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Pursuit

In-Situ Condition Monitoring of Components in Small Modular Reactors Using Process and Electrical Signature Analysis

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Components in small modular reactors (SMRs) are located in a hazardous environment and must be monitored remotely. Electrical signature analysis (ESA) is a viable option for component monitoring as it can be implemented on-line away from the actual equipment. This research attempts to use both electrical signatures from a pump motor and process variables such as flow and pressure to effectively monitor reactor components. An experimental flow loop with pump health monitoring equipment and a data acquisition system was used for experiments. Process variables analyzed include pressure, flow rate, water level, and motor vibrations. The electrical signatures monitored were the motor current and voltage drawn. It was observed that the pressure in the loop, vibration, flow and motor current signals show similar behavior in the transient region (start-up and shut-down) as well as during steady-state operation. It was demonstrated that a strong relationship exists between motor current and process variables such as flow, pressure, and motor vibrations. These relationships will be used to prove that the pump's electrical signatures can be used to monitor the pump, flow, and pressure without direct measurement of the process variables.

Introduction

Small modular reactors have emerged as a viable future application of nuclear power technology. SMR designs feature reduced initial capital costs, a longer fuel cycle, remote deployment, improved safeguards, and increased reliability when compared to traditional large reactors [1]. For long-term operation of SMRs, it is imperative that continuous *in-situ* monitoring of critical equipment must be developed and incorporated during the reactor design phase. This capability is attractive for remote deployment of SMRs with longer fuel cycle duration and for minimizing forced outages, thus enhancing the utilization of these

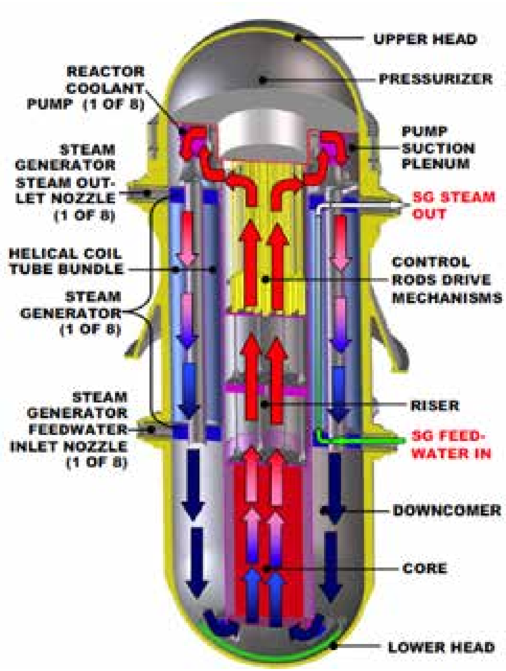

Figure 1: Steam generator, reactor coolant pumps, and CRDM are incorporated inside the reactor vessel [2].

power generating systems in small electric grid environments. These technologies contribute to smart condition-based maintenance, reduced human resources, remote monitoring, and autonomous operation. In integral pressurized water reactors (iPWR) and other designs of SMRs, the pressure vessel incorporates most of the critical equipment used for power generation (Fig. 1) [2].

SMRs have components that are somewhat different from conventional PWRs. For example, the coolant pumps may be internal to the vessel or mounted on the vessel without any additional piping, and therefore component instrumentations are limited, making electrical signature analysis (ESA) a feasible method for ascertaining component condition [3]. The study presents preliminary results of monitoring submersible pumps using ESA**.** The objective of the research is to relate changes in electrical signatures to changes in process variables so that the pump and other equipment can be monitored remotely without direct measurement of process variables such as flow, pressure, and vibration.

Methodology

Flow Control Loop

An existing experimental loop has been upgraded with instrumentation for pump-motor health monitoring (Fig. 2.1).

A submersible pump is used to circulate the water in the loop, in an attempt to approximate the use of a canned pump in a SMR. The pump is driven by an induction motor and the current drawn by the motor reflects the changing load on the motor. Thus, the motor acts as a transducer and can be used to monitor the pump conditions [4]. Several process

Figure 2.1: Experimental flow loop used for experiments and equipped with MOVs, flow and pressure sensors, along with a full data acquisition system interfaced with a PC

and equipment performance parameters are also measured. Accelerometers, flow meters, pressure sensors, and thermocouples are used to measure pump vibration, flow rate in the loop, the pump outlet pressure, and fluid temperature, respectively. A frequency converter is used to vary the line frequency of the motor, and thus change its speed and output. Both steady-state and transient data are acquired during the loop operation. Steady state data is data that is acquired when the level of the tank is constant and there are no changes in the pump operation or the valve openings. Transient data is taken for pump start-up and shut down, as well as changes in valve openings and pump speed variations. Data is needed for both modes so that the relationships of the signals can be explored completely.

