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QUANTIFYING REACTOR POWER NOISE – A CASE STUDY ON NIST RESEARCH REACTOR

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ABSTRACT

Water cooled reactors experience reactivity changes when voids are present in the coolant. The fraction of coolant in the core diminutions in the event of boiling, and the reactivity feedback can either be positive due to reducing neutron absorption in the coolant or can be negative due to reduction in the slowing down of neutrons to thermal energy because of a reduced moderator to fuel ratio. Similarly, mechanical movement of core internals, specifically within the active core volume do cause power fluctuations. Nevertheless, coolant voiding, and mechanical movements are among the main perturbations that induce reactor power oscillations, which can also be defined as the reactor power noise. A real-time noise detection system can track the reactor power measurements, and alarm if the oscillations exceed statistically significant levels. This study presents a method for estimating the noise in reactor power measurements using a real-time signal-to-noise ratio calculation. The effectiveness of the proposed noise calculation methodology is demonstrated using data from the National Bureau of Standards Reactor (NBSR) under both normal operating conditions and fuel failure events. Additionally, this paper describes the detailed design of a noise detection system hardware based on this methodology.

Keywords: Reactor power noise, noise quantification analysis, signal-to-noise ratio

NOMENCLATURE

MAE	Mean Absolute Error
MAPE	Mean Absolute Percentage Error
NBSR	National Bureau of Standards Rector
NC	Nuclear Instrument Channels
NCNR	NIST Center for Neutron Research
NIST	National Institute of Standards & Technology
RMS	Root Mean Square Error
SNR	Signal-to-noise ratio

1. INTRODUCTION

Safe operation of nuclear reactors requires an instrumentation system that supplies the necessary information for safety systems, control systems and plant monitoring systems. Neutron detectors, which measure the core neutron flux to infer reactor power, are an important part of this system. The neutron detectors have inherent randomness due to electrical interference, sensor physics, environmental factors, or physical phenomena affecting the operation of the system. The randomness in neutron detection can be considered as reactor power noise, since the noise is fundamentally randomness distinguished from regularity [1]. Physical phenomena such as partial coolant voiding and mechanical vibrations can cause fluctuations in the local neutron flux, which in turn affects the noise in reactor power measurements [2]. For example, coolant voiding, movements of structures, components, or fuel elements within the active core volume can cause fluctuations in the neutron flux. Therefore, the analysis of reactor power noise allows one to identify conditions that might be threatening the safety of the reactor such as departure from nuclear boiling.

The National Bureau of Standards Reactor (NBSR) is located at the National Institute of Standards and Technology (NIST) in Gaithersburg, MD. NBSR is one of the five U.S. high performance research reactors. It is a 20 MW, heavy water cooled and moderated tank-type research reactor operational since 1967. The NBSR has been a vital neutron source for the scientific community since then. The NBSR experienced a fuel failure event during the startup on February 3, 2021. During the start-up process, the reactor was initially operated at 10 MW before being increased to full power. As the power was increased, elevated radiation levels were observed, leading the operators to shut down the reactor (known as a "scram") and secure it. Post-incident video inspection revealed that one of the fuel elements was dislocated from the lower grid plate indicating the fuel element was unlatched. The new position of the fuel element indicates a disruption on the forced primary flow from reaching the fuel element [3].

There had been instances of unlatched fuel element events observed in the history of the NBSR, most of which were identified and corrected during pre-startup checks. On one occasion in 1993, it was observed that nuclear instrument channels had increased oscillations in the event of unlatched fuel. Therefore, the operating procedures were revised to instruct operators to operate the NBSR at 10 MW to visually check for power oscillations on reactor power indicating digital trend recorders, before proceeding to the full power level of 20 MW [4]. On February 3rd , subsequent analysis of the nuclear channels (NCs) revealed that the power oscillations at these channels were of greater amplitude compared to previous normal-startup NC oscillations. Therefore, it is important to develop an engineering system to quantify reactor power noise.

In this paper, a methodology to quantify the reactor power noise is described. The developed methodology is tested using the real operation data of the NBSR. Moreover, a discussion on the design of a noise detection system that will be installed in the NBSR control system, using the developed methodology is provided.

