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CONCEPTUAL FREQUENCY ANALYSIS-BASED PREDICTIVE MAINTENANCE*

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Abstract

The Spallation Neutron Source (SNS) Radiofrequency (RF) Systems have operated at over 98.5 percent availability for the last several operational periods. The implementation of a more stringent goal for the SNS RF – to exceed 99 percent availability – coupled with the more general desire to increase reliability for accelerator-driven systems has required a more subtle approach to reducing downtime. Close examination of the top downtime sources revealed that filament power supplies are the second leading contributor to system interruption in both frequency and duration. Power supply maintenance is nearly always reactive and there is not currently a confirmed method at the SNS to predict when they will fail. The SNS RF Systems engineering team has developed a concept, analogous to methods employed in 3-phase induction motor fault detection and mechanical vibration analysis, that uses frequency domain measurements over time to predict supply failure.

INTRODUCTION

The SNS RF Systems are comprised of over 100 individual subsystems consisting of thousands of individual components which all need to operate consistently and reliably in fulfillment of the facility mission to provide scientific users with a world-leading source of neutrons. As shown in Fig. 1, the RF systems have operated at an average annual availability exceeding 98 percent since US government fiscal year (FY) 2018. The lone dip in availability in 2019 was the result of an RF seal failure in the SNS RFQ02 [1].

Maintaining the current reliability requires continual monitoring and review of the major sources of downtime. For RF systems, the top sources of downtime by occurrence since 2018 are shown in Table 1. As is clearly shown by the data, the high power components of the RF systems contribute the most to downtime and it is these components on which the RF Group effort has been focused.

Klystron arcs are the most significant source of RF downtime and continue to be mitigated [2] over the course of regular SNS operations. Other sources, such the klystron pre-amplifier and solenoid power supply failures are monitored, but no significant mitigation effort is underway. Filament power supplies remain as a significant source of RF system downtime at nearly 4 hours per year.

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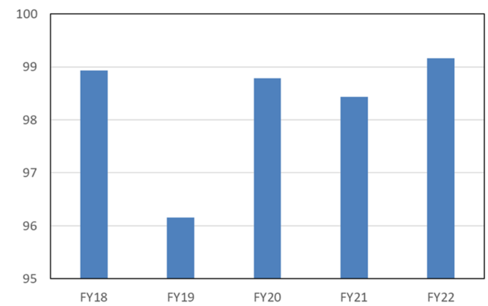

Figure 1: SNS RF systems availability from FY 2018.

Table 1: Top RF Downtime Sources From 2018

Source	Qty/Yr	Downtime per event (hours)	Annual Downtime (hours)
Klystron Arc	26.4	0.4	10.6
Filament PS	2.4	1.6	3.8
Pre-Amp	1.4	1.1	1.5
Solenoid PS	0.6	2.1	1.3

FILAMENT POWER SUPPLIES

The filaments of the SNS klystron cathodes are heated using a variable AC power supply coupled through a 4:1 isolation transformer located in a high voltage oil tank. The filament power supply (FPS) is at earth potential so that it can be easily maintained and uses a standard 120Vac, 20A input to power a 300Vdc supply internal to the FPS chassis. The 300V supply provides power to an H-bridge inverter, which then synthesizes a 60Hz, constant-current output based on operational setpoints entered on a per-klystron basis. Control of the supply output is maintained by a PLC.

Maintenance

Figure 2 clearly shows an increase in the number of FPS failures since 2018 and the overall ten-year trend is indicative of end of life. Wholesale replacement of all the supplies is ideal in this scenario but is currently cost prohibitive. While basic input and output parameters such as voltage and current are monitored, supply failure has been impossible to predict. Maintenance on these supplies is by nature reactive. A more predictive approach to the maintenance of these supplies is warranted. The RF Group has been working on the development of an in-situ failure

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prediction method based on frequency analysis techniques used in other parts of industry.

