Robust High-Average-Power Modulator

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Abstract: *Diversified Technologies Inc. (DTI) is developing a long-pulse modulator which meets the requirements of the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory and the European Spallation Source (ESS). The modulators will deliver pulses at up to 100 kV and 50 A with a pulse width of 3.5 ms and a droop much less than 1%. The modulator will be delivered to SNS for conditioning klystron tubes.*

Keywords: Spallation Neutron Source, SNS, European Spallation Source, ESS, modulator, regulator, IGBT.

Introduction

Diversified Technologies, Inc. (DTI) is developing a new long-pulse modulator under DOE SBIR grant. This modulator has two objectives: condition klystron tubes at the Spallation Neutron Source (SNS), and demonstrate the modulator specifications needed for the European Spallation Source (ESS); see Table 1. The key technical problem addressed is that the millisecond-long pulses produce a droop voltage of about 10% with a reasonably-sized capacitor bank—much larger than the 1% droop required. To eliminate the droop without a large and expensive capacitor bank, the modulator has a non-dissipative regulator, the major development here.

System Overview

The mechanical layout of the modulator is shown in Figure 1, and a simplified schematic diagram is shown in Figure 2. The major elements of the system described in this paper are the switch, regulator, capacitor, and transformer.

Table 1. *SNS and ESS modulator specifications. (Frequency and ripple are not significant for klystron conditioning.)*

	SNS	ESS
Voltage (kV)	85	100
Current (A)	13.8	50
Pulse width (ms)	1.5	3.5
Frequency (Hz)	-	14
Voltage Flatness (%)	1	1
Ripple (VRMS)	-	50

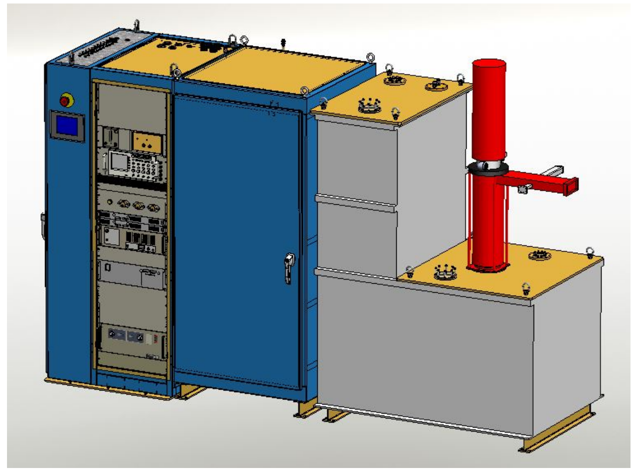

Figure 1. Mechanical layout of the system. The components are (from left to right) blue cabinet for PLC and AC power, gray rack-mount cabinet with power supplies and control boxes, power-conditioning cabinet (which contains the capacitor bank, switch, and regulator), and oil-filled transformer tank,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

Switch

The switch is made with series-connected IGBTs, which is a well-established technology at DTI. A series connection allows redundancy—since IGBTs fail short, if one module shorts, the others will continue to hold off the voltage across the switch. The switch consists of seven modules in series, two of these are redundant.

The number of good IGBTs in the switch stack is

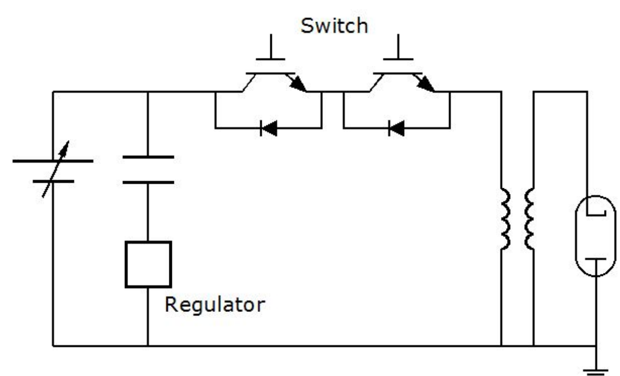

Figure 2. Simplified system diagram. The switch is actually made with seven IGBTs.

monitored, so that in the unlikely event of a failure, repairs can be appropriately scheduled.