Data Acquisition

The data acquisition system consists of several NI-DAQ (National Instruments Data Acquisition) modules and the LabVIEW (Laboratory Virtual Instrument Engineering Workbench) software. A Virtual Instrumentation (VI) panel was created to allow the user to specify what type of data was to be recorded (Fig. 2.2). Data sets were then outputted to a file and imported (into MATLAB) where it was analyzed in both the time and frequency domain.

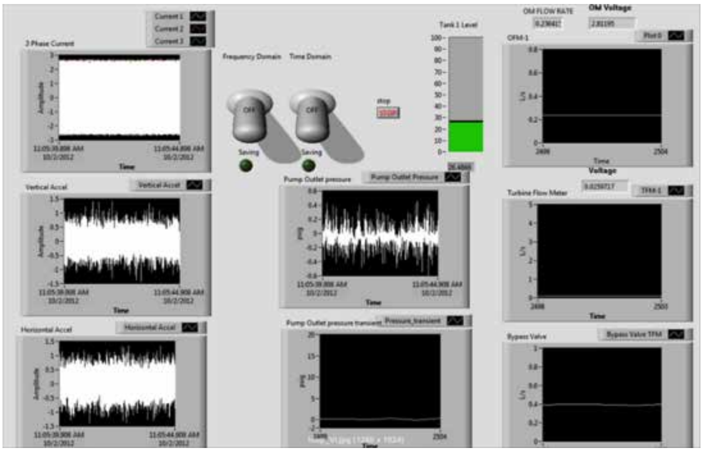

Figure 2.2: Virtual Instrument used for data collection shows real time graphs of current, vibration, pressure, tank level, and flow throughout the loop.

Experiments using the test loop are performed to demonstrate the relationship between the electrical signatures (motor current, power) and process variables such as fluid pressure and flow rate. Since motor signature can be monitored remotely (away from the machinery), this provides a method for continuous monitoring of pump behavior and changes in the reactor coolant flow and pressure fluctuations. The pump-motor system vibration is monitored using accelerometers mounted on top of the assembly (vertical) near the flow outlet and on the side of the steel shell (near the pump-motor coupling) in the horizontal direction. The vibration parameters can also be related to motor current signatures. While the test loop does not model an actual SMR, it does have a loop configuration like that found in a reactor. The similarity of the loops is sufficient enough that the relationships established in this loop can be applied to an actual reactor.

The following signals were acquired with a sampling rate of 1652 samples/sec (Hz):

- Pump discharge pressure
- Flow rate into the water tank (orifice meter)
- Water level (differential pressure transmitter)
- Motor current
- Motor voltage
- Vertical (pump-axial) accelerometer
- Horizontal (pump-radial) accelerometer.

The data sets were acquired for approximately 10 minute per test run. The number of total data points is approximately 10^6. The transient data sets were acquired during the complete run cycle, pump start-up, steady state operation, and pump coast-down. For wide-band measurements, data sets were recorded at steady-state operation by adjusting the tank inlet flow rate to maintain a steady water level in the tank. A high-pass filter was used for conditioning the pump pressure signal, thus eliminating its DC-level so that small fluctuations could be observed easier. The vibration signals were amplified with a gain of 10 decibels because the original amplitude was too low.

Results and Discussion

Pump Pressure and Current Signatures during Transient Operation

It was observed that the pump outlet pressure and the motor current signals show similar behavior in the transient region (start-up and shut-down) and during steady-state operation (Figs. 3.1 and 3.2). The speed of the pump is decreased at approximately one hundred seconds causing the current drawn by the pump to decrease and the pressure in the loop to decrease.