2. METHODOLOGY

The methodology to quantify the reactor power noise is based on a time-domain analysis of relevant neutron detector signals. These signals are a combination of actual power and noise. Therefore, while at steady state operation, reactor power noise is the difference between the measured power and the actual power of the reactor. However, the actual value of the instantaneous reactor power cannot be precisely determined. If the reactor power noise has a distribution with zero mean, the actual power of the reactor can be approximated by averaging the measured reactor power over a given time-period. If the averaging window is long enough, and there are no disturbances, the reactor power noise deviations converge, and the averaged measured power approximates to the actual power of the reactor. In this case, reactor power noise at each measurement point *n* can be calculated by the difference between measured value and the averaged value of measured power of the reactor, given by Eq. (1) below, where P_n' is the reactor power noise, P_n is the instantaneous measured power, and $\overline{P_n}$ is the average value of the measured power.

$$P_n' = P_n - \overline{P_n} \tag{1}$$

The measured power is averaged with a moving average scheme to approximate the actual value of the instantaneous value of the reactor power. For measurement n, the moving average of reactor power with a window size W_n is given by Eq. (2) below.

$$\overline{P_n} = \frac{1}{W_n} \sum_{i=n-W_n}^{n} P_i \tag{2}$$

The reactor power noise distribution can be obtained by Eq. (1) and (2) at each measurement point over the considered time interval. Signal-to-noise ratio (SNR) can be used to quantify the reactor power noise. SNR is a measure to compare the level of signal to noise, and considering the noise is being lower amplitude compared to signal, SNR can be scaled by expressing with decibels. The SNR in decibels [1] is given by Eq. (3) below.

$$SNR = 20\ \log_{10} \frac{signal\ current}{noise\ current} \tag{3}$$

If reactor power noise is normally distributed with zero mean, standard deviation of the distribution can represent the magnitude of the noise. Since the actual power is approximated by averaging the measured power, the signal needs to be normalized to have a mean value of one, so that the calculated reactor power noise is not affected by the averaging process. In this case, the signal becomes the unit signal with a value of one, and the noise is the standard deviation (σ) of the normalized reactor power noise distribution. The SNR in this case is given by Eq. (4) below.

$$SNR = 20\ \log_{10} \frac{1}{\sigma} \tag{4}$$

The quantification of reactor power noise should be based on calculation of real-time SNR for a real-time noise detection system. The real-time SNR calculation framework flowchart is given in **FIGURE *1***. It is possible to consider the calculation algorithm in two steps. The first step calculates the SNR incrementally on a stream of data as the noise detection system continuously operates. In this step, first the instantaneous noise value of the streaming input signal is calculated by approximating the actual signal with moving average scheme and subtracting the input signal from the approximated actual signal. Then the noise value is added to the noise sample pool and the SNR value of the whole noise sample is calculated. The calculation of the SNR is cumulative as the SNR value is updated with each time step.

Since the SNR calculation is cumulative, it is important to assess if convergence is achieved at a given point during the calculation. The second step checks the convergence status of the SNR calculation. The convergence of the SNR refers to the condition at which the subsequent calculated SNR values don't significantly differ from each other. This condition is quantified by calculating the root mean square (RMS) of calculated residuals for the previous N_c SNR samples in real-time. For each time-step, the residual of the SNR is obtained by subtracting the calculated SNR at the time-step from the moving averaged SNR over previous W_c samples. If the RMS is less than ϵ_c and minimum of C_{min} samples are collected, it can be said that the SNR calculation is converged. In order to limit the computation resources during the convergence check, it is further set that the convergence of the SNR is failed if the convergence is not achieved within the C_{max} samples are collected.

