REGULATOR / HARD SWITCH MODULATOR*

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Abstract

Diversified Technologies Inc. (DTI) is developing a long-pulse modulator to meet the requirements of the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory and the European Spallation Source (ESS), planned for Lund, Sweden. The modulator will deliver pulses at 100 kV at a pulse width of 3.5 ms, and a droop of less than 1%. The modulator will be delivered to Oak Ridge for conditioning klystron tubes before they are installed in the SNS accelerator.

INTRODUCTION

DTI is developing a long-pulse modulator as an alternative to the present Converter Modulator at SNS. The new Regulator / Hard Switch Modulator has two objectives: conditioning klystron tubes at SNS, and demonstrating the technology needed for future superconducting accelerators, such as ESS. The modulator specifications are given in Table 1. The key technical issue is meeting the 1% flatness specification without a large capacitor bank, using the minimum additional hardware. To meet these requirements, DTI's modulator has a small non-dissipative regulator that produces a tightly-controlled flattop and eliminates flicker on the input grid. The regulator is the major development for this new modulator design.

Table 1: Modulator Specifications (The frequency will be limited by the low-power supply used for klystron conditioning.)

Voltage (kV)	100
Current (A)	50
Pulse width (ms)	3.5
Frequency (Hz)	14
Voltage flatness (%)	<1
Ripple (% peak-peak)	<0.1

SYSTEM

Overview

The mechanical layout of the modulator is shown in Figure 1, and a highly-simplified schematic diagram is shown in Figure 2. The major elements of the system are the switch, regulator, capacitor, and transformer. This modulator is a 'hybrid' design, with a solid-state switch driving a pulse transformer. This design was chosen to accommodate the ESS preference to avoid DC high voltage and oil-immersed switching elements. The modulator could readily have been designed without a transformer; DTI has built many hard-switched solid-state modulators that reliably switch pulses over 100 kV, at much higher current and average power than required here.

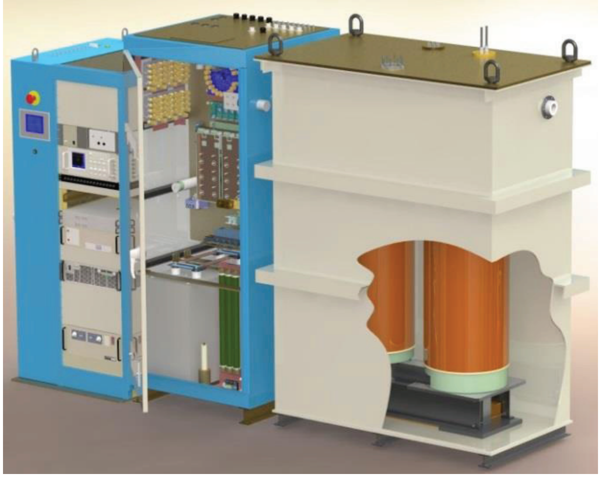

Figure 1: Mechanical layout of the system. The components are (from left to right) cabinet for PLC and AC power, rack-mount cabinet with power supplies and control boxes, power-conditioning cabinet (which contains the capacitor bank, switch, and regulator), and oil-filled transformer tank.

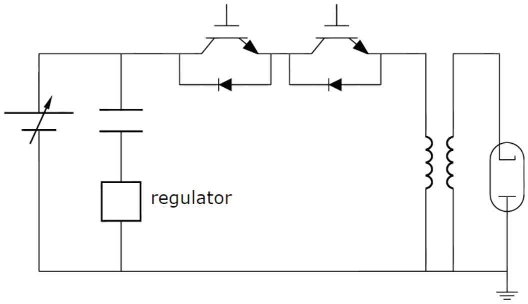

Figure 2: Highly-simplified schematic diagram. (The switch is made with seven IGBTs, not two.)

Switch

The switch is made with series-connected IGBTs, a well-established technology at DTI. The switch operates only once per pulse, in contrast to the 30 times needed by the SNS Converter Modulator. The lower switching frequency reduces the losses, and reduces the size of the switch.

The switch consists of seven modules in series; two of these are redundant. Since IGBTs fail short, if two modules short, the others will continue to support the voltage across the switch. The number of good IGBTs in the switch stack is monitored so that in the unlikely event

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of a failure, repairs can be appropriately scheduled before a modulator failure occurs. The IGBTs are mounted on a cold plate to keep their temperature low, giving high reliability.

Regulator

The regulator is the key development for this program; it keeps the output voltage constant as the capacitor voltage droops. The regulator produces only the droop voltage (±7% of the output), rather than the full voltage produced by the converter modulator. This means that the regulator can be very small and efficient.

