Leveraging Within-Bank Comparison for Anomaly Detection, Diagnostics, and Prognostics in Advanced Nuclear Power Plants

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ABSTRACT

Control rods and control rod drive mechanisms manage overall power production and power distribution across the reactor core of a nuclear power plant. The control rod drive mechanism proposed in the BWRX-300 design by GE-Hitachi uses servomotors for fine motion control. Control rods move in banks of multiple individual rods following a common demand profile, each with a dedicated servomotor. A fundamental challenge in monitoring the health of these servomotors is due to their operation in short bursts of fine movements, thereby lacking opportunities to leverage signal processing methods developed for long duration steady-state operations in other industrial applications. In this paper, we attempt to monitor the performance of each servomotor in a control rod bank by comparison to the expected behavior of the bank.

1. INTRODUCTION

The BWRX-300 reactor design by GE-Hitachi adapts features of large-scale next generation boiling water reactors (BWRs) for application in a small modular reactor (SMR) design. The BWRX-300 is sized to produce 300 MWe at full power operation. This output allows the BWRX-300 to operate in smaller markets and more flexible operational scenarios. BWRX-300 incorporates electrically-driven fine motion control rod drives (FMCRDs), similar to those in the Advanced BWR (ABWR). Electrically-driven FMCRDs enhance reactor operability by allowing finer increments of control rod movement and more precise reactivity control in the primary system. Whereas current BWRs operate in steady-state conditions between refueling outages, the BWRX-300 and other SMRs are designed to support frequently changing power production, which may require frequent small actuation of control rods. This shift in the operational paradigm will introduce additional stress on the FMCRD mechanisms, potentially leading to in-service degradation and potentially impacting reliability of the FMCRD.

The servomotors that serve as FMCRDs are a key active component in the operation of the BWRX-300. There are 57 control rods arranged throughout the reactor core, each driven by a dedicated FMCRD servomotor (GE-Hitachi Nuclear Energy Americas, LLC, 2021). The control rods move in banks distributed throughout the core to achieve desired power changes; that is, multiple rods move and their FMCRDs actuate in unison for a power maneuver. This research proposes to leverage the coordinated within-bank action to monitor the health of each servomotor in an active bank during each power maneuver. The following section summarizes the methodology used for within-bank evaluation. Section 3 presents the simulation-based data generation and results of data analysis. Section 4 summarizes the findings of this work and presents some areas of potential future research to further develop the potential for within-bank FMCRD monitoring.

2. METHODOLOGY

Within-bank condition monitoring is made possible by using the online signals available to the operator, seen in Figure 1. Representative data are generated with a Simulink model that represents the FMCRD servomotor system. The FMCRD is operated by the user supplying a command of a position changes corresponding to the desired thermal power within the reactor. The servomotor then manipulates the three phase currents using an internal three phase inverter for correction