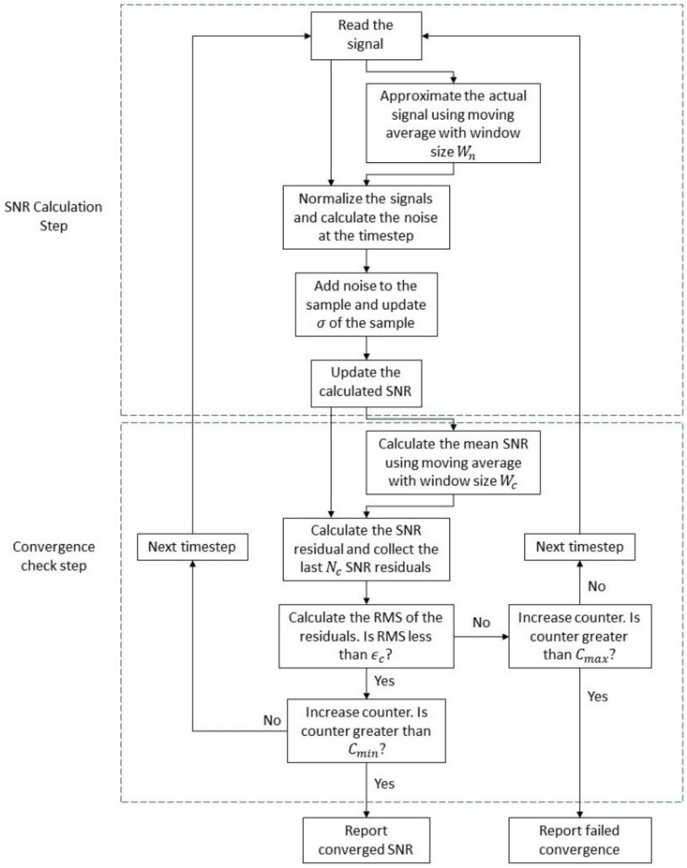

FIGURE 1: DIAGRAM OF THE CALCULATION ALGORITHM OF REAL-TIME SNR

The calculation algorithm of the SNR assumes that the reactor power noise is normally distributed with zero mean. In the next section, this assumption is verified using actual operational data from the NBSR, and the calculated SNR values are presented. Moreover, the calculation algorithm contains parameters that need to be determined before the application of the algorithm, and an example set of these parameters, applicable for the NBSR, are presented.

3. RESULTS AND DISCUSSION

The SNR calculation algorithm is tested on the operational data of the NBSR. The NBSR has five separate Nuclear Channels (NCs), NC-3 through NC-7, to monitor the reactor power level ranging from subcritical state at startup through full power. Each channel employs a compensated ion chamber to measure the leakage neutron flux from the core. While NC-5 is for automatic control of the reactor through motion of the regulating rod, the remaining NCs are used for reactor power indication.

The February 3rd event happened on Cycle 654. The previous four cycles along with the event cycle are used to test the SNR calculation algorithm. The main assumption in the SNR calculation algorithm is that the reactor power noise is normally distributed with zero mean. This assumption is tested at the full power operation data from the NBSR. The analysis of Cycle 652 is shown as an example in this paper. Cycle 652 contains 120,000 measurement points at 20 MW with 10 seconds recording interval. The relatively long recording interval limits maximum W_n because a moving average scheme with such window size would fail to capture the trends in the data especially during transients. This results in an inaccurate approximation of the actual reactor power and synthetic noise in the SNR calculation. A sensitivity analysis on the available NBSR operational data implies that a window size, W_n, of 10 is optimal for SNR calculations, which corresponds to 100 seconds for the moving average.

Using NC-3 data, the magnitude and density of the reactor power noise is given in **FIGURE 2**. The SNR calculation is incremental, and once the whole 120,000 measurement points are considered, the final value of mean (μ) and σ values of noise and SNR value are obtained. In this figure, using the calculated μ and σ, a normal distribution is plotted as a black line. The close match of the black line and the histogram plot of the reactor power noise provides evidence that the assumption of our calculations, a normally distributed zero mean reactor power noise, is applicable for the NBSR at full power. It must be noted here that the SNR calculation is observed to be converged after 2000 measurement points when NC-3 data at Cycle 652 was used.