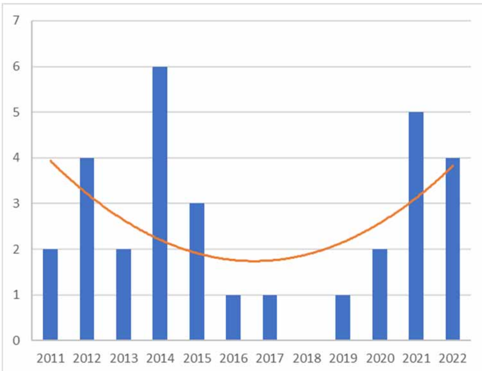

Figure 2: Annual filament power supply failures.

PREDICTIVE CONCEPT

The conceptual method under development at SNS involves analyzing the frequency spectrum of the filament power supply output. Similar analysis is used in diagnosing 3-phase induction motor faults [3] and capacitor degradation monitoring [4]. In short, a baseline frequency output is monitored over time for any changes in resonance or amplitude. When changes are detected, maintenance can be planned when the SNS accelerator can be shutdown without a negative impact on program output.

Preliminary Model Development

As stated previously, the SNS FPS use kilohertz-range switching of up to 300Vdc to synthesize a 60Hz AC output that is "driven" through power electronic-rated inductors and capacitors before coupling to the primary of the klystron filament isolation transformer. As shown in Fig. 3, the FPS can be modeled as a multi-stage H-bridge inverter with lump-element inductors and capacitors on the output using a simple circuit simulation tool. Three stages were used in the SNS model, and the load value was selected to match the impedance seen by the output of the actual operational supply. High-level model parameters are summarized in Table 2.

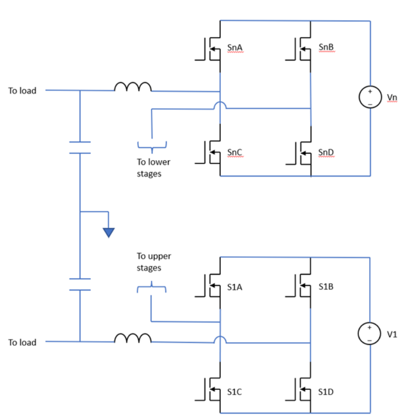

Figure 3: Simplified power supply model.

Table 2: Model Parameters

Inverter Stage Qty	Switching Freq, max (kHz)	Output Inductors (mH)	Output Capacitors (mF)	Load (ohms)
3	1	1	10	10

It is important to note that the switching frequency, output inductance, and output capacitance values do not match the values of the actual supply though they are of the same magnitude. They were tuned in the preliminary model to give a smooth, 60Hz AC waveform output, as shown in Fig. 4.

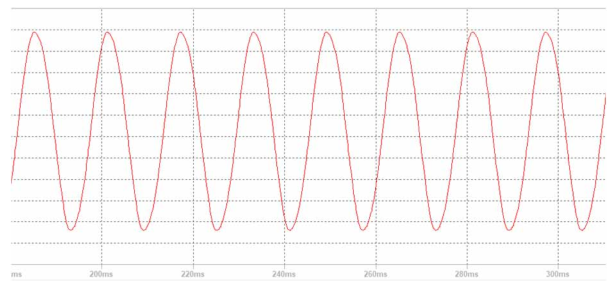

Figure 4: Preliminary model 60 Hz AC output.

Simulation Procedure

Once the model parameters were finalized, the next steps were to simulate four different scenarios, with the associated frequency spectrum as the simulation output:

- Base case, no performance degradation
- Degrading inductor
- Degrading capacitor
- Loss of a switch

Figure 5 shows the frequemcy spectrum of the base case, while Fig. 6, Fig.7, and Fig. 8 show the spectrums of the degrading inductor, degrading capacitor, and the loss of a switch respectively. The corresponding values of degraded inductance and capacitance are listed for the associated simulations. "Degrading" is defined as a drop in component value to 80 percent of nameplate or less. [4].

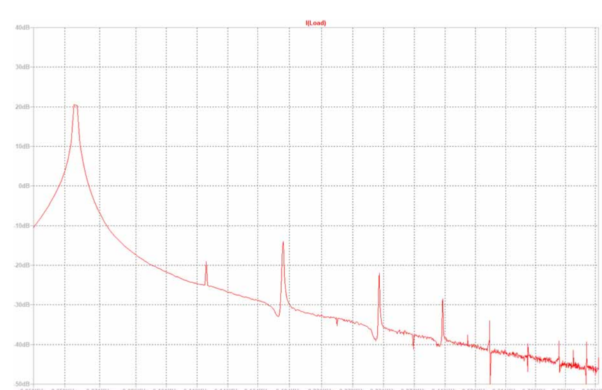

Figure 5: Base case frequency spectrum.

