DEVELOPMENT OF A SOLID STATE THYRATRON REPLACEMENT FOR THE LCLS KLYSTRON MODULATOR *

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Abstract

This paper discusses the development of a solid state replacement for the L-4888 thyatron, which is presently used in the eighty-three high-power klystron modulators of SLAC's Linac Coherent Light Source (LCLS). The motivations are to improve modulator performance, increase availability and decrease operational costs. The solid state switch is based on an array of SGTO thyristors. The challenging dI/dt (10 kA/ μ s), peak power (150 MW), and average power (100 kW) requirements of this application differentiate this work from prior solid state thyatron replacement efforts. Herein, are described the application (including system specifications), the present development status (demonstrated performance and reliability), as well as future development plans.

I. INTRODUCTION/MOTIVATION

Considered state-of-the-art at the time of its design, the LING 6575 line-type modulator [1] has been operated continuously and reliably at SLAC National Accelerator Laboratory for nearly a half century, supporting a variety of missions, each placing unique demands of the

modulator. A key component of the modulator, illustrated in Figure 1, is the thyatron switch that controls the discharge of the PFN into the klystron load. Several thyatron models have been evaluated, their performance has been reported previously [2].

The LCLS mission places unprecedented requirements on the modulator performance. Relatively small variations in the output voltage translate into variations in the RF phase that cause the accelerated electron beam to move, pulse-to-pulse. Such beam motion results in pulse-to-pulse variation in the undulator efficiency, and hence, photon output, as well as the apparent photon source location; both adversely impact users of the LCLS photon beam [3]. These factors constrain the modulator output pulse-to-pulse voltage stability to an RMS value of 30 ppm for critical RF stations. For a line-type modulator this translates into constraints on the stability of the PFN recharge voltage and the turn-on characteristics of the output switch. Due to ripple on the output voltage, jitter in the switching times produces amplitude variation. The decreasing gas pressure in a thyatron as it ages, increases both the time delay between application of the trigger and switch closure as well as switch closure time. Further, changing gas pressure produces variations in switch commutation/reverse recovery, illustrated in Figure 2.

Figure 1. Simplified schematic of the 6575 klystron modulator.

* Work supported by US Department of Energy under contract DE-AC02-76SF00515

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Figure 2. Thyatron commutation, illustrating reverse recovery instability; CH1 - thyatron trigger voltage (20 V/div), CH4 - klystron (modulator output) voltage (97 kV/div).

The PFN is recharged resonantly; the reverse recovery instability introduces jitter into the initial, and hence final, PFN voltage.

From the foregoing, it is clear that an extremely stable switch is required to meet the LCLS specifications, which for a thyatron, translates to stable gas pressure. The average thyatron life in LCLS is ~ 8 k-hr, and end-of-life is almost exclusively due to reservoir depletion. Therefore, the reservoirs require frequent adjustment and the tube pressure is constantly varying. SLAC is working with the vendor to increase the reservoir capacity and pressure stability in the thyatrons for the LCLS operating conditions, but it is clear that a solid state switch that would eliminate these variations would enhance the modulator voltage stability and improve LCLS performance. Furthermore, a properly engineered solid state switch should reduce total operation cost (purchase and maintenance costs normalized by average hours of operation before failure). Lastly, the number of qualified thyatron vendors is decreasing; it is believed that solid state offers a more secure future switch supply.

II. SOLID STATE SWITCH DEVELOPMENT

A. Major Specifications

The goal requirements for a solid state switch are summarized in Table 1. The replacement of thyatrons with solid state has been demonstrated previously. What differentiates the present work is; high peak power (0.15 GW), high average power (0.1 MW), and high dI/dt . The forward and reverse non-repetitive currents are based on the worst-case fault, which is a breakdown of the high voltage cable between the PFN and pulse transformer.

The requirements were published for competitive bid. Multiple vendors submitted switch proposals. SLAC selected, and has been working very closely with Applied Pulsed Power, Inc. (APP) on the development of the solid state switch.

Table 1. Goal modulator switch parameters

Parameters	Requirements
PFN charging voltage	50 kV
Transient overvoltage	80 kV
Repetitive forward pulse current	6.5 kA
Peak non-repetitive forward current	17.5 kA
Forward RMS current	170 A
Repetitive reverse pulse current	2.3 kA
Peak non-repetitive reverse current	17 kA
Pulse width	6 μ s (fwhm) 4 μ s (flat top)
Pulse repetition rate (max)	120 Hz
Switch turn on dI/dt	10 kA/ μ s
Peak non-repetitive dI/dt	37 kA/ μ s
Turn on time jitter (RMS over 10 sec time sample)	< 2 ns
Switch life	4.3×10^{10} pulses 10^5 hours

B. Solid-state Switch Design

The switch is a 16-stage series stack of the module illustrated in Figure 3. The stack configuration provides N+2 redundancy; the switch can continue to operate even with failed stack modules. The stack module incorporates two thyristor modules, APP S38, in parallel. The S38 module incorporates a ThinPak SGTO and APP-proprietary gate drive circuitry in an encapsulated package. Low frequency voltage balancing between stages is achieved via resistor R1. The snubber, R2/C2, is to limit dV/dt during transient conditions. The MOVs provide transient voltage balancing between stages and overvoltage protection. Additionally, there is an anti-parallel diode array across the switch to minimum voltage reversal.