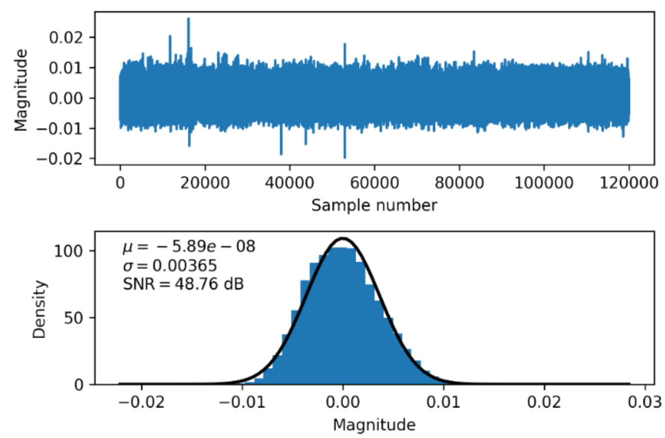

FIGURE 2: NC-3 FULL POWER NOISE DISTRIBUTION AT CYCLE 652

The analysis was expanded to the other NCs and cycles of the NBSR, and similar observations are made. For brevity, the results are not repeated here. For other NCs and cycles, the final calculated values of the SNRs are given in **TABLE 1**. Cycle 651 and Cycle 653 are divided due to operational deviations, and they are represented with two columns. After Cycle 653, the regulating rod system is upgraded which decreased the nominal reactor power noise [3]. The closeness of the calculated SNRs for all NCs at the cycles show that the reactor power noise signature of the NBSR can be identified with the SNR calculation algorithm.

TABLE 1: SNR values at full power

	Cycle 650	Cycle 651_1	Cycle 651_2	Cycle 652	Cycle 653_1	Cycle 653_2
NC-3	48.58	48.64	48.28	48.76	51.95	52.92
NC-4	48.21	48.38	48.09	48.51	51.77	52.55
NC-5	48.07	48.19	48.04	48.34	51.44	52.51
NC-6	48.32	48.49	48.19	48.60	52.00	52.88
NC-7	48.21	48.36	48.16	48.49	51.80	52.85

An important question is how many samples are required for the SNR to converge on the streaming data. This number is represented with C_{min} in the algorithm. The minimum required measurement points determine how long to stay at power and collect reactor power noise. The σ is calculated incrementally as the NC measurements are taken and the reactor power noise sample size increases. Final SNR should be calculated with the σ of the reactor power noise population. However, during the initial steps of the SNR calculation, σ is calculated with the observed reactor power noise and it is dependent on the observed samples. There should be enough samples so that the calculated σ from the observed samples converges to be representative population σ.

To calculate the minimum number of samples for convergence, the calculated SNRs with 1000-point slices are compared against the final SNR values given in **TABLE 1**. On the streaming data, mean absolute error (MAE) of the difference between SNR values of the previous 1000 samples and calculated final SNR for the given NC and cycle are calculated. The point at which the MAE dropped below 0.1 is assumed to be the minimum sample size required for the SNR convergence. Minimum sample size is calculated for all NCs and cycles, and it ranges between 1800 to 4200 with a mean value of 2900.

The NBSR is operated at 10 MW for a specific time interval during the startup to check power oscillations. With the current operating procedure and data collection system, the total number of data points range between 40 to320 for previous cycle startups, which is not enough to get a clear noise distribution. Cycle 653_1 has the most measurement points, and the magnitude and density distribution of the reactor power noise for this cycle are shown in **FIGURE 3**. The SNR calculation is not yet converged, and the reactor power noise distribution is not a complete normal distribution. In the figure, the black line represents a normal distribution with μ and σ calculated from the given noise distribution. The comparison with the noise distribution and the black line shows that the noise distribution can still be represented with a normal distribution with zero mean. The analysis of Cycle 653_1 provides evidence that the reactor power noise has a normal distribution with zero mean at startup.