The response of the current, pressure, and bypass water flow due to flow perturbations and frequency changes of the pump were evaluated (Figs. 3.3 – 3.5.). Event 1,

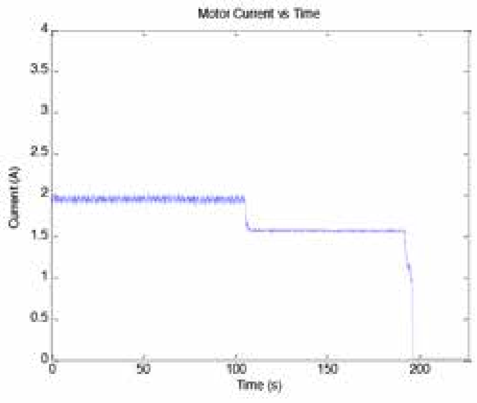

Figure 3.1: The pump speed is decreased which lowers the current drawn by the pump.

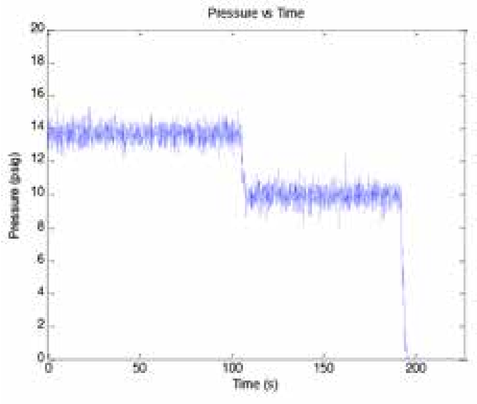

Figure 3.2: The exit pressure of the pump decreases when the speed of the pump is lowered.

corresponding to the sharp decrease in current, is due to a manual blockage of the bypass valve. After the bypass valve was closed, the pressure in the loop increased, current decreased, and the bypass flow stopped. Events 2 and 3 correspond to subsequent decreases and increases of the pump speed. When the pump speed is decreased, the current drawn decreases, the pressure decreases, and the bypass flow decreases as expected. Furthermore, an increase in the pump speed leads to an increase in the current and process variables (bypass flow and pressure). Event 4 corresponds to the shutdown of the pump which returns all signals to zero.

These results indicate that the current drawn from the pump is highly related to both loop pressure and flow.