Figure 3. Schematic diagram of a stack module.

The thermal loss simulations [4] estimate the total switch loss to be 3550W at full power operation, necessitating liquid cooling. The thyristor modules in each stage are attached to an oil-cooled cold plate. There is an oil/water heat exchanger that transfers the waste heat to the linac cooling water system.

Diagnostic access in a series stack presents challenges in signal translation, generally limiting access. However, each thyristors module has over-current detection at two levels; warning and fault. Each stack module incorporates over temperature detection (klixon), which activates a trigger inhibit. Overall, there is monitoring for coolant flow rate, inlet, and outlet temperature. Diagnostics are interfaced with the modulator PLC to interrupt operation and notify the control system of the fault state.

The switch design meets IEC61010 standard for compliance and SLAC Electrical Equipment Inspection Program standards. Figure 4 shows a photo of the solid-state switch installed in the modulator cabinet.

Figure 4. Solid state switch installed in modulator.

C. Performance

The switch was initially installed during Nov. 2011, and has now been operated for approximately 3300 hours. Most of this has been at nominal operating parameters, 44 kV PFN charge voltage, 5.9 kA peak discharge current, and 120 Hz. Representative waveforms are shown in Figure 5. In addition to normal operation, the

Figure 5. Modulator waveforms with solid state switch, CH1 - thyatron trigger voltage (20 V/div), CH2 - PFN charging voltage (10 kV/div), CH3 - Switch current (1.8 kA/div), CH4 - Klystron voltage (49 kV/div).

system was subjected to arc-down tests; a spark gap switch in parallel with the load (primary-side of transformer) is triggered mid-pulse to introduce a short-circuit condition to the modulator. This produces a doubling of switch current and nearly 100% voltage reversal. The solid state switch passed these test, with no lasting impact on the system, after the over-current fault condition was cleared.

Many of the desired performance improvements have been demonstrated with the solid state switch. The switching jitter, measured over a 10-second window, has consistently measured 1.9 ns over the test period. This is an improvement over the best thyatron performance and is free from degradation as tube pressure varies. The switch has not suffered from the commutation instability that affects thyatron operation, which has improved the stability of the output voltage amplitude. A technique, developed at SLAC [5], allows the pulse-to-pulse stability to be measured with a resolution of 10 ppm. The solid state-switched modulator stability is 205 ppm, down from 315 ppm, prior to the replacement of the thyatron. This does not yet meet the LCLS specifications, as there are numerous other factors that must be corrected to achieve the 30 ppm goal. However, the modified modulator phase jitter (goal is 0.07°) performance is among the best of the LCLS stations, as illustrated in Figure 6.

Figure 6. RF phase jitter comparison of solid state-switched station (28-1, in red) to other LCLS stations.

The primary deficiency of the solid state switch to date has been reliability. The longest period of operation without modification or repair has been 1650 hours. Failures have occurred to a broad range of components and sub-systems, including the thyristors. Although it is believed that these are not due to any fundamental limitation of the thyristors in this application, that cannot be ruled out until additional lifetime data is obtained.

III. FUTURE WORK

As discussed in the foregoing, resolving reliability issues is the primary limitation of the solid state switch and will be the focus of future efforts. At this point, the switch under evaluation incorporates numerous modifications to the device delivered to SLAC by APP in September of 2011. This opens the door to quality control issues that are beyond the control of either organization. The stack will be disassembled and the individual stack models will be characterized at full peak and average operating parameters to minimize the potential for defective components and sub-systems. Qualifying the modules individually provides greater diagnostic access than is possible after they are assembled in the stack. Elements will be replaced, as needed, to assure the re-assembled solid state switch is of sound construction. Life testing of the switch will resume after re-assembly.

IV. SUMMARY

The solid state thyatron replacement switch design meets most of the LCLS modulator requirements; voltage, current, pulse repetition frequency, and fault tolerance. Switching jitter is <2 ns and commutation is free of the instabilities that affect thyatron-switched modulators. These improvements combine to decrease the output voltage jitter by over 33% compared to thyatron-switched operation. This contributes to the low RF phase jitter of the modified station.

The station has operated for 3300 hours, but acceptable reliability has not yet been demonstrated. The focus of future efforts will be to identify and address the reliability-limiting faults in the present implementation. It is believed that these are not intrinsic to the topology or thyristors, but rather are quality issues that once identified will be easily corrected.

V. ACKNOWLEDGEMENTS

The authors would like to thank Stephen Jenks, Philip Seward, Mark Kemp, and Briant Lam for their contributions to the solid state switch development project.

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