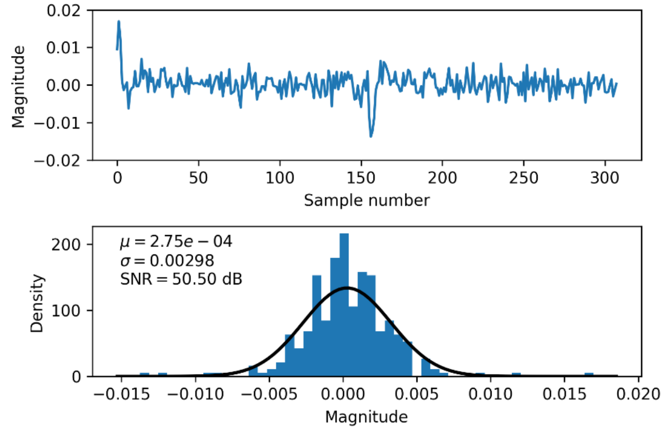

FIGURE 3: NC-3 STARTUP NOISE DISTRIBUTION AT CYCLE 653_1

The increased power oscillations during the February 3rd event implies that the SNR calculation algorithm would identify such abnormal condition. Cycle 654 is the cycle with the fuel failure. When we apply the SNR calculation method to the available incident data, we cannot get a clear noise distribution because of the small sample size. The magnitude and density distribution of noise for Cycle 654 are given in **FIGURE 4**. Noise distribution can either be a normal distribution with higher σ, or it can follow a different probability distribution due to the presence of boiling. Both cases can be detected via the presented SNR calculation. If σ is high, it results in a lower SNR. If it is a different distribution, the σ would not be a statistical indicator, resulting in a lower SNR. The calculated SNR is lower at Cycle 654 compared to other cycles, indicating that the SNR calculating algorithm would have identified the abnormality at the February 3rd event.

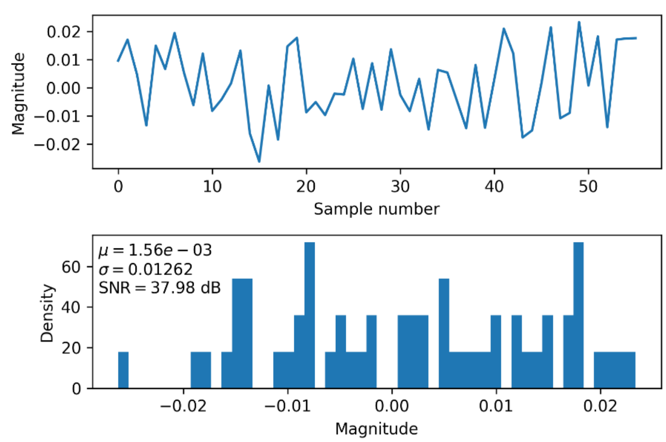

FIGURE 4: NC-3 STARTUP NOISE DISTRIBUTION AT CYCLE 654

Calculated SNR values at startup are given in **TABLE 2**. Cycle 654 has a lower SNR, indicating that the reactor power noise is higher in this startup compared to previous cycles, which is compatible with the subsequent analysis of the NCs after the incident. It's important to note that Cycle 651_2 has a lower SNR compared to other cycles, which is due to a sudden drop in reactor power followed by a quick recovery. Averaging of this transient behavior caused an incorrect approximation of the actual reactor power and added artificial noise to the SNR results. Equation (4) shows that 40 dB corresponds to 1% noise, meaning that the σ of the reactor power noise distribution is 1% of the normalized reactor power measurements. Cycle 651_2 shows that the SNR dropped below to 40 dB during a power transient. Cycle 654 shows that the SNR dropped below to 40 dB at the February 3rd incident. These events point out that 40 dB is a limiting threshold for the NBSR operations.

TABLE 2: SNR VALUES AT STARTUP

	Cycle 650	Cycle 651_1	Cycle 651_2	Cycle 652	Cycle 653_1	Cycle 653_2	Cycle 654
NC-3	47.47	42.65	31.06	50.78	50.50	46.49	37.98
NC-4	47.14	42.10	30.86	49.86	51.96	46.36	36.63
NC-5	46.36	42.68	30.80	49.79	51.06	46.26	35.97
NC-6	46.75	42.48	30.83	50.45	51.65	46.16	36.54
NC-7	47.40	42.58	30.83	50.21	51.55	46.04	36.35

It is observed in Cycle 651_2, long window size makes the averaging scheme vulnerable to transients and increases the artificial noise due to transients. A window size of 10 was used in the analysis of past NBSR data, and the analysis showed that the assumption of reactor power noise has a normal distribution with zero mean is valid for full power, and acceptable for startup.