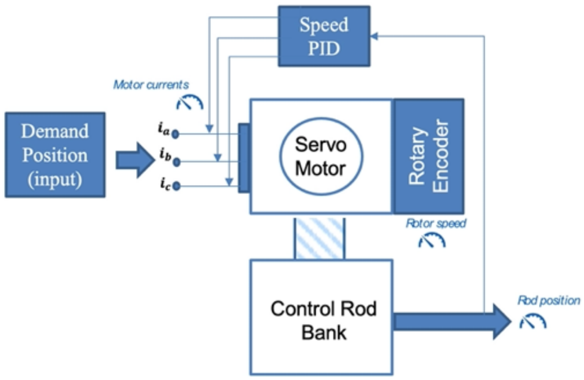

Figure 1. Simplified schematic of the Simulink servomotor model

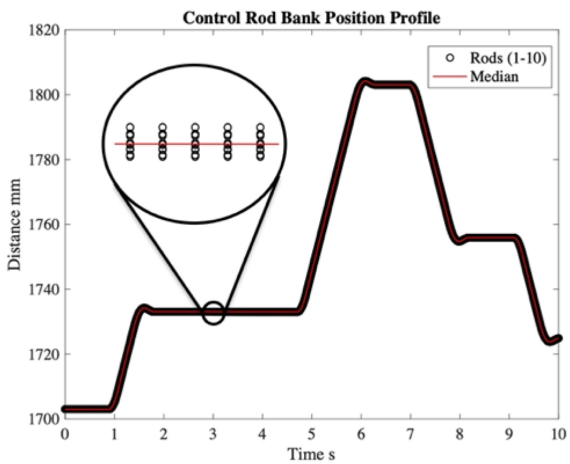

Figure 2. Median position profile of a bank of ten control rods during a specified power maneuver

of the rotor speed to achieve the desired position. From the simulation, available signals for a single servomotor include the motor's rotor position, measured by the servomotor's rotary encoder; rotor speed; and the three-phase current signals.

A bank's group of control rods are operated within the reactor core with shared position demands; slight differences in healthy position signals can be present due to signal noise and minor fluctuations in operating environment. Hence, healthy individual position profiles may deviate marginally from their family of rods. Knowing that a bank's servomotors actuate the associated control rods with the same position demand, a median actuated position profile signal can be created as seen in Figure 2.

The median bank position signal is used to detect anomalies in the actuation of individual FMCRD servomotors by comparing the position of an individual rod to the median position of the bank of rods. The median is chosen to generate average within-bank behavior because it is robust to outliers in the data and may not be significantly affected by a single faulty FMCRD. The congruence of each FMCRD to its bank is characterized by the root mean squared error ($RMSE_{pos_i}$) between the position of a particular rod and the median position profile to capture overall deviations of the rod and ignore spurious deviations that may be due to sensor measurement noise. If the $RMSE_{pos_i}$ exceeds a specified threshold, a fault is detected and isolated to the i^{th} control rod and its FMCRD.

In this initial investigation, the fault detection threshold is determined according to the $RMSE_{pos_i}$ of a set of healthy FMCRD simulations given by Equation 1.

$$thresh = \mu_{RMSE_{pos_i}} + \Phi^{-1}(0.975) \times \sigma_{RMSE_{pos_i}} \quad (1)$$

where $\mu_{RMSE_{pos_i}}$ is the mean of the $RMSE_{pos_i}$ of healthy FMCRDs across a variety of position profiles, $\sigma_{RMSE_{pos_i}}$ is the standard deviation, and $\Phi^{-1}(0.975)$ is the value of the inverse normal distribution to produce a 95% confidence interval.

3. WITHIN-BANK SIMULATION AND MONITORING RESULTS

3.1. Simulated Bank Performance

For this investigation, a control rod bank is arbitrarily assumed to include ten control rods; however, the same methodology applies to a bank with a different number of control rods ($n > 2$) without loss of generality. Six position profiles were investigated with random variation in the time and magnitude of demanded control rod maneuvers. For each position profile, four sets of bank movement were simulated: (1) all ten control rods and FMCRDs are operating in a healthy condition; (2) one FMCRD is experiencing a stator electrical fault and nine FMCRDs are healthy; (3) one control rod is experiencing a step increase in the motor load, representative of a stuck or sticking rod, and nine control rods have no change in motor load; and (4) one control rod is experiencing a gradual increase in motor load, representative of increased rod friction, and nine control rods have no change in motor load. In each simulation of a bank with one FMCRD or control rod fault, the fault is arbitrarily simulated in the tenth FMCRD or control rod. Normally distributed white noise was introduced as measurement noise into the sensed parameters used for controller feedback, the position measurement of the control rod, resulting in a propagation of noise through the Simulink model due to the closed loop feedback control of the servomotor's speed.

