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FINAL CONVERSION OF THE SPALLATION NEUTRON SOURCE EXTRACTION KICKER PULSE FORMING NETWORK TO A HIGH VOLTAGE SOLID-STATE SWITCH*

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Abstract

The Spallation Neutron Source (SNS) extraction kicker 60 Hz pulsed system uses 14 Blumlein pulse-forming network (PFN) modulators that require timing synchronization with stable rise times. A replacement design has been investigated and the kickers have been converted to use a solid-state switch design, eliminating the lifetime and stability issues associated with thyratrons and subsequent maintenance costs. All kickers have been converted, preventing thyratron jitter from impacting the beam performance and allowing higher-precision target impact. This paper discusses the completion of the conversion of the high-voltage switch from a thyratron to a solid-state switch with improved stability of the extraction system and associated accelerator beam stability.

INTRODUCTION

The Spallation Neutron Source (SNS) extraction kicker system performs magnetic deflection of the proton beam during a gap in beam current to transfer beam to the target. Variations in the extraction kicker pulsed current timing, amplitude, and width can cause beam loss during extraction and transport to the mercury target [1]. The magnet field transitions from zero to full amplitude during the 250 ns gap. Turning on too early or too late will cause the head or tail of the beam to intercept the septum, likely resulting in beam loss and activation of the structures downstream [2].

Each extraction kicker is a pulsed modulator charged to 33 kV and fired 60 times a second. Each kicker can be controlled independently for trigger timing and high-voltage charge set point. The high-voltage switch in the extraction kicker system is a model C1925X thyratron from E2V Technologies. These thyratrons are stable upon initial installation but require daily monitoring to maintain low jitter and drift.

The original thyratron-based system required constant maintenance of the thyratrons after an initial period of stability. This involved adjusting a filament resistor shunt and verifying that the filament and reservoir heater supplies were in the correct ranges and were stable without movement [3]. Improvements have been made to the heater power supplies on each of the extraction kickers, which eliminated line sync and daily excursions related to AC power and improved jitter [3]. But the end-of-life mechanism of excessive turn-on jitter and drift continued to be an issue, with thyratron replacement occurring after an average of 11,794 hours of high-voltage operation. A solid-state thyristor-based high-voltage switch model from Silicon Power, the S56-12, was installed and tested in a test stand PFN [2]. The average yearly cost of thyratron replacements is $150,000. The chosen thyristor stack has no defined end of life or yearly cost for replacement, making thyristors an attractive solution.

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EXTRACTION KICKER CONVERSION

Turn-On Time Reduction

The initial testing of the thyristor on a PFN tank into a dummy resistor load was positive with pulse jitter reduced, but turn-on and rise times were slower, leading to excessive time from triggering to full current flow that was resolved by raising the capacitance of the first 2 stages [2]. The magnet current rise time decreased to 150 ns, which is above the 91 ns seen on a thyratron. The gap in the beam for extraction is derived from the configuration of the proton beam pulse width to obtain 1.3 GeV. This results in a gap time of 251 ns. With a thyratron, there is allowed margin for jitter in the width of the gap as the tube ages. With a thyristor, the aging jitter factor does not occur and a 150 ns rise time that is extremely stable is sufficient to extract the beam without losses (Fig. 1). A saturable inductor was considered to shorten the risetime, but due to the previous discussion was deemed unnecessary.

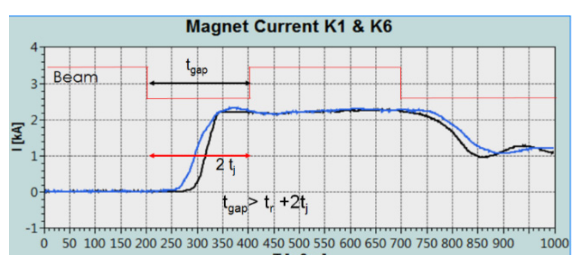

Figure 1: Gap time vs. rise time of thyratron (kicker 1) and thyristor (kicker 6).

Cooling Testing

An initial installation on an operational kicker in 2015 showed promise as well, but it failed at 108 days by destroying one of the stages. A detailed analysis was performed and thermal data were taken, looking at the rise

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time of the temperature close to the thyristor metal baseplate for all 12 stages. The stages were numbered 1 through 12, corresponding from lowest to highest voltage, and fiber optic probes were placed on all 12 thyristor modules. The temperature data revealed a fast 3–5 minute rise time to nearly 135°F. This was followed by a slower rise over 4–5 hours of another 5–10°F (Fig. 2) as the oil tank reached thermal equilibrium.