4. SYSTEM DESIGN

The reactor power noise detection system is being developed as an auxiliary monitoring system for NCs. This system is computer-based that is connected to the NCs which tracks the measurements from these channels. If the reactor power noise in the measurements exceeds a predetermined threshold, the system alerts operators about the anomaly. Reactor power noise detection system contains two primary components, a Speedgoat Baseline S Real-time Target Machine [6] (hereby referred to as "RT-Machine"), and a Yokogawa GX20 Digital Recorder [7] (hereby referred to as "Recorder"). RT-Machine contains the SNR calculation software and calculates the SNR for each nuclear channel. Recorder displays the SNR and initiates alarms if the SNR values drop below the predefined threshold. Additionally, the Recorder allows control of the SNR calculation software by providing a start/stop signal to the RT-Machine. The hardware component diagram of the noise detection system is provided in **FIGURE 5**.

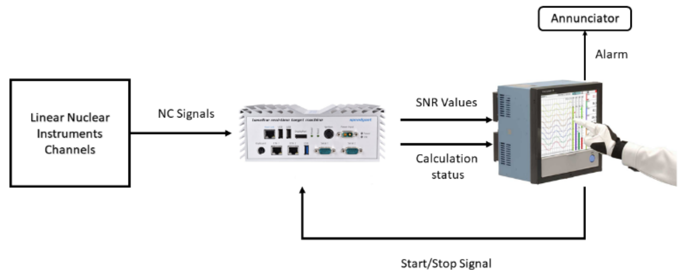

FIGURE 5: REACTOR POWER NOISE DETECTION SYSTEM DIAGRAM

The SNR calculation software is implemented using MATLAB/Simulink® R2022a version. The SNR calculation algorithms written in MATLAB/Simulink® were compiled and deployed to the RT-Machine.

RT-Machine has an IO module to connect with the Recorder and NC signals. The input signals to the RT-Machine are 0 V to 5 V analog signals from the nuclear instrument channels, and output signals from the RT-Machine are calculated SNRs scaled to 0 V to 5 V analog signals delivered to the recorder. The start/stop and calculation status connections between the RT-Machine and the Recorder are configured as digital signals.

Noise detection system recorder screen is given in **FIGURE 6**. The operator can start the noise calculation by pressing the start/stop button, which is shown as green box with a text "Stopped". After the start button is pressed, the button lights and the text changes to "Started". At this point, the software calculates the SNR based on the NC measurement signals, and the calculations are displayed as both a time dependent function and an instantaneous value. Pressing the start button again finishes the noise calculation and resets the software. Instantaneous numerical values of the SNRs are displayed on the right of the screen, black if the SNR is above the threshold, and red if the SNR is below the threshold. The annunciator is alarmed if any of the SNR values drop below the threshold.

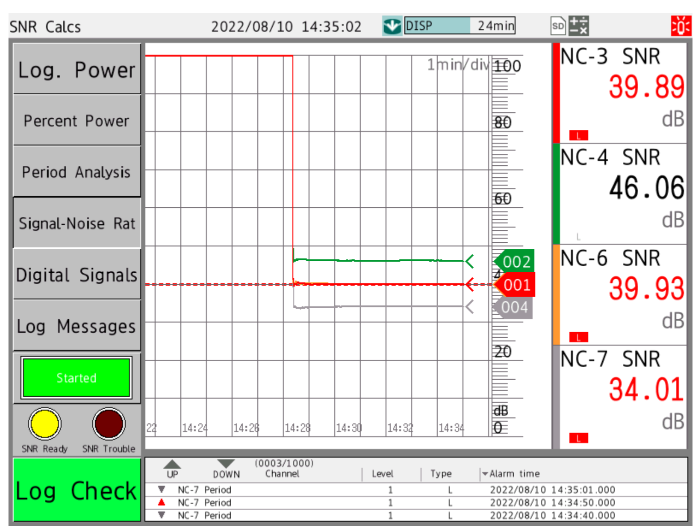

FIGURE 6: SNAPSHOT OF THE RECORDER SCREEN

To notify the operators about the status of SNR convergence, "SNR Ready" and "SNR Trouble" indicators are also placed on the recorder screen, below the start/stop button. These indicators will be lit based on the calculation status signals from the RT-Machine. The convergence algorithm is shown in **FIGURE 1**, and the following parameters are used in the algorithm, $W_c = 1000$, $N_c = 1000$ and $\epsilon_c = 0.3$. W_c and N_c are selected with a sensitivity study, and ϵ_c is selected as 0.3 because allowed $1\,\%$ error in the calculated SNR corresponds to an RMS of 0.2. To account the system uncertainty and the fact that the actual noise distribution is not the ideal normal distribution, a 50% margin is added to the RMS threshold. C_{min} is set as 3000 based on the analysis of previous NBSR data, and C_{max} is chosen as $30{,}000$.

