PULSED POWER SYSTEMS FOR ESS KLYSTRONS

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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 European Spallation Source (ESS) requirements. The prototype system was built under a DOE SBIR effort, and the first production modulators were built for, and installed at, CEA Saclay, Franc, and the National Institute of Nuclear and Particle Physics (IN2P3) in Orsay, France, where they will be used in support of RF component development and testing.

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.

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 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%.

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 1: DTI's prototype solid -state ESS-class klystron modulator, developed under a DOE SBIR grant. This design is optimized for long pulse operation with highest possible reliability and availability required for particle accelerator user facilities and test stands.

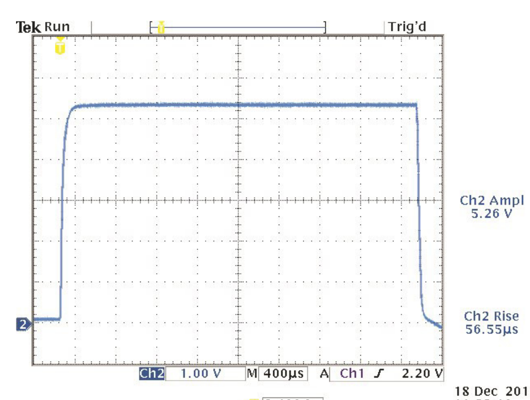

Figure 2: Modulator pulse at 108 kV, 3.5 ms, 0.07% flattop into a Thales TH2179A klystron during site acceptance testing at IN2P3, 18 December 2015.

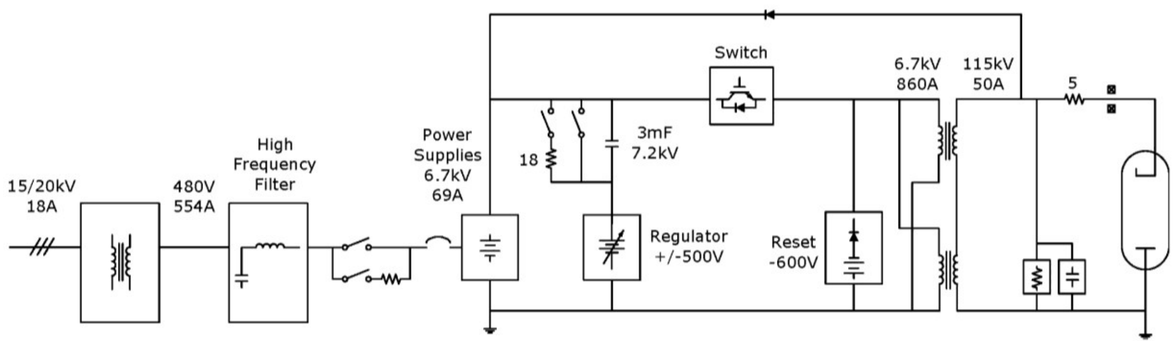

Figure 3. Simplified schematic of the complete transmitter. The turn-key system included all components up to the klystron.

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

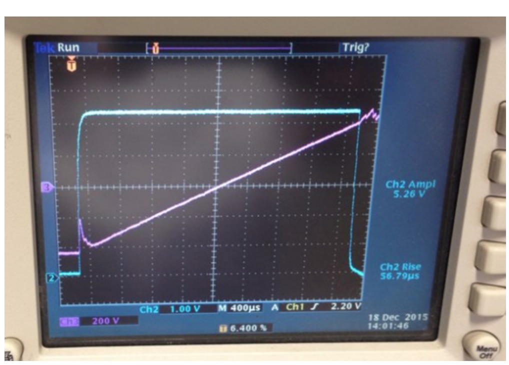

Figure 4: Regulator voltage during a klystron pulse . Ch 2 (blue) shows pulse voltage, 20 kV/div, 400 µs/div. Ch 3 (pink) shows regulator voltage, 200V/div, 400 µs/div. The pulse settles rapidly and remains extremely flat (< 0.1%) over the long pulse flat top (3.5 ms).

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.

PULSE TRANSFORMER

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%.

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ESS APPLICABILITY

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.

Four Klystron Operation

The recent decision to move to 4-klystrons per modulator raises the pulse current to 100 A peak, and requires ~ 660 kW average power. Driving four ESS klystrons is straightforward, and within the inherent capabilities of the design. The major modification is achieving the average power. The IPNO design was built and tested at 440 kW, with two power supplies. Upgrading this design to 660 kW simply requires a third power supply. DTI has delivered systems combining up to eight of these supplies in a single transmitter, providing approximately twice the ESS average power.