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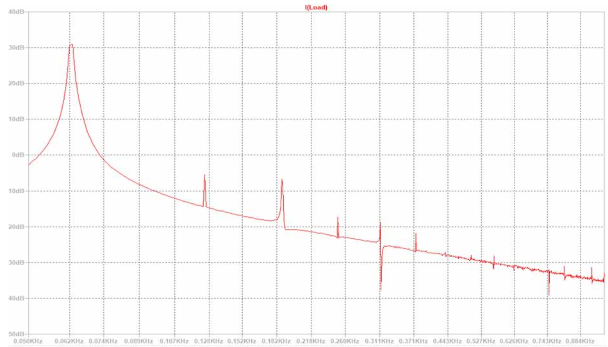

Figure 6: Degrading inductor (from 1mH to 600μH). Plot shows new peaks at 250 and 370 Hz.

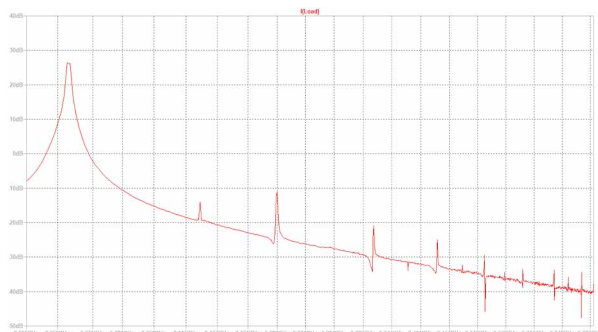

Figure 7: Degrading capacitor (from 10 to 8mF). Plot shows increased ripple amplitude.

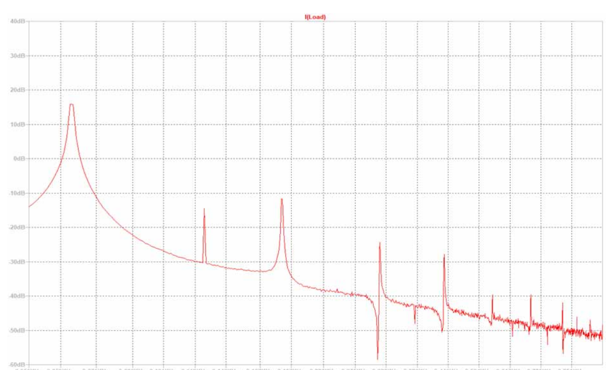

Figure 8: Failed switch. Plot shows increased ripple amplitude as well as the band widening at 180Hz.

FUTURE DEVELOPMENT

The next step in the concept development is to determine how best to capture this data in-situ. A simple external means such as a current transducer placed on the output is desirable, but any diagnostics must be carefully selected to prevent inadvertent filtering of the desired signals. Work on the next step is ongoing, however, as is shown in Fig. 9.

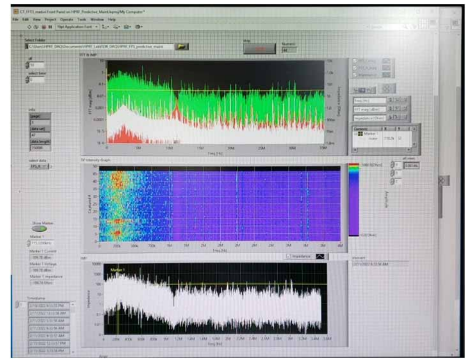

Figure 9: Initial field data capture.

In addition, plans are underway to hasten the failure of a supply by using an environmental chamber available to the RF Group for testing purposes.

CONCLUSION

The simulation output suggests that the use of frequency analysis as a means of failure prediction for the SNS FPS is possible. When compared to the base frequency plot, all three simulated degradation cases showed distinct and detectable differences. It is feasible that these changes could be detected by a future control system as another process variable and provide indication of the need to swap out the associated supply.

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