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Remote Monitoring of Equipment in Small Modular Reactors

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Small Modular Reactors (SMR) are being developed by several vendors for remote deployment and for small grid applications. These reactors have the additional advantage of load-following, process heat application, and improved safeguards features. The pressure vessel incorporates most of the critical equipment used for power generation, including the steam generators, control rod drive mechanisms, and the pressurizer. For example, the reactor coolant pumps may be internal to the vessel or mounted on the vessel without any additional piping. The control rod drive mechanisms in many SMRs are also internal to the reactor vessel. These features limit the in-vessel instrumentations, thus making it a challenge for monitoring critical in-vessel components and measurement of process variables. On-line monitoring of SMR components, using electrical signature analysis (ESA), is presented and application to an experimental flow loop is outlined. Both stationary and non-stationary signal processing techniques are applied to pump-motor signatures, vibration measurements, and pump discharge pressure. The pump is a submersible device which is fitted with underwater accelerometers. The results of analysis indicate a high correlation between the motor current and pump discharge pressure. Furthermore, frequency domain analysis indicates that varying vibration bands correlate with the features of motor current signatures in the power spectral density plots. A physics model of an integral pressurized water reactor has been developed and used to simulate anomalies in sensors, equipment, and in the reactor dynamics.

1. Introduction

For reliable and economic long-term operation of Small Modular Reactors (SMR), it is imperative that continuous in-situ monitoring of critical equipment must be developed and incorporated in 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 power generating systems in small electric grid environments. These technologies contribute to smart condition-based maintenance, reduced human resources, remote monitoring of reactor components, and autonomous operation. In SMR designs, the pressure vessel incorporates most of the critical equipment used for power generation. Examples of such plant components include: motors, coolant circulation pumps, motor-operated valves, control rod drive mechanisms (CRDM), in-core instrumentation, and reactor internal structures. The need for new instrumentation and continuous monitoring of these systems is a unique challenge in the design and operation of SMRs (Clayton and Wood, 2011).

Designs of light water reactor SMRs have been developed by NuScale (45 MWe), Babcock & Wilcox (mPower-180 MWe), Westinghouse SMR (225 MWe), and SMART (Korea-100 MWe). The forerunner of these reactors is the IRIS design by Westinghouse which is a 1000 MWth integral pressurized water reactor (iPWR). Figure 1 shows the layout of this reactor (Upadhyaya and Perillo, 2011) with a large pressure vessel (20-meter high, 6-meter diameter). The reactor vessel houses the reactor core, eight helical coil steam generators (HCSG), and the pressurizer. The primary water is pumped from the upper plenum down through the annular space between the reactor vessel and the shielding, and around the steam generator tubing

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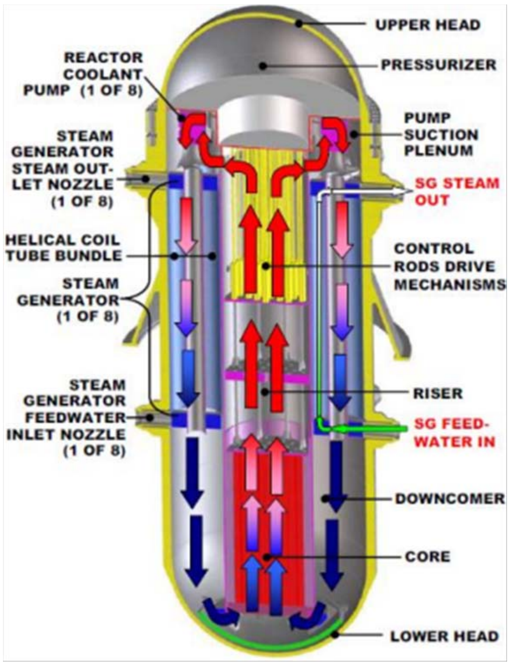


Figure 1: Schematic of the IRIS system (Upadhyaya & Perillo, 2011).

This research, specific to the SMRs, is necessary because of their special features. 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, thus limiting sensor placements. This makes ESA one of the attractive techniques for monitoring component condition. Furthermore, the control rod drive mechanism is internal to the vessel (in some designs). Monitoring electrical signatures of critical components could help in diagnosing anomalies in these devices and thereby facilitate their timely maintenance. This would reduce maintenance costs and forced outages. Remote monitoring technologies would also reduce human resources. Because most of the critical components are internal to the vessel and thus inaccessible during normal operation, remote monitoring via electrical signal analysis provides a means for monitoring their performance. The induction motor acts as a transducer, potentially indicative of the faults in the driven devices such as pumps, valves, and other electrically driven actuators. This paper demonstrates the development of this approach with application to an experimental flow control loop.