The second issue is maintaining the desired risetime and efficiency of the pulse at 100 A. The regulator grows from two to four bridges in parallel to provide the 100 A current required, while their frequency may be allowed to decrease.

Maintaining the risetime seems challenging, since for a given transformer inductance, the risetime will increase in proportion to the peak current. While it is possible to re-design the pulse transformer for lower inductance, cutting it significantly seems unlikely without making other compromises. Examination of the klystron voltage pulse (Figure 5), however, shows that the majority of the risetime occurs between 90 and 99% of full voltage – the 0 - 90% occurs very quickly. The total risetime, therefore, can be significantly improved by adding a small voltage 'kicker' at the beginning of the pulse - essentially making 90% of the kicked pulse equal to the final cathode voltage. This 'kicked' pulse can be much lower voltage (~12 kV) and much shorter (~20 – 30 µs) than the main pulse, so very little energy is required. DTI has demonstrated a version of this approach on other modulators, with great success.

Power Quality

The inherent design of the ESS-class Modulator provides flicker-free operation, due to the operation of the regulator. The switching power supplies, however, are 6-pulse designs, which can create harmonics on the mains without filtering (as provided in IN2P3 and CEA). The increase to 660 kW for ESS significantly simplifies harmonic reduction, since three independent power supplies are now required. Winding the MV stepdown transformer with multi-phase secondaries allows the three supplies for each modulator to appear as an 18-pulse rectifier without any other modifications. A single multi-MVA step-down transformer could power multiple modulators.

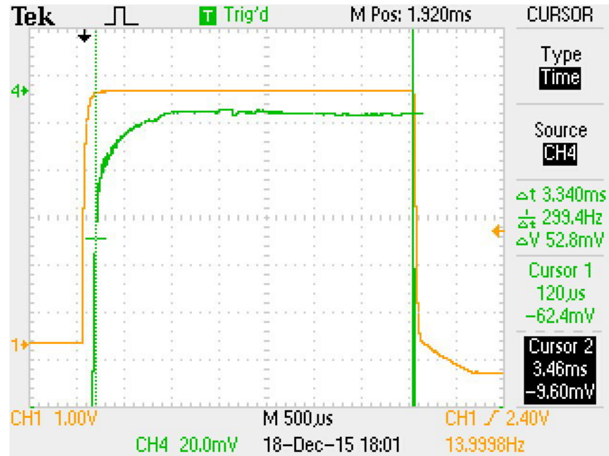

Figure 5: Output voltage and zoomed-in flattop pulse from a klystron pulse. Ch 1 (orange) shows pulse at 120 kV (20kV/div), 500 µs/div. Ch2 (green) shows a zoomed-in flattop, at 400 V/div, with total ripple < 100 V (~0.07%).

MBIOT Operation

ESS is considering the use of Multi-Beam IOTs (MBIOTs) for the HEBT segment of the accelerator, which operate at higher efficiency and lower cathode voltage than the klystrons. The DTI/SPE modulator is equally capable of driving these MBIOTs. While the klystron modulator itself could be used for the MBIOT, dedicated MBIOT modulators would simply use pulse transformers with lower step-up ratios, to minimize costs and maximize supportability. In either configuration, the cathode of the MBIOT would be pulsed in synchronization with the RF drive being applied. The same pulse flattop and ability to provide arc protection to the MBIOT would be preserved.

Reliability / Maintainability

The DTI/SPE ESS-class Modulator was designed for very high reliability, with an expected MTBCF over ten years, based on operational experience on the majority of assemblies. The cooling of the electronics is sized for very long life. The individual modules comprising the system are easily replaceable, and readily transportable in the accelerator tunnel.

The exception is the pulse transformer itself, which is similar to a utility distribution transmitter. The failure rate for 33 – 110 kV utility transformers is estimated at 1 failure per decade per 25 transformers*. Because the pulse transformer is water-cooled and situated indoors, its reliability will be much higher than a passively cooled transformer subject to weather extremes – potentially as low as one failure every century for 25 pulse transformers (based on typical derating factors). While it might be troublesome to replace a pulse transformer, the probability of ever needing to do so is extremely low.

* Roos, F. and Lindahl, S., *Distribution System Component Failure Rates and Repair Times –An Overview*, Nordic Distribution and Asset Management Conference, 2004.