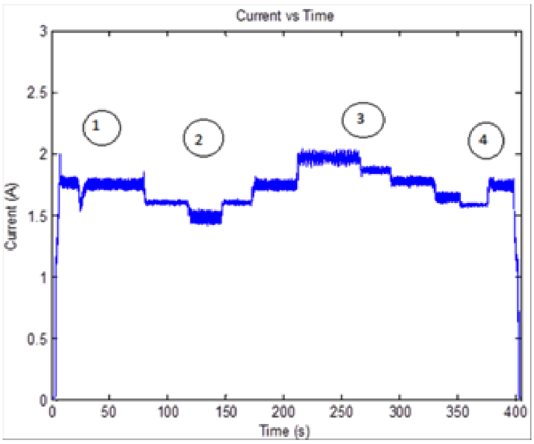

Figure 3.3: Current changes due to events one through four

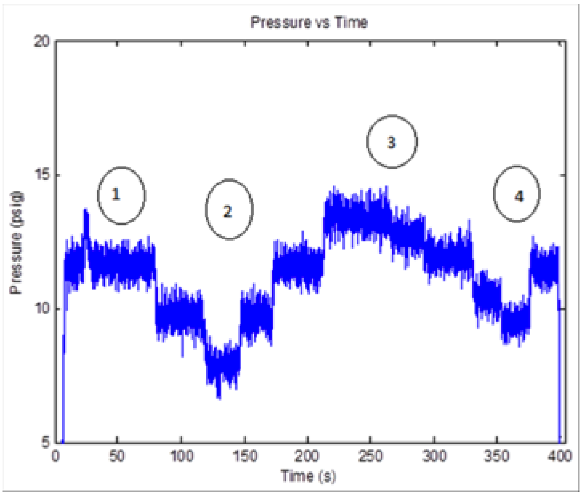

Figure 3.4: Pressure changes due to events one through four

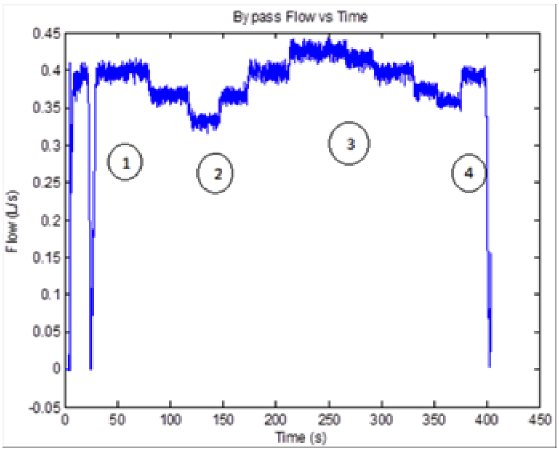

Figure 3.5 Bypass valve flow rate changes due to events one through four

Frequency Analysis of Wide-band Data

In order to achieve a high level of A/D converter resolution, a high-pass filter was used to eliminate the DC-level in the pressure signal. This pre-conditioned signal was then routed to the DAQ module. Power spectral density (PSD) plots of pump outlet pressure and motor current were generated (Figs. 3.6 and 3.7).

Large peaks were observed at the motor frequency of 60Hz and its harmonics indicating a healthy pump. The presence of other prominent peaks would indicate a problem with the pump motor. The low bandwidth of the pressure transmitter is not expected to generate higher frequencies in the pressure spectrum.

To better understand the similarity between these signals in the frequency domain, their coherence was calculated. Coherence was calculated to determine if the signals were related to each other in the frequency domain. If a high coherence was present, then it can be stated that the two signals show similar behavior at certain frequencies. A coherence value approaching unity indicates a linear relationship between the two signals. If the coherence is small, approaching zero, this indicates no commonality or relationship between

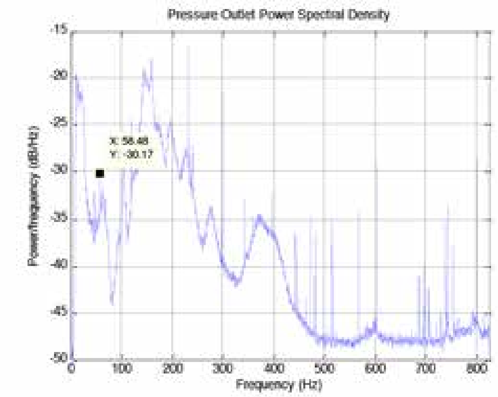

Figure 3.6: PSD plot for pump outlet with a block size of 8192 and a frequency resolution of 0.2 Hz

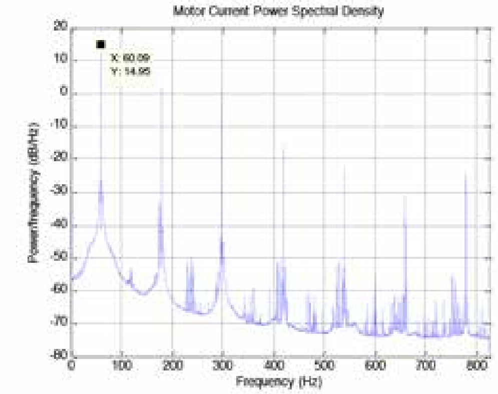

Figure 3.7: PSD plot for motor current with a block size of 8192 and a frequency resolution of 0.2 Hz

the two signals at frequency f. The spectral dependencies of the various signals can be determined by estimating the coherence function between any two signals. If x(t) and y(t) are two signals (related to each other by a linear relationship), then the coherence function between the two signals at frequency *f* (Hz) is given by the formula in Figure 3.8 [5].

The coherence between current and pressure (Fig. 3.9) was evaluated and apart from the initial peak, the coherence between the signals is very low in the frequency domain.

Coherence was also calculated to determine the relationship between pump vibrations and motor current (Figs. 3.10 and 3.11).

$$\gamma_{xy}^2(f) = \frac{|S_{xy}(f)|^2}{S_{xx}(f)S_{yy}(f)}, \quad 0 \le \gamma_{xy}^2(f) \le 1$$

Figure 3.8: S_{xy} is the cross-spectral density between x and y, S_{xx} and S_{yy} are the auto spectral densities of x and y, respectively.