The IGBTs are mounted on a cold plate to keep their temperatures 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. Since the regulator and capacitor present a constant voltage to the power supply, this allows the system to draw constant power, eliminating flicker as a potential concern. The regulator is non-dissipative, and supplies no average power to the system.

The regulator is based on a full-bridge circuit (Figure 3). A full bridge has the advantage that it transfers all the energy in the filter inductor to the filter capacitor, rather than returning some of it to the bus capacitor. Because of this, a full bridge can operate at a lower current (with correspondingly lower losses) than a half-bridge.

A key element of the regulator operation is the switching sequence. The switches are operated so there is no discontinuity in the switch duty during the pulse, keeping the feedback signal continuous. This eliminates any voltage ripple that would have been caused by a mode transition in the middle of the pulse.

The switches in the bridge operate at 100 kHz during pulsing, and 5 kHz during charging. The regulator is made with two full bridges in parallel, connected to the same filter capacitor. Their switching is staggered, making an effective switching frequency of 200 kHz during pulsing. With this high-switching frequency, and a filter capacitor that has very low inductance, we calculate a ripple voltage of 40 mV peak-to-peak. (The actual ripple voltage will be somewhat higher than this, limited by electro-magnetic pickup – it will, however, be very small in comparison to the 100 kV output.)

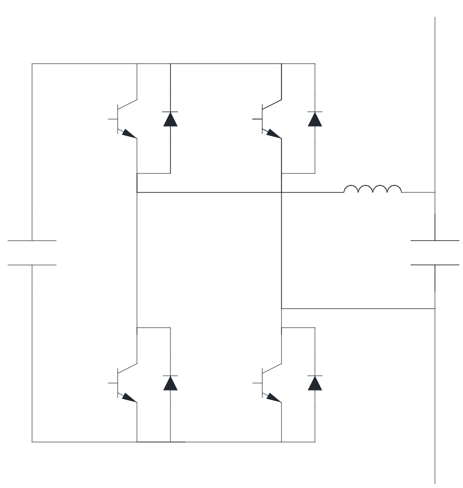

Figure 3. Full Bridge Circuit

Capacitor

The capacitors at 6 kV will be made with metallized-film, also referred to as “self-healing”, a technology which is well-established at this voltage. 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 of this is a small reduction in capacitance. In contrast, a film-foil capacitor cannot tolerate any arcs, and so must operate at a lower electric field.

The total bank capacitance is 4 mF, which stores 82 kJ at a voltage of 6.4 kV (the additional 400 V above 6 kV allows for droop). The high electric field of the metallized-film capacitors gives a high energy density, and so a relatively-small capacitor bank. The bank is being built with three 1333-μF capacitors with dimensions approximately 14” x 15” x 25” tall. This bank is roughly one-quarter of the volume and cost of a capacitor bank made with film-foil technology.

Transformer

A topology involving a pulse transformer was selected because of a customer belief that frequent servicing is needed for new modulators. Because of this, the customer preferred an air-insulated system one that is insulated with oil. (We chose a design in accord with this preference, though DTI’s modulators rarely require maintenance, and when it is required, it can be done in only a few hours.) Because air does not insulate as well as oil, the switch voltage was chosen to be low, necessitating a pulse transformer to produce the high-voltage output.

A key issue for the transformer is producing a pulse with a fast rise time to minimize the energy wasted. The rise time is largely determined by the series leakage inductance of the transformer (the leakage inductance), so it is desirable to minimize this inductance. Since the pulse is so slow (3.5 ms) the transformer design will resemble a power transformer rather than the design used for a microsecond pulse.

Future Work

As a reliable, low-cost system, the droop control provided by this modulator for long pulses make it an attractive choice for applications which would otherwise require prohibitively large and expensive capacitor banks. DTI’s future efforts will include exploration of ways to improve the system, including investigation of directly-switched, oil-cooled systems.