Representative voltage waveforms for this system are shown in Figure 3. The capacitor voltage droops during the pulse, then is recharged between pulses, returning to its original level. The regulator output is opposite to the variation in capacitor voltage. This produces both a flat output pulse and a constant power-supply voltage. As a result, the power supply can operate at constant current and constant power – and so does not produce flicker, regardless of the switching frequency. The regulator is non-dissipative, since it neither supplies nor sinks net power over a cycle.

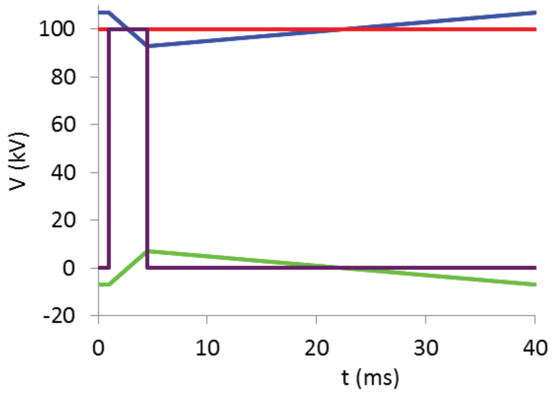

Figure 3: Voltage waveforms for the modulator system. Capacitor (blue), regulator (green), load (purple), main power supply (red).

The regulator is based on a full-bridge circuit rather than a half-bridge. A full bridge transfers all the energy in the filter inductor to the filter capacitor, unlike a half-bridge, which returns some of the energy to the bus capacitor. Because of this, a full-bridge can operate at a lower current (and correspondingly lower loss) than a half-bridge.

The bridge circuit has different phases of operation, depending on whether the modulator is pulsing or charging, and whether its output voltage is positive or negative. Operation during the first half of the pulse is shown in Figure 4. The A switch cycles on and off. When it is closed (top), current builds up in the inductor; when it is open (bottom), the current in the inductor discharges into the bus capacitor. The bridge circuit operates as a boost regulator, transferring energy from the filter capacitor (which is charged by the main capacitor) to the bus capacitor.

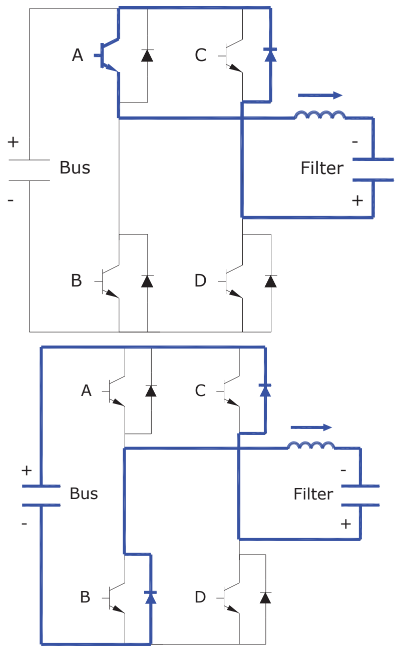

Figure 4: Regulator operation during the first half of the pulse, when the regulator output is negative. The blue traces show the current path. (Top) A switch is closed, and current builds up in the inductor. (Bottom) A switch is opened, and energy in the inductor discharges into the bus capacitor. Energy flows from the filter capacitor to the bus capacitor.

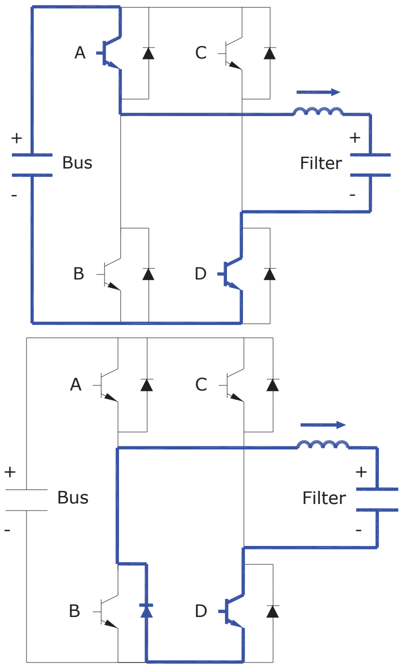

Figure 5: Regulator operation during the second half of the pulse, when the regulator output is positive. (Top) A and D switches are closed, and current builds up in the inductor. (Bottom) A switch is opened, and energy in the inductor discharges into the filter capacitor. Energy flows from the bus capacitor to the filter capacitor.

Operation during the second half of the pulse is shown in Figure 5. In this case the D switch is closed. When the A switch is closed (top), current builds up in the inductor; when the A switch is open (bottom), the current in the inductor discharges into the filter capacitor. In this case the bridge circuit operates as a buck regulator, transferring energy from the bus capacitor to the filter capacitor (and then to the load).