As part of further validation and verification testing, the noise detection system is tested with an artificial noise generator. The noise generator generated signals with various μ and σ ranging from 0.001 to 0.1 to simulate signals with different noise magnitudes. For the first test, noise detection system is run 17 times with artificial signals with different σ. In these tests, $10\,Hz$ sampling rate and window size of 10 were used to calculate SNR. For the second test, the sampling rate is increased to $50\,Hz$, which covers more than twice the delay time of the PID controller of the regulating rod of the NBSR. The window size of the moving average scheme is selected at 500, which covers the last 10 seconds for averaging.

Calculated Mean Absolute Percentage Errors (MAPE) for both tests for NCs are given in **TABLE 3**. Mean and standard deviation of the artificial signals are known; therefore, the theoretical true SNR values can be calculated precisely by using Eq. (4). The methodology of SNR calculation inherently introduces uncertainty to the SNR calculations. To estimate this uncertainty, the SNR calculation algorithm is modeled with a computer using random numbers with the same characteristics of the artificial signals. The calculated values are considered as calculated SNR. The SNR values that are read from the recorder screen are considered as measured SNR. The model error is calculated considering true and calculated SNR. The experimental error is calculated considering calculated and measured SNR, and the total error is calculated considering true and measured SNR. By increasing the sampling rate and window size, the experimental error doesn't change significantly, but the model error is reduced by a factor of 10. Nevertheless, the experimental error is bounded by the reported IO module limitations of the RT-Machine and the Recorder, and the upper bound of the expected system error considering the maximum uncertainties of IO modules is $0.15\,dB$. Therefore, for the actual design of the noise detection system to be installed to the NBSR console, a $50\,Hz$ sampling rate and window size of 500 were selected.

TABLE 3: MAPE OF CALCULATING SNR OF THE ARTIFICIAL SIGNALS

Sampling rate	Window size	Sensor	Model error (%)	Experimental error (%)	Total error (%)
10 Hz	10	NC-3	1.25	0.47	1.03
		NC-4	1.20	0.43	1.02
		NC-6	1.28	0.31	1.15
		NC-7	1.78	0.41	1.64
50 Hz	500	NC-3	0.13	0.33	0.27
		NC-4	0.11	0.31	0.22
		NC-6	0.10	0.19	0.13
		NC-7	0.11	0.18	0.17

5. CONCLUSION

This study presents a real-time reactor power noise quantification methodology that works with the reactor power instrumentation. The methodology is based on estimating the noise in the reactor power measurements via a moving average filter. The level of noise in the measurements is represented with signal-to-noise ratio (SNR), and the reported methodology estimates the SNR using the standard deviation of the noise distribution. The analysis of the NBSR data showed that the assumption of NBSR reactor power noise is a normal distribution with zero mean is applicable. The analysis of NBSR fuel failure event shows that given SNR calculation algorithm would successfully identify the increased reactor power noise due to the coolant voiding.

With the developed SNR calculation algorithm, an industrial reactor power noise detection system is designed. The system will directly interface with existing NBSR reactor instrumentation. The signals for reactor power will be wired to the system as inputs to be analyzed via the SNR calculation algorithm. The system will also actuate annunciator alarms to inform operators of unsafe anomalies in the reactor power measurements in real-time. The model parameters of the noise detection system are determined with the analysis of the NBSR data and artificial noise generator. The system is designed in a way that it alarms if the SNR drops below $40\,dB$. The total error of the system is estimated to be $\sim 0.2\,\%$ with an upper bound of $0.15\,dB$.

DISCLAIMER

Certain commercial equipment, instruments, or materials are identified in this study in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials and equipment identified are necessarily the best available for the purpose.

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