DESIGN AND OPERATION OF PULSED POWER SYSTEMS BUILT TO ESS SPECIFICATIONS

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Abstract

Diversified Technologies, Inc. (DTI), in partnership with SigmaPhi Electronics (SPE) has built three long pulse solid-state klystron transmitters to meet spallation source requirements. Two of the three units are installed at CEA Saclay and the National Institute of Nuclear and Particle Physics (IN2P3), where they will be used as test stands for the European Spallation Source (ESS). The systems delivered to CEA and IN2P3 demonstrate that the ESS klystron modulator specifications (115 kV, 25 A per klystron, 3.5 ms, 14 Hz) have been achieved in a reliable, manufacturable, and cost-effective design. There are only minor modifications required to support transition of this design to the full ESS Accelerator, with up to 100 klystrons. The systems will accommodate the recently-determined increase in average power (~660 kW), can offer flicker-free operation, are equally-capable of driving Klystrons or MBIOTs, and are designed for an expected MTBCF of over ten years, based on operational experience with similar systems.

INTRODUCTION

Diversified Technologies, Inc. (DTI), in partnership with SigmaPhi Electronics (SPE), has designed and installed advanced, high voltage solid-state modulators for European Spallation Source (ESS)-class klystron pulses (Figure 1). These klystron modulators use a series-switch driving a pulse transformer, with an advanced, patent-pending regulator to maintain a precise 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.

Figure 1: DTI's prototype solid-state ESS-class klystron modulator, developed under a DOE SBIR grant.

Table 1: ESS Klystron Modulator Requirements

Specification	
Voltage	-115 kV
Current	25 A per Klystron
Pulse Width	3.5 ms
Frequency	14 Hz (max)
Average Power	160 kW (per Klystron)
Droop	< 1%
Pulse Repeatability	< 0.1%

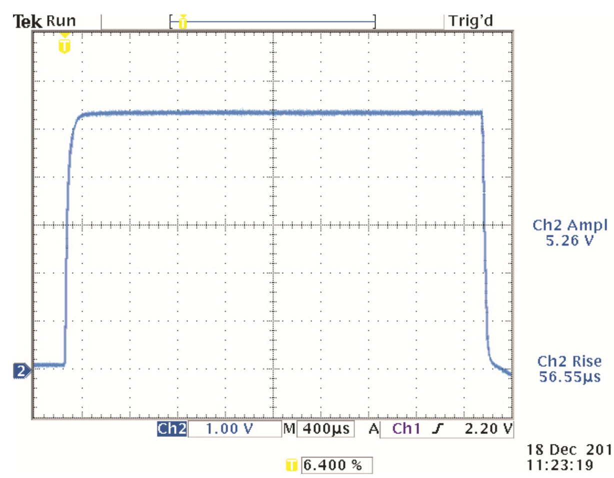

Figure 2: Modulator pulse at 108 kV, 3.5 ms, 0.07% flattop into a Thales TH2179A klystron during site acceptance testing at IN2P3, 18 December 2015.

The DTI/SPE klystron modulator is now a fully 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

With the delivery of these initial modulators, the transition to production for the ESS system itself is straightforward.

DESIGN

The heart of the DTI/SPE modulator design is a high voltage solid-state switch driving a pulse transformer. The switch is made of seven series-connected IGBT modules, and operates at 6.7 kV. This design enables a measured

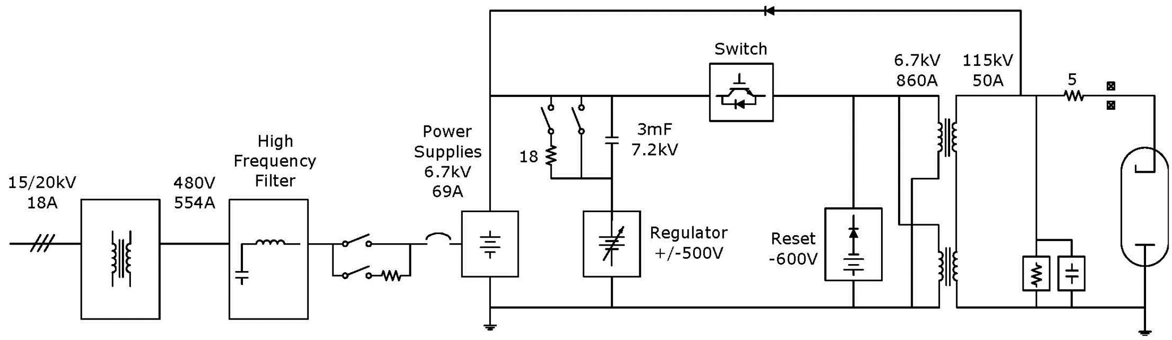

Figure 3: Simplified schematic of the complete transmitter. The turn-key system included all components up to the klystron.

modulator efficiency of 95.7%, primarily due to the fact that the peak power is only switched once per pulse (in contrast to a switching converter, where the peak power is switched at high frequency during the pulse). With a power supply efficiency of 96.9%, this gives an overall wall plug to cathode efficiency of 92.8%.

The IGBTs in the switch give N+2 redundancy, meaning two of seven 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 from 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 modulator 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 DTI/SPE modulator has a much smaller capacitor, which droops by ~15% during a pulse. This droop is eliminated by the switching regulator shown in Figure 3. The regulator supplies only the droop voltage (+/- 7.5% of the output) rather than the full voltage (Figure 4). 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. As a result, the power supply can operate at constant current and power – and thus does not produce flicker, regardless of the pulse 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 switches ~5% of the peak power via two full bridges in parallel. The IGBTs switch at 100 kHz during pulsing and 5 kHz during charging. Their switching is staggered, achieving 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 0.0015% peak-to-peak.

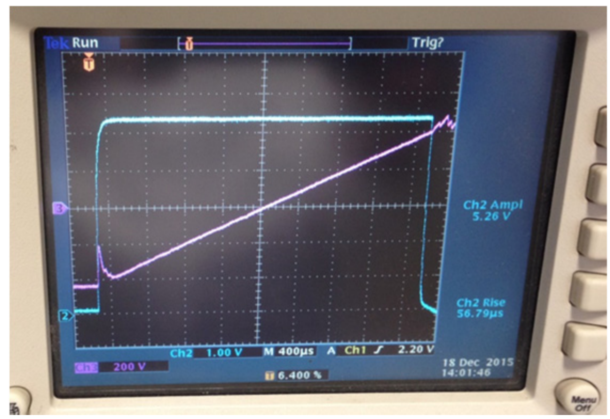

Figure 4: Regulator voltage during a klystron pulse. Ch 2 (blue) shows pulse voltage, 20 kV/div, 400 µs/div. Ch 3 (pink) shows regulator voltage, 200V/div, 400 µs/div. The pulse settles rapidly and remains extremely flat (< 0.1%) over the long pulse flat top (3.5 ms).

Regulation

The pulse 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 supplies are commercial units designed by DTI. Nearly 100 of these 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. Each high voltage DC power supply is rated for 240 kW, with a demonstrated MTBF over 10 years, and regulation much better than 0.02%.