

PULSED POWER SYSTEMS FOR ESS KLYSTRONS

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Abstract

Diversified Technologies, Inc. (DTI) is building three long pulse solid-state klystron transmitters to meet spallation source requirements. Two of the three will be installed at CEA Saclay and the National Institute of Nuclear and Particle Physics (IN2P3) in 2015, to be used as test stands for the European Spallation Source (ESS). The third system will be installed at Oak Ridge National Laboratory (ORNL) for the Spallation Neutron Source (SNS).

INTRODUCTION

Diversified Technologies, Inc. (DTI), in partnership with SigmaPhi Electronics, has designed an advanced, high voltage solid-state modulator for the European Spallation Source (ESS) klystron tubes (Figure 1). The ESS modulator uses a series-switch design driving a pulse transformer, with an advanced, patent pending regulator design to maintain a highly regulated cathode voltage as well as a constant load to the external power grid. The success of the design in meeting the ESS pulse requirements (Table 1) is shown in Figure 2.

The ESS modulator is a proven design, delivering significant advantages in klystron performance through:

- Highly reliable operation, demonstrated in hundreds of systems worldwide, and predicted to significantly exceed ESS requirements
- Flicker- and droop-free operation over a range of operating parameters
- All active electronics in air for easy maintenance

Table 1: ESS Modulator Requirements

Specification	
Voltage	-115 kV
Current	50 A
Pulse Width	3.5 ms
Frequency	14 Hz (max)
Average Power	290 kW
Droop	< 1%
Pulse Repeatability	< 0.1%



Figure 1: System designed for Oak Ridge National Laboratory Spallation Neutron Source. Design is optimized for long pulse operation with highest possible reliability and availability required for particle accelerator user facilities and test stands. High voltage cables connect to dummy load or klystrons not shown in figure.

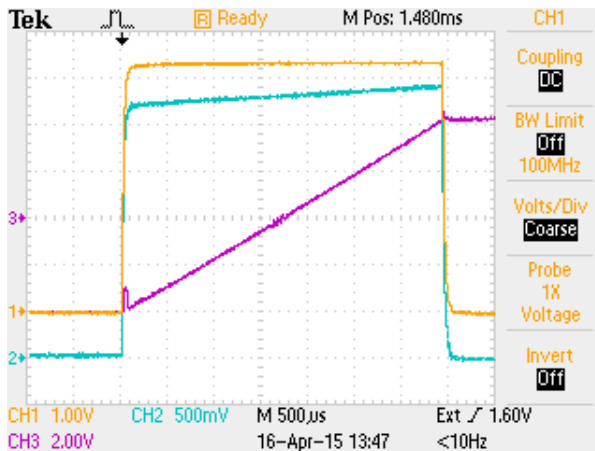


Figure 2: 106 kV, 58 A test pulse showing output voltage (yellow, 20 kV/div), current (blue, 10 A/div) and regulator voltage (purple, 200 V/div). Current increases slightly with time due to heating of the resistive load.

DESIGN

The heart of the ESS modulator is a high voltage solid-state switch. The switch is made of seven series-connected IGBT modules, and operates at 6.7 kV. The IGBTs in the switch give N+2 redundancy: two of the devices can fail without affecting the ability of the switch

to operate at full rated voltage. This is possible because the devices always fail as a short circuit. The series switch also protects the klystron against damage in the event of an arc by opening in less than 800 ns. This rapid opening time limits the dissipated energy from the modulator to 27 mJ, significantly extending the klystron lifetime. As soon as the arc extinguishes, the switch can reclose. Since the arc extinction time is well under 10 ms, this allows the switch to resume operation before the next pulse.

REGULATION

A capacitor bank capable of directly meeting the ESS pulse requirements would be unrealistically large and expensive. The ESS modulator has a much smaller capacitor, which will droop by 15% during a pulse. This droop is eliminated by the switching regulator.

The regulator (shown in Figure 3) supplies only the droop voltage ($\pm 7.5\%$ of the output) rather than the full voltage. This means that the regulator can be small and efficient. The regulator operates in opposition to the variation in capacitor voltage, and produces both a flat output pulse and a constant load voltage to the DC power supply (Figure 2). 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. Because the regulator sinks and sources the same energy during each pulse / charge cycle, the regulator itself is non-dissipative – it uses no net power over a cycle.

The regulator bridge circuit has four different phases of operation, depending on whether the modulator is pulsing or charging, and whether its output voltage is positive or negative.

The regulator is made with two full bridges in parallel; their outputs are connected to a common filter capacitor (Figure 3). 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. The switching transients are filtered by the output filter and the pulse

transformer, producing a ripple of only $1.5 \times 10^{-3}\%$ peak-to-peak; this is 200 times less than the 0.3% specification.

TRANSFORMER

The transformer design is similar to that of a heavy-duty power distribution transformer. The cylindrical windings are on two core legs, with the primary windings closer to the core, and a single secondary winding around each primary. The primaries are connected in parallel, and the secondaries in series.

The low-loss silicon-steel core has a cruciform cross-section with five step sizes, giving a packing fraction of 90.6%. The core cross-sectional area and number of turns were chosen to give a flux swing of 3.4 T for the 110 kV, 3.6 ms pulse. The design is based on well-established criteria for the electric fields. To reduce the electric field at the ends of the windings, there are round field shapers. The transformer tank has voltage and current monitors, and a termination for the high voltage output cable.

POWER SUPPLIES

The high voltage DC power supplies are commercial units designed and built by DTI. Nearly 100 of these supplies have been successfully installed worldwide in large military and civilian radar and accelerator transmitters, operating in both shipboard and land-based systems, where reliability, high performance, and compact footprint are of the utmost importance.

The High Voltage DC Power Supplies are rated for 250 kW, and have the following benefits:

- High reliability, with a demonstrated MTBF of over 90,000 hours
- High efficiency (96.9%)
- Regulation much better than 0.02%, and ripple of $1.5 \times 10^{-3}\%$ peak-to-peak

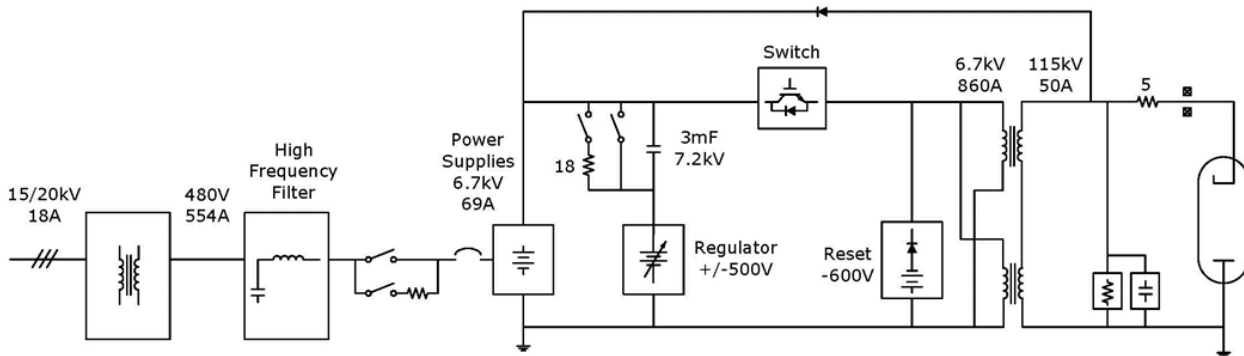


Figure 3: Simplified schematic of the complete transmitter. All components except klystrons are included in the deliverables.