SNS LINAC MODULATOR OPERATIONAL HISTORY AND PERFORMANCE*

V.V. Peplov, D.E. Anderson, R. I. Cutler, J.D. Hicks, R.B. Saethre, M.W. Wezensky, Oak Ridge National Laboratory (ORNL), Oak Ridge, TN 37831, U.S.A.

Abstract

Fourteen High Voltage Converter Modulators (HVCM) were initially installed at the Spallation Neutron Source Linear Accelerator (SNS Linac) at the Oak Ridge National Laboratory in 2005. A fifteenth HVCM was added in 2009. Each modulator provides a pulse of up to 140 kV at a maximum width of 1.35 msec. Peak power level is 11 MW with an 8% duty factor. The HVCM system must be available for neutron production (NP) 24/7 with the exception being two, 6-week maintenance periods per year. HVCM reliability is one of the most important factors to maximize Linac availability and achieve SNS performance goals. During the last few years several modifications have been implemented to improve the overall system reliability. This paper presents operational history of the HVCM systems and examines failure mode statistical data since the modulators began operating at 60 Hz. System enhancements and upgrades aimed at providing long term reliable operation with minimal down time are also discussed in the paper.

INTRODUCTION

The high frequency switching Megawatt-class High Voltage Converter Modulators at the Spallation Neutron Source Linear Accelerator serve as HV pulsed power supplies for the RF system. They have been in service since 2005 and are used to support scheduled neutron production. During these years many improvements, changes and upgrades were implemented in the system to achieve the desired reliability. In this paper, a brief description of the system will be given at the beginning, then history of HVCM failures and failure mode analysis will be discussed, and then all the activities that provided HVCM performance improvements during the last few years will be presented.

HVCM SYSTEM OVERVIEW

A simplified block-diagram of the SNS HVCM is shown in Figure 1. One can find a more detailed description of the system in specific papers which have been presented and published earlier [1, 2]. Here is a brief overview of the modulator power flow.

A high power 3-phase 13.8 kV: 2.1 kV substation delivers power to a 3-phase regulated SCR rectifier which charges two large storage capacitor banks up to +/-1250 V. Three IGBT H-bridge switching networks are used to generate 20 kHz drive currents to the primaries of boost transformers located in the oil-filled modulator tank. The transformer's leakage inductance is resonant with capacitors placed across the secondary to achieve semi-soft switching of the IGBTs. Coupling the neutral of the secondary to the midpoint of the output filter achieves the required voltage level at the rectifier outputs. The signals are combined and filtered and then the output voltage pulse feeds the klystron's cathode.

There are two main parts of the linear accelerator: the Normal Conducting Linac (NCL) which consists of Drift Tube Linac (DTL) and Coupled Cavity Linac (CCL), and the Super Conducting Linac (SCL). Accordingly there are various configurations of the modulators: DTL and CCL modulators feed one to three Megawatt-level klystrons and produce output pulses up to 135 kV and 95 A. SCL modulators supply ten or eleven (SCL-1 only) 550 kW klystrons with voltage and current up to 75kV and 124A.

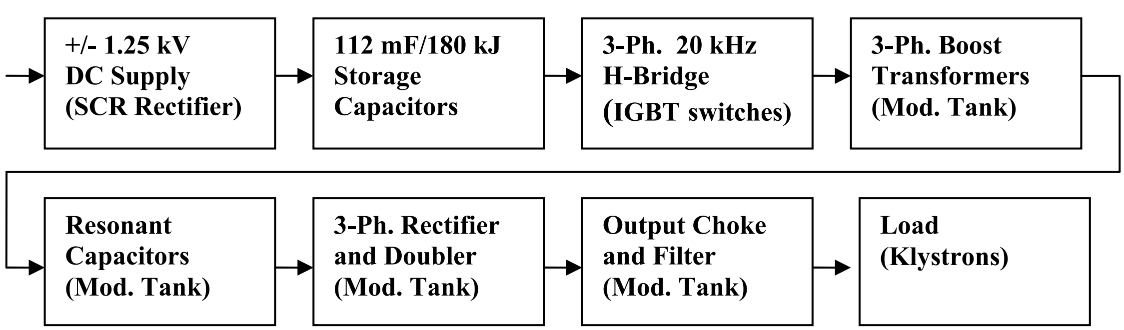

Figure 1: SNS HVCM power flow block-diagram.

