PULSED HIGH POWER AMPLIFIERS

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Diversified Technologies, Inc. (DTI) has built two short pulse, solid-state klystron transmitters for Lawrence Berkeley National Laboratory and Daresbury Laboratory in England. The units are similar, and part of DTI's plan to establish standard laboratory transmitter for short pulse (microseconds) and long pulse (milliseconds) accelerators. The DTI design for short pulse klystron transmitters is based on the combination of a high voltage solid-state switch with a conventional 1:10 pulse transformer and a simple passive pulse corrector (bouncer). The unique passive circuitry gives an extremely flat output pulse as required for advanced accelerator applications. The optimized primary voltage (~35 kV) allows key simplifications in the transformer and the overall transmitter. The combination of a simple and proven circuit topology with properly de-rated components ensures long lifetime and reliable operation.

Keywords : Klystron; Daresbury; LBNL; Solid-State Modulator; High Voltage Pulse-Transformer

1. INTRODUCTION

In 2014, Diversified Technologies, Inc. (DTI) delivered two newly designed solid-state pulsed klystron transmitter systems. Though not identical, the units are similar in design, and were installed at Lawrence Berkeley National Laboratory (LBNL) and Daresbury Laboratory in England.

DTI's goal across these two projects was to develop a complete, replicable package for the high peak power laboratory transmitter market. The modulator is a pulse transformer-coupled hybrid system, including ancillary klystron components (i.e., focus coil, socket) up to the customer-supplied klystron. The RF components include the drive amplifier, protection circuitry, and output waveguide from the klystron. A PLC-based controller with touch-screen interface and ethernet communication is incorporated into the transmitter.

2. MODULATOR

Both systems employ a hard switch, solid-state modulator, which consists of an energy storage capacitor, a high voltage series switch, a step-up pulse transformer, and a passive pulse-flattening circuit. This arrangement gives an extremely flat pulse and allows the use of a moderate value of storage capacitor. The DTI switch can open or close as commanded, so the pulse width is adjusted by the gate pulse to the system. Each system operates with a 35 kV primary voltage supplied by a DTI high voltage switching power supply. The solid state switch consists of a series-parallel array of switch modules, which operate in synchronization, as if they were a single 35 kV switch. The high primary voltage allows optimization of all components to give a simple, reliable, and high stability system.

Fig. 1. Installed Daresbury modulator, consisting of a controls rack, electronics rack, high voltage power supply and modulator tank

Table 1. Key Specifications of PHPA Klystrons

Specification	DAR	LBNL	Unit
Peak RF Power	40	25	MW max
Average RF Power	45	2.5	kW max
Pulse width	3.0	10	microseconds
Repetition rate	1-400	10	Hz
Anode Voltage	350	270	kV
Beam Current	375	250	A
Voltage Flatness	.1%	1%	better than
Voltage reproducibility	.25%	0.1%	better than
Pulse to pulse jitter	4	5	nanoseconds

3. DTI HIGH VOLTAGE SOLID-STATE SWITCHES

A high voltage switch is a crucial, proven building block of most DTI transmitters. The switch consists of a series/parallel combination of commercially-available insulated gate bipolar transistors (IGBTs). Under normal operation, the switch acts as a modulator, controlling the pulses to the pulse transformer. In addition to providing pulsing, another important function of the switch is circuit protection. When a klystron gun arc occurs, the fault is sensed and the switch will open in less than 1 μs to disconnect high voltage. The current rate of rise is limited to a safe value by the inductance of the pulse transformer. This rapid

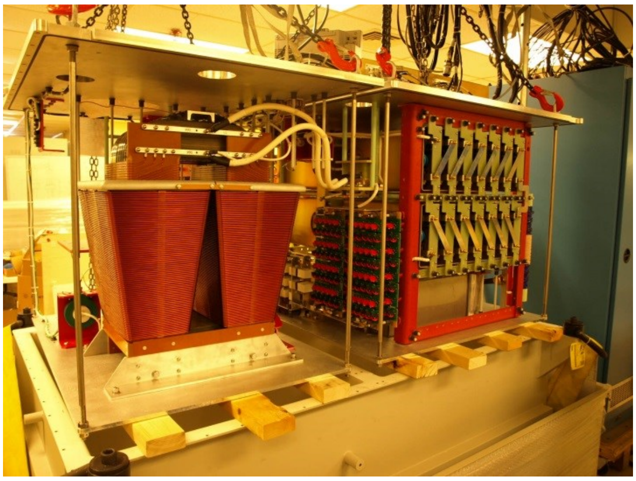

Fig. 2. The LBNL unit suspended above tank. On the left is the tapered pulse transformer; on the right, diodes and solid-state switch array. Far right: power supply cabinets.

current interruption limits fault currents to ~ twice the pulse current, and minimizes the fault energy deposition in the klystron gun, which promotes a long and stable klystron lifetime. These characteristics make the solid-state opening switch an ideal building block for high availability applications such as particle accelerators and mission critical radars. A generous high voltage design margin is included at both the individual switch stages and for the overall switch assembly, so that several switch module failures could be tolerated without affecting system performance.