2. Development of the Flow Control Loop

An existing experimental loop is upgraded with instrumentation for pump-motor health monitoring. Figure 2 is a photograph of the flow control loop (Upadhyaya et al., 2012). A submersible pump is used to circulate the water in the loop, in an attempt to duplicate 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. Several process and equipment performance parameters are also measured. These include water flow rate in the loop (orifice and turbine flow meters), pump outlet pressure, motor current and voltage, vibration (underwater accelerometers), and fluid temperature (using thermocouples). A frequency converter is used to vary the motor power supply frequency. Both steady-state and transient data are acquired during the loop operation.

The data acquisition consists of several NI-DAQ modules and the LabVIEW software. Motor-operated valves (MOVs) are used to control the flow in the loop. The valve position is adjusted through interface with the data acquisition and analysis computer and a Virtual Instrumentation (VI) panel. The experiments in the test loop are used to demonstrate the relationship between the electrical signatures (motor current, power) and process variables such as pump discharge pressure and flow rate. Since the 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 underwater 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

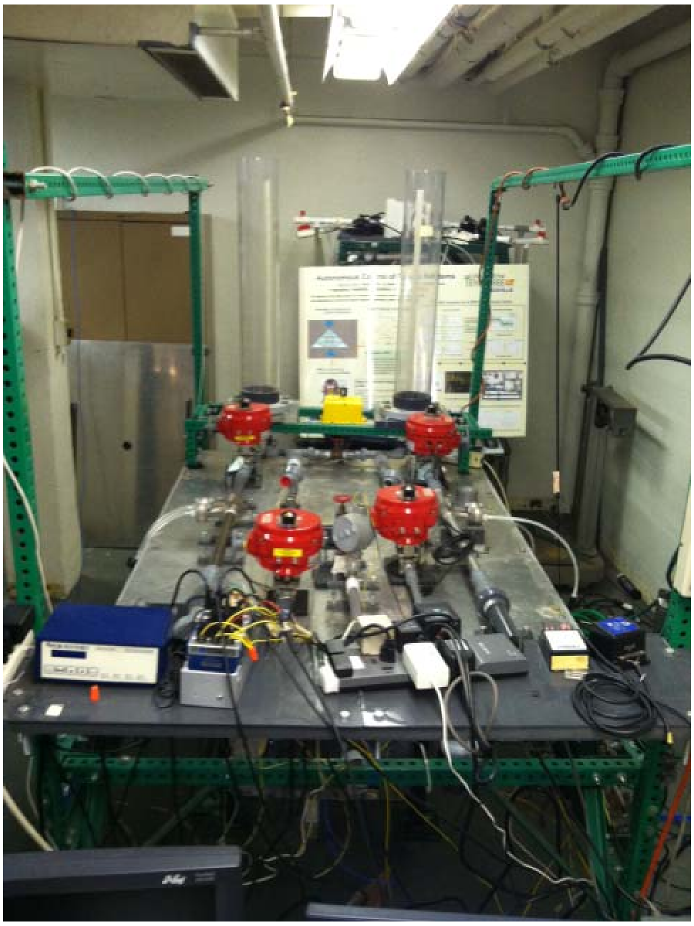


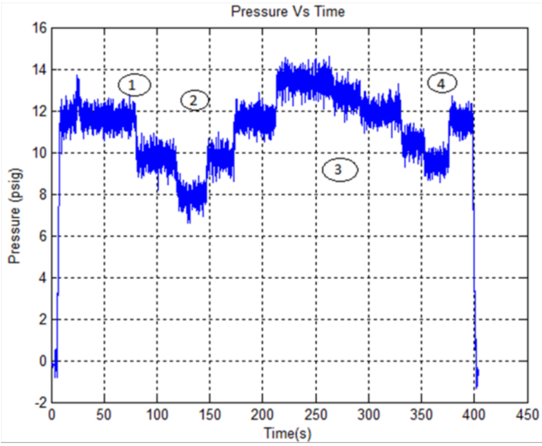
Figure 2: Experimental flow control loop