In total, 222 healthy FMCRD responses and 18 faulted FMCRD responses were simulated across six position profiles for healthy operation and three potential fault modes. The same six position profiles are used in each of the four sets of bank movement. Figure 3 shows an example set of position

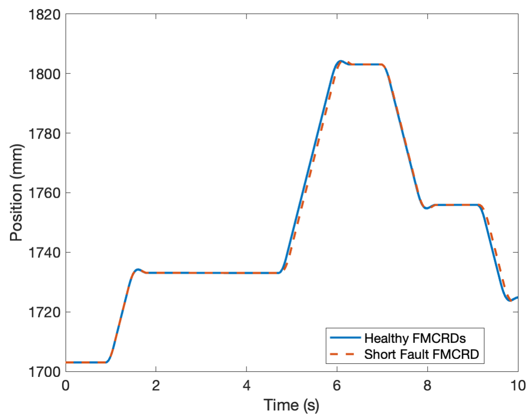

Figure 3. Position profiles for stator fault in one FMCRD of a bank of 10 control rods

profiles for a bank of FMCRDs with one experiencing a stator short fault. The stator short fault initiates around $3\,s$, after which time the response differs visibly during position changes.

3.2. Results

The median position profile was calculated for each healthy and faulted simulated bank movement. The $RMSE_{pos_i}$ of each control rod and FMCRD position signal was calculated and the $RMSE_{pos_i}$ values for the sixty healthy FMCRD position profiles were used to determine the detection threshold, resulting in a nominal $RMSE_{pos_i}$ acceptance threshold of $0.0127\,mm$. With this detection threshold, one healthy FMCRD in the sixty healthy position profiles is erroneously flagged as faulty.

The ten control rod position profiles in each of the six banks for each fault class were evaluated using the same methodology and the calculated detection threshold. The results are summarized in Table 1. For each fault mode, the results are compiled across the six position profiles. In each case, at least 90% of healthy FMCRDs are correctly identified as healthy. In the stator short case, all of the faulted FMCRDs are correctly identified as faulted. In the load step and load ramp cases, the proposed detection routine is less effective, identifying 33.3% and 50% of faulted FMCRDs, respectively.

4. DISCUSSION

The proposed anomaly detection method utilizes sensed variables that will likely be monitored and recorded for system control to detect and isolate FMCRD faults. Of the three fault modes considered, this approach was effective for one fault mode with 100% detection and isolation accuracy.

Although the proposed approach is not sufficient for all the considered fault modes, it provides a straightforward approach for detecting a stator short. This method could be combined with other routines designed and optimized to detect one or more of the remaining fault modes. Concurrent research under this project is investigating bespoke methods for detecting and isolating load faults (e.g., stuck control rods or increased rod friction). These methods could be combined to provide a holistic FMCRD monitoring system. As additional fault modes are identified and implemented in simulation, the current approaches will be evaluated for detecting these new anomalies and new approaches developed as necessary.

Table 1. Detection and isolation results for faulted cases

Fault Case	FMCRD Status	Assigned Class	
		Healthy	Faulted
Stator Short	Healthy (54)	49 (90.7%)	5 (9.3%)
	Faulted (6)	0 (0%)	6 (100%)
Load Step	Healthy (54)	53 (98.1%)	1 (1.9%)
	Faulted (6)	4 (66.7%)	2 (33.3%)
Load Ramp	Healthy (54)	50 (92.6%)	4 (7.4%)
	Faulted (6)	3 (50%)	3 (50%)

4.1. Ongoing Work

The proposed within-bank detection routine will be further developed and evaluated considering (1) other measures of central tendency across the bank of FMCRDs, (2) additional measured performance signals, (3) more sophisticated classification and pattern recognition approaches for multivariate systems, and (4) the number of FMCRDs included in a bank and the number and types of faults occurring in a single bank.

ACKNOWLEDGMENT

Research funding for this work was provided by Advanced Research Projects Agency-Energy (ARPA-E), U.S. Department of Energy, under Award Number DE-AR0001290 towards advancing the use of AI for reducing O&M costs in the Nuclear generation. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

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