduced energy storage bank (Figure 3).

Optimizing this configuration for size, cost, and complexity gives an interesting hybrid design – where we have a small number of "core" modules to deliver the base pulse efficiently, and a larger number of "corrector" modules at much lower voltage to finely ratchet the flattop and correct out the droop. The use of the higher voltage core modules allows the recharge current to be kept low, and keeps the capacitor packaging efficient – these modules will be about 7.5 kV each. The corrector modules must have lower voltage authority to correct the droop within the flattop specifications – hence they operate at about 1 kV. Table 1 summarizes this construction.

Cost modeling confirms our 100 kJ target as being optimal. A smaller bank requires too much correction hardware, while a larger bank is too large and more expensive.

Table 1. Preliminary values for ILC Marx Modulator

# Core Modules	16
Core Module Voltage	7.5 kV nominal, 9.0 kV max, 10.5 kV rating
Core Capacitor	110 µF (6 kJ) each
# Corrector Modules	~ 30
Corrector Module Voltage	900 V nominal, 2.0 kV max & rating

0-7803-8859-3/05/$20.00

The choice of ~10 kV for prime input power yields one further bonus. By rectifying raw 13.8 kV mains and stepping down to the operating voltage with a solid state buck regulator (an extremely cost effective and efficient power supply configuration), we can greatly reduce the cost and size of the DC input section. A similar solid-state buck regulator will be used to step down the ~10kV core voltage to the ~1kV corrector voltage at the junction between these sections. Both of these DC-DC conversions use "off the shelf" technology, and typically perform at 95% or better efficiency.

ILC HARD SWITCH

The hard switch represents, in many ways, the simplest modulator design, consisting of only a capacitor and a full-voltage switch. Using the same 100 kJ goal, we examined a number of techniques for correcting the flattop. Many of these are well known to the modulator community, and several of them yield nearly equivalent performance tradeoffs.

The resonant bouncer, shown in Figure 4 appears to be the optimal choice for the ILC specifications. In this circuit, the bouncer capacitor produces an increasing voltage that compensates for the droop on the main capacitor. Initially the main and bouncer capacitors are charged, but to opposite polarities. The bouncer switch is then closed, and the bouncer capacitor voltage becomes less negative. When the bouncer voltage is increasing linearly (at 2 ms in the figure) the main switch is closed, producing the output pulse (waveforms are shown in Figure 5). At the end of the pulse, the main switch is opened. Finally, the voltage in the bouncer rings back, recharging the bouncer capacitor.

Both the main and bouncer power supplies for the hard switch are conventional inverter/transformer/rectifier units, using "off the shelf" DTI designs. The 170 kW at 120 kV needed for the main PS is within the standard product range for this architecture.

The cost estimates for a hard switch with bouncer are remarkably similar to those for a similarly specified incremental Marx switch. This is not too surprising, as the primary cost drivers – the switch IGBTs, gate drive infrastructure, and energy storage capacitors – are nearly identical for both systems, and only the HV wiring and the controls differ materially.

CONCLUSION

DTI is developing a Marx bank and a hard switch, both using solid-state switches. Both these configurations limit the total energy stored to 100 kJ while meeting the ±0.5% pulse flatness. As these designs are built and tested, the overall ILC program will be in an excellent position to select a design for construction to minimize the overall ILC life cycle cost.

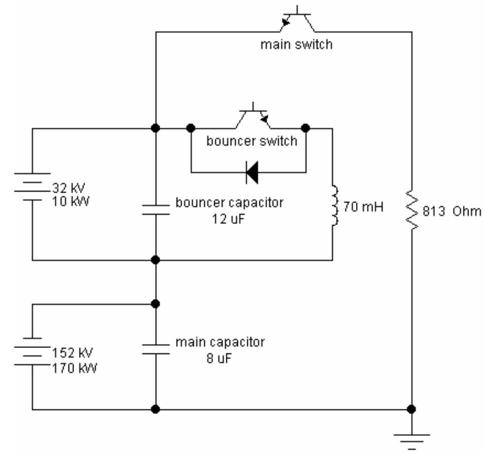

Figure 4. Hard-switch circuit, including bouncer to give flat pulse.

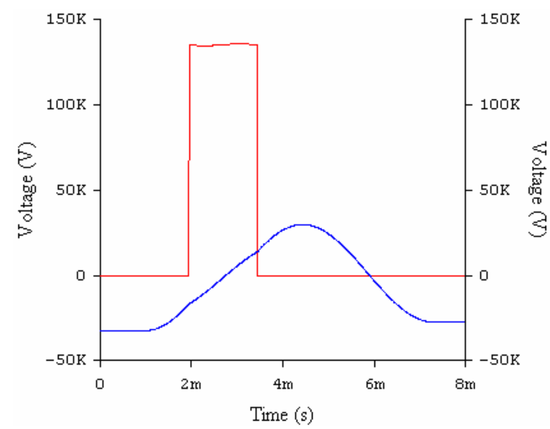

Figure 5. Voltages in bouncer circuit. Upper trace, output voltage; lower trace, voltage across bouncer capacitor.

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