3. Results

3.1. Time Domain Analysis

Experiments were performed by varying the motor frequency to observe the changes in the motor current and the pump discharge pressure. It is observed that the pump discharge pressure, motor current and the flow rate show close correlation with each other. The pump motor is started at 55 Hz, and then the pump frequency was decreased to 45 Hz. Motor frequency is then increased in steps of 5 Hz to 60 Hz, and then decreased gradually to 50 Hz. The pump was then shut down after increasing the speed back to 55 Hz. This operation is explained by dividing the entire experimental run into four regions, as shown in Figure 3a, 3b and 4.Region 1 involves initial start up of the pump at 55 Hz, and removal of air bubbles from the loop. The bypass valve was closed to remove air bubbles in the loop. During this time there is increase in the pressure but the motor current decreases, and as expected the bypass flow goes to zero. The pressure increases to nearly 14 psig and the current decreases to 1.45 Amp. After the air bubbles are removed, the bypass valve is opened completely and the flow increases to 0.4 L/s.

Region 2 is where the pump speed is first decreased to 45 Hz, and then increased to 60 Hz in increments of 5 Hz, in order to determine its effect on the motor current and pressure. The motor current decreases to 1.4 Amp at a motor frequency of 45 Hz and increases to 2 Amps at 60 Hz. The discharge pressure falls to as low as 7.5 psig at 45 Hz, and reaches its maximum value of 15 psig at 60 Hz. As expected, the water flow rate also decreases to 0.33 L/s and increases back to 0.45 L/s at 60 Hz line frequency.



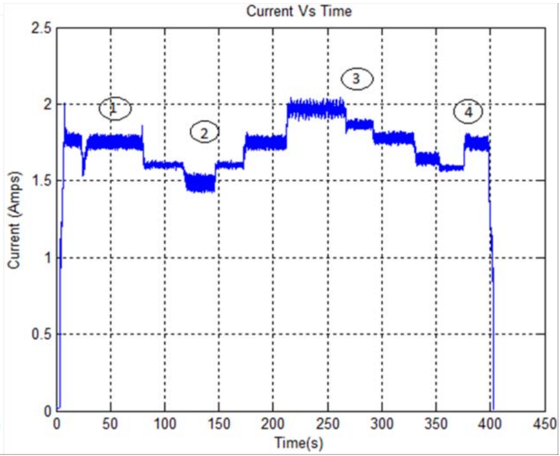


Figure 3a: Pump discharge pressure. *Figure 3b: Motor current signature*

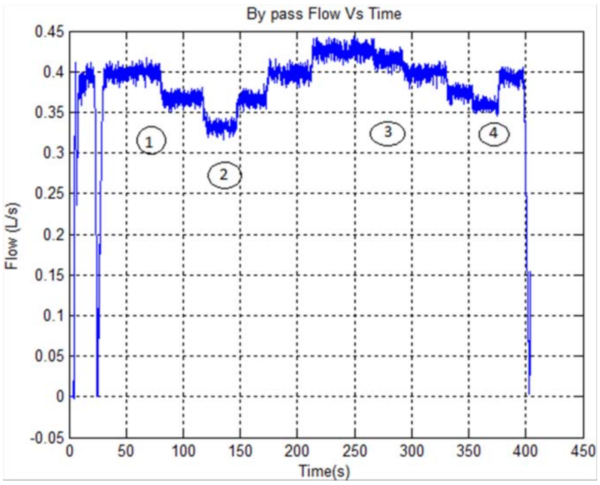


Figure 4: Bypass flow rate

Region 3 involves reducing the speed in steps to 50 Hz. Pressure changes here can be clearly related to the change in flow rate and the motor current. As seen, the pressure change of 15 psig to 8.5 psig is also reflected in the current which decreases to 1.5 Amp from a value of 2 Amp. Bypass flow also decreases to 0.35 L/s. This region shows how even a small change in the pressure is reflected in the current and the bypass flow. Region 4 basically deals with the shutdown of the motor. Correlation coefficients were calculated for the three process variables to check whether a relationship could also be shown statistically. It is observed that the correlation coefficients show strong relationship of the pressure with the current and the bypass flow. The motor current has a correlation of 0.90 whereas flow has the correlation 0.77 with the pump discharge pressure. The observations show that based on the changes in process variables and electrical signatures, the condition in the loop can be determined. In other words, the change in the current drawn by the motor can determine whether the pressure and flow in the loop are changing due to a blockage or a change in the speed. As observed there is noise in the pressure signal at steady state which is due to peaks that are observed in the pressure output signal. These peaks affect the steady state analysis and are currently being investigated.