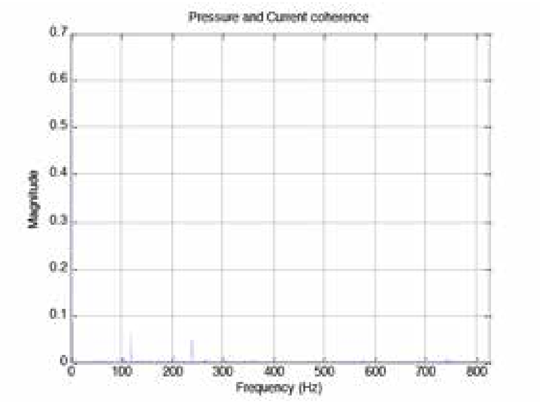

Figure 3.9: Low coherence between pressure and current indicate there is no relationship between current and pressure in the frequency domain.

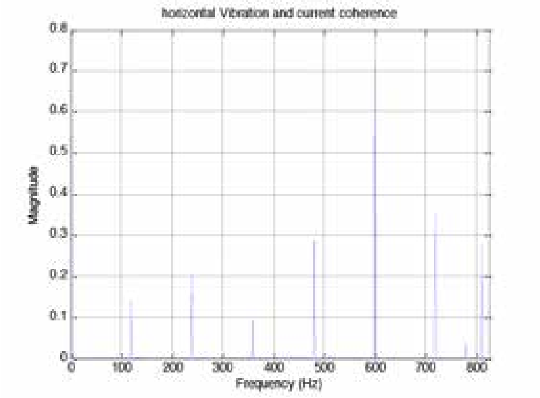

Figure 3.10: High coherence was found at some frequencies for horizontal vibrations and the motor current.

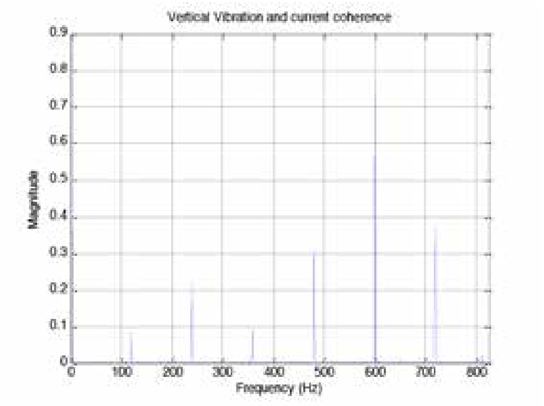

Figure 3.11: High coherence was also found at some frequencies for vertical vibrations and the motor current.

High coherence peaks occur at the same frequencies for vibrations in both the vertical and horizontal directions. This observation was expected since both accelerometers will pick up similar signals. The coherence between current and vibration mean that the current signature can pick up much of the same frequency information of the accelerometers.

Conclusions and Future Work

A fully instrumented flow control loop, with a submersible pump and a variety of sensors, has been developed to establish the feasibility of using electrical signatures for remote monitoring of reactor internals in a SMR. Preliminary results show a strong relationship between motor current and process variables such as flow and pressure. These relationships will be used to show that the motor and other components can be monitored using electrical signature analysis. ESA will also be shown to be capable of monitoring flow and pressure. Continuing work includes the development of simulation models interfacing system dynamics with pump-motor models, and further developing relationships among motor current, vibration, and process variables in the flow control loop. A parallel effort includes the development of models of SMR and pump-motor dynamics. This physics model will be used to determine the sensitivity of electrical signatures as a function of process and pump conditions. Data-based models are also being developed to characterize the relationship among the measurements. The process and equipment monitoring (PEM) toolbox will be used to develop these models and estimate the response of the process variables and electrical signatures.

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About the Author

Victor Lollar was born and raised in Maryville, TN, only twenty minutes away from the University of Tennessee. He chose to attend the University of Tennessee because of its top 10 Nuclear Engineering program. He plans to attend graduate school in the nuclear field where he hopes to find a long career expanding the current knowledge of nuclear engineering.

About the Advisor

Dr. B.R. Upadhyaya is a professor in the Department of Nuclear Engineering at the University of Tennessee. He received his undergraduate degree in Mechanical Engineering at the University of Mysore in India, his master's degree in Applied Mechanics at the University of Toronto, and his Ph.D. in Systems Science at the University of California at San Diego. He has taught and researched around the world, including at the Commissariat a L'Energie Atomique in France, the Netherlands Energy Research Foundation, and the National University of Mar Del Plata in Argentina. He is also a consultant at Oak Ridge National Laboratory. His research interests include motor-operated valves, automated diagnostics systems for eddy currents, and the life prediction of plant components.