4. PULSE TRANSFORMER

The high primary voltage of the DTI switch allows a moderate transformer step-up ratio (10:1). This gives fast rise and fall times and good efficiency. The transformer has a bifilar wound secondary on a sloped basket (constant gradient). The transformer design is optimized to work with the small passive bouncer circuit to give a precise flat top (Figures 3 and 4). A commercial power supply supplies the DC core reset current for the transformer, fed through a core reset inductor. DTI's pulse transformers for these short pulse transmitters are typically built by Stangenes Industries (Palo Alto, CA) to our detailed specifications. DTI has built similar transformer-coupled modulators up to 500 kV and 500 A peak.

5. SYSTEM PERFORMANCE

Klystron pulse voltage flatness and stability are crucial to proper linac operation, and the DTI design accommodates proper operation with both of the specified klystrons. The modulators give good pulse fidelity over all conditions but will be optimized near the nominal peak power of the preferred klystron. DTI systems are inherently amenable to modification for potential system upgrades in the field. The modulators have the capability to run approximately 10% over the respective nominal output voltages; if required, the pulse transformer turns ratio may be changed to adapt to higher voltages within the peak current rating of the switch. The 200 kW HVPS similarly has a substantial margin over the requirement, and additional power supplies may easily be added to double the average power at any time in the future.

The simple DTI pulse circuit includes a filter capacitor, a nearly ideal high voltage switch, and straightforward pulse transformer to give a very flat pulse with rapid rise and fall times. Any small imperfections are removed by the passive pulse compensation circuit (bouncer). Pulse to pulse voltage stability is better than 0.1 %. Pulse-to-pulse timing variation is low in DTI systems and meets the $< \pm 4$ ns specification. When combined with the flat pulse, RF phase errors are minimized.

6. RELIABILITY

DTI has installed high voltage transmitter systems for numerous high reliability and high maintainability applications, such as military shipboard radars and high power physics experiments. A combination of conservative design and low operating temperatures (typically 20 – 30 °C junction temperature rise in the IGBTs) contributes to the high reliability of DTI's equipment. The majority have had no field failures after initial commissioning, with some DTI systems achieving over 120 system-years of failure free operation to date.

DTI's high voltage solid-state opening switch technology minimizes the stress on the system in the event of a fault (such as a tube arc). This contributes to long tube life and high availability and allows for rapid recovery in the event of most faults. In addition, these diagnostics allow for the rapid detection and

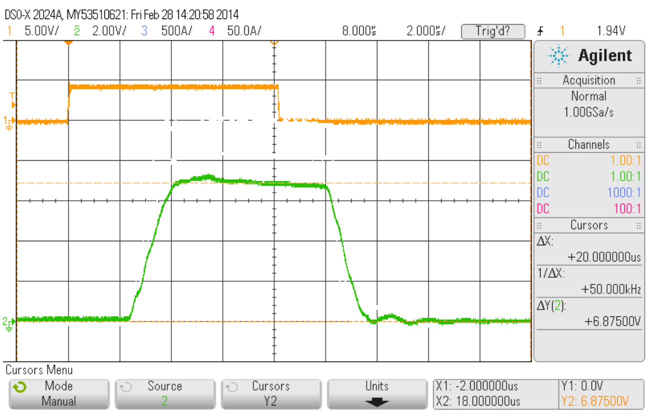

Fig. 3. Test pulse of LBNL system. Pulse is 275 kV, 250 A, with 8µs command pulse.

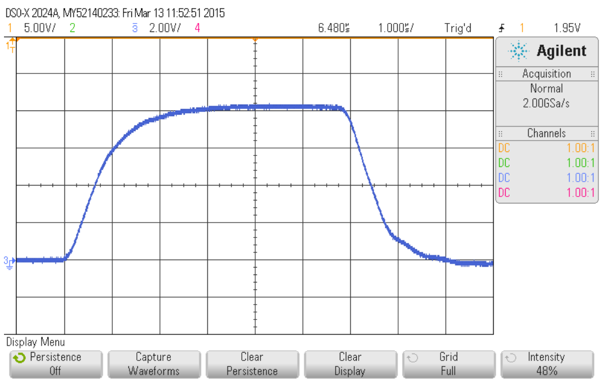

Fig. 4. Daresbury system pulse into a resistive load. Pulse is 350 kV (40 kV/V) for 3.5 µs with less than .01% voltage flatness.

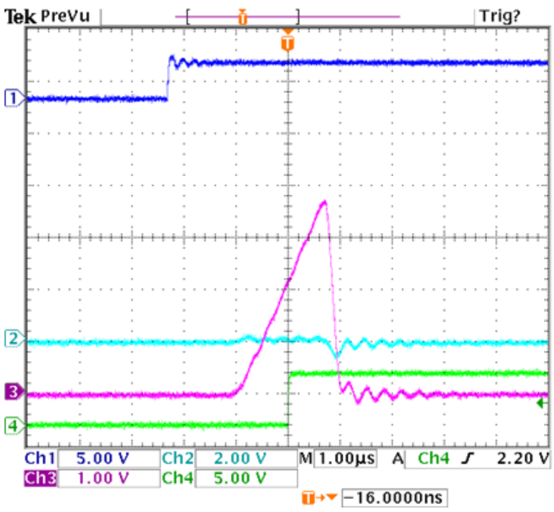

Fig. 5. Arc test for a DTI modulator. Channel 3 is the current at 100 A/div; Channel 4 is the detected fault; time scale is 1 µs/div. The current is interrupted 800 ns after the fault is detected.

isolation of repetitive or hard faults in the overall system (see Figure 5).

The estimated mean time to repair (MTTR) with the recommended spares on site is 4 hours. This results in a system availability of 99.99 %.