* SNS is managed by UT-Battelle, LLC, under contract DE-AC05-00OR22725 for the U.S. Department of Energy

HVCM OPERATIONAL EXPERIENCE

Operational History

Fourteen HVCM systems were installed at the SNS Linac in 2005. Initially, operation was limited to a 30 Hz repetition rate to optimize system availability. Many upgrades have been implemented to improve entire modulator reliability [1, 2]. The list of major changes to CY-2008 includes:

- SCR controller upgrades (new fiber optic driving cables; new hard firing cards; fast response protection circuit; new snubber board; wiring);
- Modulator tank upgrades (new boost transformer; oil cooling system; new inductive choke; resonant capacitors value adjustment);
- New dynamic fault /magnetic flux detection system;
- Modulator “Interlock” circuitry upgrade;
- “Smoke Alarm” system for fire suppression.

The fifteenth modulator was added to reduce the number of klystrons per modulator in the SCL section in early CY-2009. Since the spring of 2008, the HVCM systems run at 60 Hz according to the NP schedule, 24/7 over a year with two 6-7-week shutdowns in winter and summer. There are two runs each calendar year (CY). The last five runs are considered here. HVCM down time statistical data, failure mode analysis and improvement activities will be discussed in the following sections.

Downtime Statistics

The diagram of beam interruption downtime caused by any type of HVCM failure beginning in September 2008 (run 2008-2) is presented in Figure 3

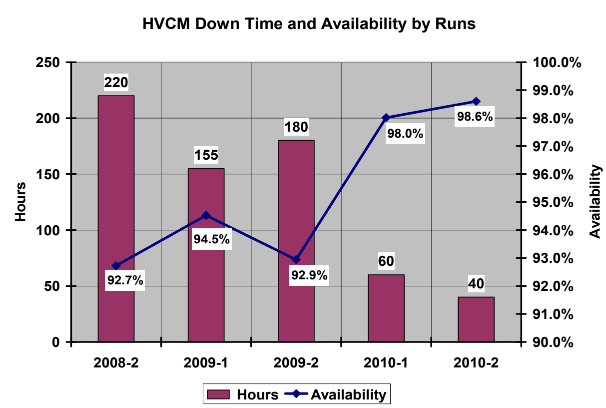

Figure 2: HVCM Downtime and Availability by Runs.

HVCM availability is defined as a ratio of modulators total running hours to total hours for neutron production and accelerator physics study in each run period, is also shown on the diagram. The total number of operational hours during each run period is roughly from 2,500 to 3,300 hours.

One can see the poor HVCM reliability in 2008-2009, and a big improvement of overall system reliability and availability in CY-2010.

FAILURE MODE ANALYSIS

The diagram of HVCM downtime caused by different types of failure from September 2008 is presented in Figure 3. Depending on the nature of the fault, each event may bring the system down from anywhere between a few minutes up to tens of hours. The major contributors are shown. Where no bars are shown, there were either no failures or an insignificant number of hours attributed to that particular component / subsystem for that run period. While most major component / subsystem class failures are trending down, “miscellaneous” nuisance trips are presently dominating the HVCM downtime.

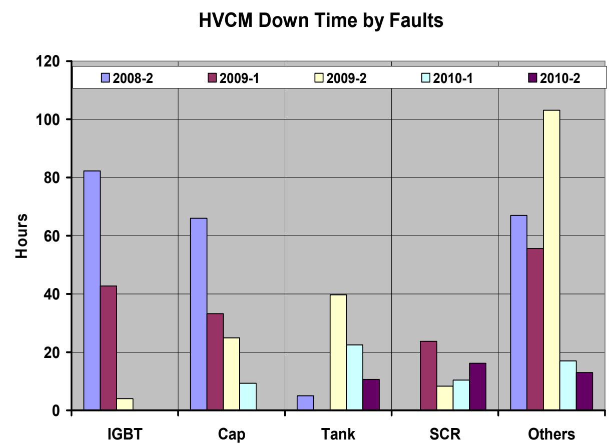

Figure 3: HVCM Downtime by Failure Mode.

IGBT and Bypass Capacitors

Since 60 Hz running began in 2008, IGBT and large H-bridge bypass oil-filled capacitor failures were the main contributors to HVCM down time. IGBT failures occurred due to over-voltage, excessive current stress and shoot-thru conditions. Usually an IGBT explosion was accompanied by dramatic damage to other components inside the modulator enclosure. The problem of IGBT end-of-pulse over-voltage was thoroughly investigated in spring 2009 [3]. It was found that changing the pulse width by only 5 us may lead to voltage transients approaching IGBT device ratings. An adjustment of the pulse width for all HVCMs was done and a quantum fixed modulator pulse width defined. Since that time there were only two IGBT failure events, and downtime due to IGBT failure decreased from 82 hours in 2008-2 (10 events, 37% of total HVCM downtime), to only 4 hours in 2009-2, and “0” in CY-2010.