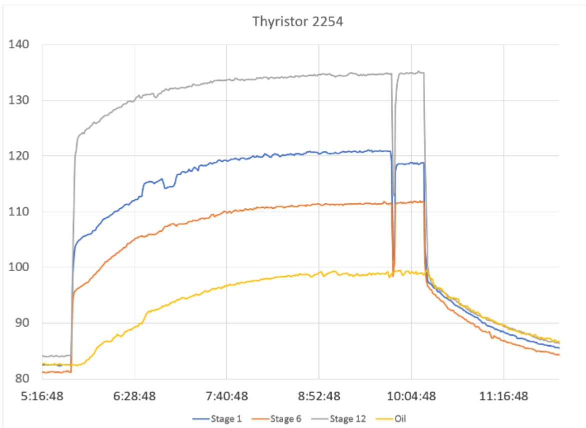

Figure 2: Temperature testing of thyristor, stages 1, 6, and 12 shown. Stages 1 and 6 are below 120°F while stage 12 is above 135°F. Differences in temperature are attributed to cooling flow differences between each stage.

The challenge of cooling a stack immersed in a tank with 300 gallons of silicon oil was solved by using an oil manifold that distributed oil flow across each stage individually. This setup was crafted and tested in various configurations to reveal the ideal placement and to ensure it was adjustable upon installation in any of the tanks. To duplicate the results on multiple manifolds and multiple tanks, a baffling system was crafted and placed around the thyristor stack to guide oil flow across the stack consistently (Fig. 3). The oil system is required to cool the 25Ω impedance-lowering resistor and high voltage capacitors in addition to the high-voltage switch, requiring that the oil flow be balanced between the two. The oil flow–regulating valve to the resistor was not changed from the existing configuration. The flow meter for the oil into the tank experimentally established a minimum of 10 GPM to limit the temperatures to below 125°F.

Manifold adjustment played a large part in the final temperature of each stage. A manifold that was adjusted to increase the flow to the higher-voltage stages could lead to higher temperatures on the low-voltage stages. Each system was validated upon conversion for a minimum of 4 hours of runtime with permanently installed temperature probes on stages 1, 6, and 12. It was important to monitor stages 1 and 12, as they are up against the edges of the end plates on the thyristor assembly and are more temperature-sensitive to manifold adjustments due to restricted cooling flow. Stage 6 was selected as a middle stage; testing revealed the temperatures were more consistent between stages 2 and 11 when the manifold position was optimally adjusted.

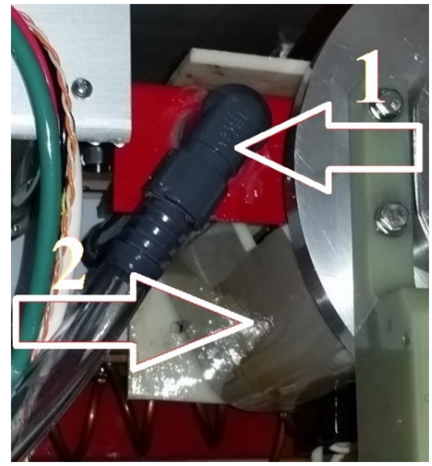

Figure 3: Thyristor baffling and manifold. Manifold is indicated by arrow at location 1 and baffling by arrow at location 2.

Final Conversion

The first permanent thyristor stack was installed in a kicker having a thyratron that was nearing the end of its life and the jitter was becoming problematic, kicker 6, in May of 2017. The jitter measured 2 ns and remained consistent there over months without any adjustments needed. A second kicker, kicker 12, was converted after significant runtime had been accumulated on the first system. After 625 days on kicker 6 and 325 days on kicker 12, the thyratron jitter of kicker 5 was compared (Fig. 4). The remaining kickers were converted and the drift of all 14 kickers settled into a 15 ns range with minimal excursions (Fig. 5).

