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EFFICIENCY, POWER LOSS, AND POWER FACTOR MEASUREMENT OF QUADRUPOLE MAGNET POWER SUPPLIES AT THE SPALLATION NEUTRON SOURCE*

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Abstract

The linear accelerator (LINAC) quadrupole magnets are powered by 42 silicon-controlled rectifier (SCR) based power supplies at the Spallation Neutron Source (SNS) facility of Oak Ridge National Laboratory. These 35 V, 525 A power supplies are bulky, inefficient and require both air and water cooling. The reliability of the SNS facility is impacted due to water leaks internal to power supplies and current readback issues associated with their unique control system interface, resulting in multiple downtime events. Hence, an alternate solution is necessary for the continued reliable operation of the SNS. To mitigate the above-mentioned problems, this paper proposes the use of off-the-shelf Switch Mode Power Supplies (SMPS) rated for 20 V, 500 A with serial control interface. These SMPS are air-cooled, more efficient and more compact owing to their switching speeds of approximately 160 kHz. The performance enhancements of the SMPS in comparison with the existing SCR power supply are discussed in detail in this paper. The features of the SMPS, along with experimental results for both power supplies, like efficiency, power losses and stability, are presented. Ongoing work is also discussed.

INTRODUCTION

The Spallation Neutron Source (SNS) at the Oak Ridge National Laboratory (ORNL) is an accelerator-based pulsed neutron source facility. The ion source at the front end of the SNS produces negatively charged hydrogen ions which travel through the LINAC to the accumulator rings, ultimately extracted to a mercury target to produce neutrons.

The dc power supplies in the LINAC supply constant current to the magnets which helps to focus the beam. The quadrupole power supplies play a vital role in the overall functioning of the SNS facility as failure of one of the power supplies would prevent beam from focusing and result in beam losses in the LINAC. Furthermore, the power supplies are interlocked to operations through the Machine Protection System (MPS), with a faulted supply resulting in machine downtime. Therefore, an alternative solution is necessary to ensure continued reliable operation of the SNS.

POWER SUPPLY OVERVIEW

The installation, testing and commissioning of all the power supplies were conducted in 2005 [1]. There are a total of 511 power supplies in the SNS. The Medium Energy Beam Transport (MEBT), the Coupled Cavity LINAC (CCL), and the Superconducting LINAC (SCL) have 14, 8, and 39 quadrupole magnet power supplies, respectively [2]. These LINAC quadrupole magnet power supplies are the least reliable compared to the rest of the power supplies due to problems stated previously.

These quadrupole magnets are powered by silicon-controlled rectifier power supplies (SCR PS). These are 6-pulse rectifier supplies which regulate the output at 60 Hz based on the phase angle adjustment. As a result of this, a bigger transformer is utilized which increases the overall size of the power supply. The efficiency of these power supplies is approximately 75% at the operating point of 280 A, 8 V, resulting in high power losses and thus require water cooling. Water cooling has led to internal water leaks which have caused considerable downtime.

The power supplies utilize a unique power supply interface (PSI) [3] which has current readback issues. The measured current drifts arbitrarily from its setpoint, occasionally exceeding the threshold and tripping the power supply and disabling beam in the LINAC. Due to the above-mentioned problems, alternative solutions are imperative to further increase the power supply reliability and sustainability. This is crucial for the availability of the SNS to maximize neutron production for the science community.

NEW STANDARD OFF-THE-SHELF LINAC POWER SUPPLY

The SNS upgraded the MEBT portion of the LINAC with a standard off-the-shelf SMPS in 2018. Since initial installation, these power supplies and their controls have been extremely reliable and experienced no failures. The SMPS has many advantages when compared to the SCR PS. The magnetics of the SMPS occupy less volume due to their high switching speed of approximately 160 kHz. As a result of this, the power supply occupies less space and generates less heat. There is a serial control interface to control the power supply which eliminates the need for the PSI and the SCR PS control interface. The SMPS is completely air cooled, eliminating the need for water cooling. This eliminates the potential for internal

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water leaks and improves reliability. The SMPS outperformed the SCR PS in major areas like efficiency, power factor, power losses and stability as will be discussed in detail in the upcoming sections.

Figure 1: Test cage with water-cooled resistive load.

EXPERIMENTAL RESULTS

In order to verify the viability of the proposed SMPS and compare it with the SCR PS, the power supplies were installed on a test stand with a high-power water-cooled resistive load inside a protective cage as shown in Fig. 1. This test cage consists of a deionized water-cooled high-power load that is constructed from stainless-steel tubing to achieve the desired resistance. This stainless-steel tubing can be connected either in series or parallel to achieve resistances as high as 225 mΩ. The power limit of this load is 30 kW. Table 1 compares the operating parameters of the two supplies such as nominal three phase voltage and input frequency, maximum output voltage (V_{DC}), maximum output current (I_{DC}), and load resistance.

Table 1: System Parameters

Parameter	SMPS	SCR PS
Input	480 V, 3 Φ, 60 Hz	480 V, 3 Φ, 60 Hz
Rated output V_{DC}	20 V	35 V
Rated output I_{DC}	500 A	525 A
Test Stand Load resistance	33 mΩ	33 mΩ

From Table 1 we can see that the full-scale DC operating points of the SMPS are slightly lower than SCR PS which could be a cause of concern. However, for this application the maximum operating point of the power supplies in the SCL is 430 A at 10.4 V which is still well within the maximum rating of the SMPS.

The efficiency was calculated as a percentage by dividing the output power (P_0) by input power (P_{in}).