Original oil-filled, bypass, 10uF/4kV capacitors cracked or blew up because of extensive post-pulse current ringing, internal overheating and degradation. The temperature measured on the surface of the capacitor reached 165°F. Capacitor explosions also led to catastrophic damage inside the safety enclosure. MTTR was extensive. Several iterations were tested prior to identifying a reliable capacitor. Finally, during CY-2009 all oil-filled capacitors were replaced with new solid self-healing capacitors. Now temperatures on the surface of new capacitors do not exceed 110°F. There have been no failures since they were installed. Downtime due to this type of failure reduced from 66 hours in 2008-2 run (10events, 30% of total HVCM down time), to "0" in CY-2010.

In-Tank Failures

Failures of HV components inside the modulator tank lead to long recovery times. All in-tank HV capacitors operated successfully for more than 20,000 hours running at 30 Hz. Then after 6,000 hours of operation at 60 Hz with extended pulse width, 4 boost capacitors in the NCL section failed in 2009-2. The failures were due to high dissipation losses and internal overheating. The measured temperature on capacitor surface reached 145°F.

New higher rated components were installed in the NCL tanks during summer 2010 shutdown. The temperature on the surface of the new boost capacitors did not exceed 120°F, but inspections made in January 2011 revealed another problem. Several of the units exhibited severe damage from corona and arcing, including punch through of the case, surface tracking of the insulator brackets and degradation of adjacent oil. The most likely cause for this was the presence of air bubbles either inside or external to the capacitor. Careful investigation has been carried out and ways for improvement were defined [4].

SCR Controller

Another contributor to downtime is the SCR controller. A series of failures in the new modulator explains the peak on the diagram in 2009-1. Later there were several events where SCRs, snubbers, line current fuses, driver cards or fibers failed randomly. Temperature monitoring revealed the components inside the SCR cabinet were overheating. The temperature of AC line fuses reached 180°F. A Forced air cooling and temperature monitoring system for the SCR cabinet was designed and installed on the two most stressed modulators in summer 2010.

Other Failures

The last contributor shown on the diagram is named "Others". This includes different types of faults, such as: HV cable arcing, IGBT driver and fiber link failures, damage in oil pump assembly, cooling water leakage, balance resistor damage, etc. Also, a large number of miscellaneous trips (even if each is of short duration) caused by electrical noise and disturbances in the HVCM control system made a great contribution to the total down time. Careful monitoring, diagnostics and routine maintenance activities helped to resolve many of the existing problems and improve the reliability in CY-2010.

HVCM HARDWARE UPGRADES

The summarized list of the most important enhancements and upgrades made in CY-2009 and 2010 is presented below:

- New modulator installed;
- New solid capacitors installed on IGBT switch plates;
- IGBT driver cards upgraded (easier to replace, more robust connections);
- IGBT switch plate upgraded (gaps increased, additional insulation, new 120V AC power distribution wiring);
- Cables to switch plates replaced with flame-proof cables inside safety enclosure;
- "Banana" type termination of cable header replaced with hard bolted (better contacts);
- Replacement feed thru insulating plates on the top of tanks (flame-proof material);
- Oil pumps modified (seal - to prevent water leak, assembling – easier to access and repair);
- SCR snubber boards modified;
- New 150kV boost capacitors installed in DTL and CCL tanks;
- New forced air cooling system for SCR cabinet installed on two modulators.

FUTURE PLANS

As there are plans to increase accelerator beam power, modulator pulse width should be extended, thereby increasing the stress on the HVCM. Additional developments which intend to better operational performance are ongoing at the SNS [3]. The primary proposed improvements are:

- New IGBT gate driver;
- State-of-the-art new controller;
- Series opening IGBT switch;
- "N+1" redundant H-bridge topology.

CONCLUSION

The HVCM system was a major contributor to the accelerator down time until 2009. Thorough investigation and analysis of failure mode helped to understand root causes of the failures and find proper solutions for subsystems enhancements. All changes and upgrades performed during the last two years lead to a remarkable reduction in HVCM downtime, and overall system reliability has been improved considerably in 2010.

REFERENCES

[1] D.E. Anderson, et al., "Enhancements for the 1MW High Voltage Converter Modulator Systems at the SNS," Proc. PAC 2005. Conf., May 2005, p. 3313-3315.

[2] D.E. Anderson, et al., "Operational Performance of the Spallation Neutron Source High Voltage Converter Modulator and System Enhancements," Proc. 2006 IEEE 27th Int. Power Mod. Symposium, May 2006, p. 427-430.

[3] D.E. Anderson, "Developments in Solid-State Modulator Technology towards High Availability," Proc. PAC 2009, 2009, p. 117-121.

[4] D.E. Anderson, R. Saethre, "SNS Warm Linac High Voltage Converter Modulator (HVCM) Boost Capacitor Failure Analysis and Conclusions", ORNL Internal Report # 104010200-TD0020, R00, March 2011.