Operation during charging is similar, but with the C and B switches operating, rather than the A and D switches.

The regulator is made with two bridges in parallel, connected to a common filter capacitor. The IGBTs in the bridges switch at 100 kHz during pulsing, and 5 kHz during charging. Their switching is staggered, making an effective switching frequency of 200 kHz during pulsing.

We have demonstrated regulator operation at its full output power. (While the switch voltage was low for this test, the regulator operation depends only on the regulator voltage and current.) The output voltage without the regulator is shown in Figure 6; the capacitor droop is exaggerated from the actual modulator design, and is obvious. Waveforms with the regulator operating are shown in Figure 7. The regulator produces up to ±400 V, and is clearly compensating for the droop. The initial dip in the voltage waveform is due to the initial voltage drop across the switch; this will be eliminated by feedback compensation in the regulator controls.

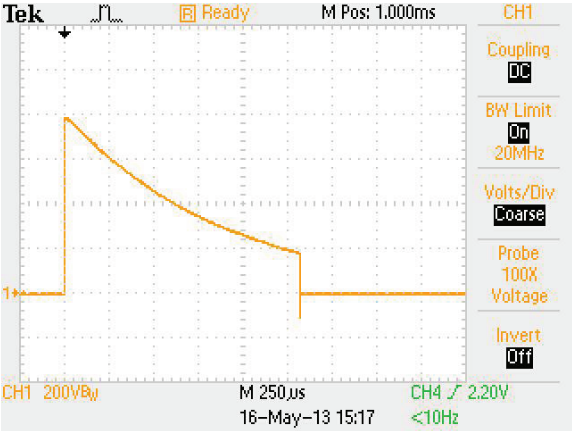

Figure 6: Pulse voltage without the regulator, 200 V/div, 250 µs/div.

Capacitor Bank

The capacitors are made with metallized film (also referred to as "self-healing"), allowing them to be roughly one-quarter of the volume and cost of capacitors made with film-foil technology. Metallized-film capacitors can tolerate arcs in the film, and so can operate at a relatively-high electric field. This is because when a metallized-film capacitor arcs, the metallization near the arc blows off, isolating the shorted section from the rest of the capacitor. The only impact is a small reduction in capacitance. In contrast, a film-foil capacitor cannot tolerate arcs, and must operate at a lower electric field. In general, the allowable current in metallized-film capacitors is lower than the current in a film-foil capacitor. However, the RMS current in the modulator (184 A) is low enough that is this not a concern.

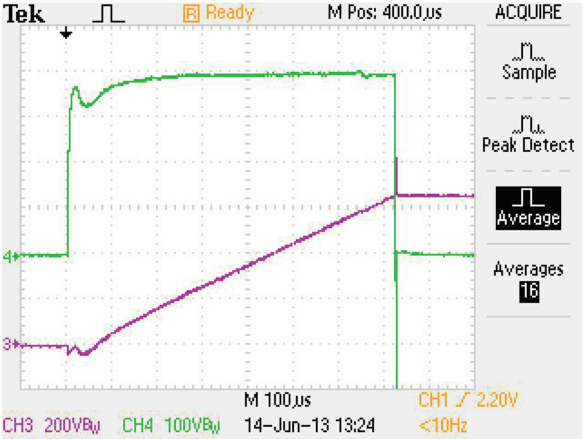

Figure 7: Pulse voltage (green) and regulator voltage (purple), 200 V/div, 250 µs/div.

The total bank capacitance is 4 mF; it stores 82 kJ at 6.4 kV. The bank is made of three 1333 µF capacitors in parallel, each 14" x 15" x 25" tall.

Transformer

The pulse transformer enables the DC power supply to operate at 6 kV, allowing the switch to be air-insulated. Since the pulse is 3.5 ms long, the transformer will be built like a power transformer, rather than the basket design typically used for microsecond pulses.

The long pulse width makes the transformer large, so the hybrid modulator is larger than a comparable hard-switch system. The leakage inductance of the transformer limits the pulse rise time. There is a design tradeoff between leakage inductance and size; reducing the leakage inductance increases the transformer size.

CONCLUSION

The droop control for long pulses provided by this regulator modulator makes it attractive for applications which would otherwise require prohibitively large and expensive capacitor banks, or more complex switching arrangements. The first system will be tested at DTI in early 2014, prior to its installation at SNS.

DTI's future efforts will include investigating directly-switched oil-cooled systems, and applying the regulator to correct pulse droop in long-pulse Marx modulators, rather than adding numerous corrector modules or complex Marx stages.