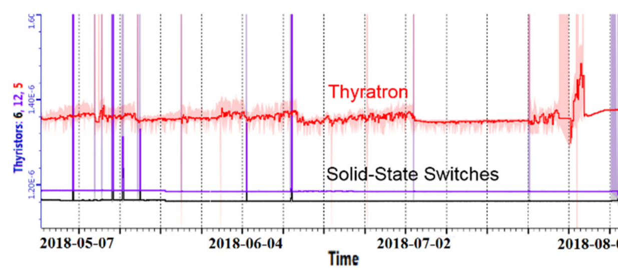

Figure 4: Kickers 6 and 12 thyristor and kicker 5 thyratron jitter over 100 days. Thyristors ±2 ns, thyratron at ±50 ns by end of life.

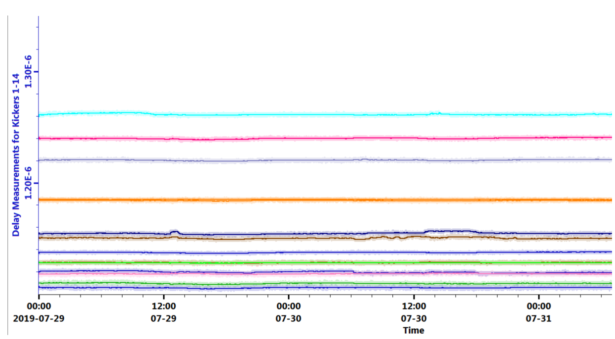

Figure 5: All 14 kickers' jitter/drift after conversion over 2 days.

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The measured current rise time of each thyristor stack was found to be approximately 150 ns. A typical thyratron rise time is closer to 90 ns; but as the rise time across all 14 units (Fig. 6) was consistent and the jitter was substantially less than a thyratron system, the difference in time did not have any noticeable impact on beam extraction.

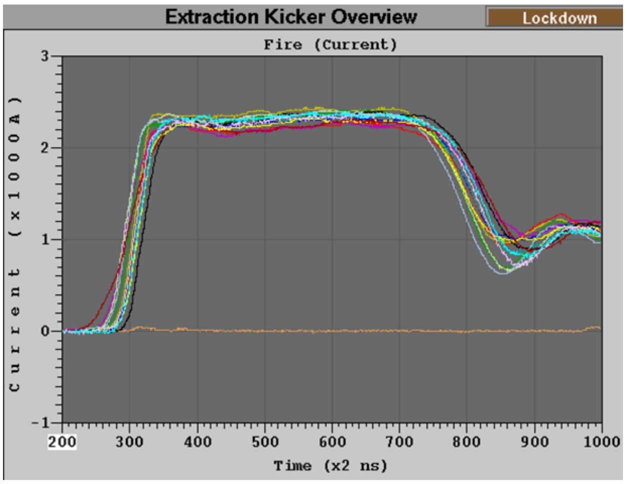

Figure 6: Magnet currents for 14 kickers (1 is spare and out of time) matching rise times. 1000 A/division, 100 ns/division.

Operator intervention in the form of magnet steering adjustments required to ensure beam on target has been reduced from approximately 4 adjustments per day with solely thyratrons to approximately 2 adjustments per day. Whether this improvement is solely due to thyristors will be verified as more data are collected for the machine in the future.

During the machine outage in April of 2019, a thyristor conversion in kicker 6 experienced a drastic failure. The cause of the failure was determined to have been a failure of the cooling pump. The thyristor overheated as a result of a lack of cooling and catastrophically failed. At the time of failure, the thyristor had run for 16,600 hours without any incidents related to it. This was a 41% lifetime improvement compared with an average thyratron life, with more stability and less maintenance intervention. A flow interlock will be installed on the return and feed lines of the oil manifolds to verify that the pumping system is functioning and to shut down the system before thyristor damage can occur. Kicker 6 was repaired with a new stack and has run for 1611 hours without incident.

The only other failures to date have been a failure of the trigger board assemblies. A 200 V power supply failed due to excess current draw, leading to a no-trigger state. The thyristor recovered without issue and resumed operation once the trigger board was replaced.

The remaining thyristor stacks continue to run and allow the SNS to deliver neutrons with minimal downtime compared with the former thyratron-based system. Occasional pre-firing of the thyristor stack 1 ms early is experienced and continues to be investigated.

CONCLUSION

The thyristor replacement project began on May 30, 2017, with one kicker and finished on March 25, 2019, with the 13 remaining kickers converted without a single thyristor failure in that time period. All thyratron-related hardware was removed from the kickers and mothballed for other projects.

ACKNOWLEDGMENTS

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