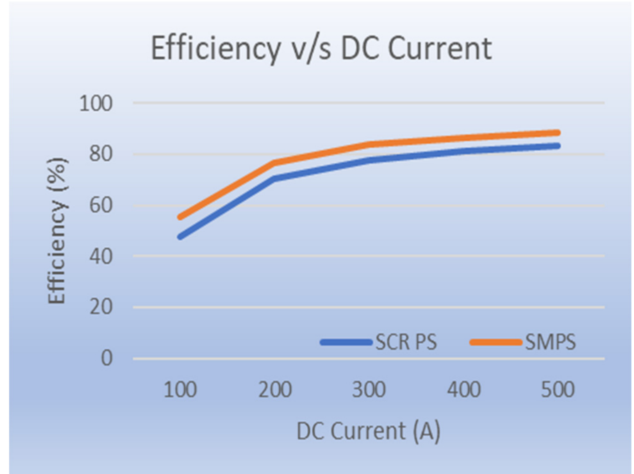

Figure 2: SMPS & SCR PS efficiency comparison.

P_0 was calculated by multiplying V_{DC} with I_{DC}. P_{in} was measured using a power quality analyzer. Figure 2 shows the efficiencies of both SMPS and SCR PS. As we can see, the SMPS is slightly more efficient than the SCR PS because of its topology and efficient semiconductor switches.

As the current setpoint increases and reaches close to its full-scale value, the power factor of the SMPS also increases. This can be confirmed from the Fig. 3.

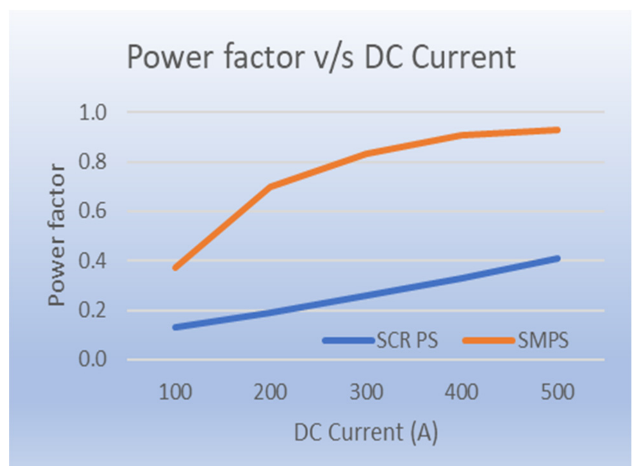

Figure 3: SMPS & SCR PS power factor comparison.

Since the SMPS is completely air cooled, it is also important to understand how much additional heat is being dumped into the heating, ventilation, and air conditioning (HVAC) system. A calorimetric analysis was conducted to determine the heat loss of the SCR PS through water. The heat lost through air was then calculated by subtracting the heat lost through water with the total heat loss. This was then compared with the heat loss of the SMPS to quantify the additional heat rejected to the HVAC system. This information is explained in detail in Table 2. The calorimetric analysis was conducted by using Eq. (1).

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Table 2: Calorimetric Analysis

						SCR PS		SMPS	
I_{DC} (A)	**T_1 (ºC)**	**T_2 (ºC)**	**ΔT (ºC)**	**Flow Rate (GPM)**	**Heat Loss to Water (W)**	**Heat Loss to Air (W)**	**Total Heat Loss (W)**	**Total Heat Loss, Air (W)**	**SMPS Additional Heat Loss into air (W)**
100	22.4	23.2	0.8	1	210.6	155.4	366.0	266.2	110.8
200	22.5	23.6	1.1	1	289.5	270.5	560.0	412.0	141.5
300	22.5	24.3	1.8	1	473.8	408.2	882.0	588.0	179.8
400	22.6	25.3	2.7	1	710.7	525.3	1236.0	840.0	314.7
500	22.6	26.0	3.4	1	895.0	800.1	1695.0	1115.0	315.0

$$P_{loss}^{water} = c_p . V . \Delta T . \rho \,, \qquad (1)$$

where P_{loss}^{water} is the heat lost through water, c_p is the specific heat capacity of the fluid, V is the flow rate of the coolant, ΔT is the temperature difference between the inlet (T_1) and the outlet water flow (T_2), and ρ is the mass density of the liquid. The total heat loss into the air of the SMPS is a couple of hundred watts more than the heat loss to the air dissipated by the SCR PS. However, this additional power loss is negligible when compared to all the other advantages of the SMPS like better efficiency, higher power factor, lower losses, and reliability. The total power loss of the SMPS is lower than the SCR PS as it is more efficient.

Another important factor in a quadrupole magnet power supply is stability. Table 3 gives a detailed information on stability measurements. The mean, minimum, maximum, and standard deviation were measured with the help of an oscilloscope. The stability (coefficient of variation) was calculated by dividing the std. deviation by the mean and expressed as a percentage. From Table 3, we can see that the SMPS has better stability compared to the SCR PS.

Table 3: Stability Measurements

Parameter	SMPS	SCR PS
Measured value	501.5 A	537.1 A
Mean value	501.1 A	536.6 A
Minimum value	499.6 A	527.1 A
Maximum value	502.9 A	552.1 A
Std. deviation	0.34	3.05
Stability	0.07%	0.57%

ONGOING WORK

A campaign to replace several power supplies during scheduled outages is currently underway. Nine power supplies were replaced recently and 12 more are set to be replaced in the summer of 2021. Completion of replacement of the remaining 26 SCR PS in the LINAC are expected by spring of 2023.

CONCLUSION

In this paper a new standard SMPS was proposed as a replacement for the SCR PS. Both SMPS and SCR PS were tested under similar conditions, with SMPS exhibiting better efficiency, higher power factor, lower power losses and greater stability. A comprehensive calorimetric analysis was conducted to determine the additional heat load on the HVAC system which was later determined to be negligible. Due to its various advantages and higher performance, the SMPS is considered as a viable option for replacement of the SCR PS.

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