3.2. Frequency Analysis of Transient data

Fourier transform, which is widely used to analyze the frequency characteristics of a signal, loses information when variation of frequency is involved in the signal, such as in transient data. This can be partially overcome by using a finite data window. This is achieved by multiplying the signal by the window function, and then performing a Fourier transform to determine the time-frequency characteristics. Using a Gaussian window function, this transform is given by

$$G_x(t,f) = \int_{-\infty}^{\infty} e^{-\pi(r-t)^2} \,.\, e^{-j2\pi f\tau} x(\tau)\, d\tau \qquad (1)$$

where, x is the signal, f is the frequency, and τ is the transform parameter. This is referred to as the windowed Fourier transform and often called the short-term Fourier transform (STFT). This transform works best if the segments are made smaller to make the signals look stationary in each segment. A note should also be made about the trade-off between frequency and time resolution. A smaller window length reduces the frequency resolution of the transform and fewer samples for STFT (Sharp 2012). By decomposing a single signal into an overlapping series of Fourier transforms, the Gabor transform allows the evolution of frequencies over time to be more directly analyzed. The STFT has a fixed time-frequency resolution and may not provide information about the signal that may require a higher frequency and time resolution. In the Gabor transform, the frequency features are captured by a frequency modulation of the Gaussian window. However, the window size is kept constant.

For the experimental data, STFT is used in order to extract frequency information from process signals. Data analyzed earlier is used in this section. Figure 5 shows the STFT performed on the vibration data. Frequency changes are clearly observed. The motor frequency and its harmonics show a decreasing trend, the reason being the slowing down of the motor with the help of the frequency drive. Figure 6 shows the STFT of the pump discharge pressure signal. The submersible pump used in the experimental loop has 4 vanes, giving a vane pass frequency of four times the pump rotor speed. The dark red lines are prominent at the vane pass frequency and its harmonics. In case of the pressure signal, similar relationship is found at the third harmonic of the vane pass frequency.

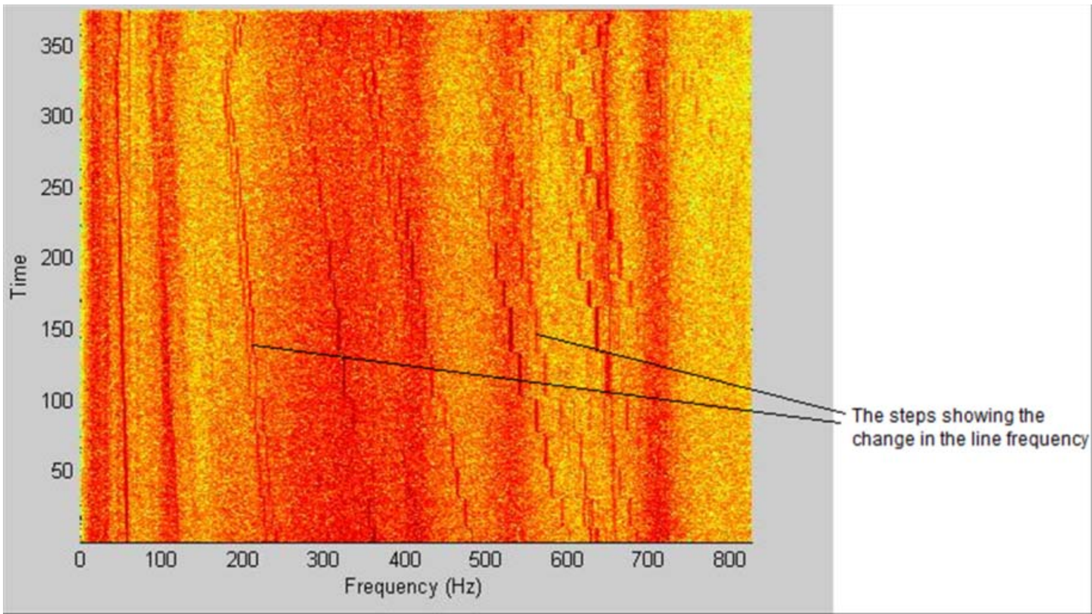


Figure 5 : STFT of Vibration signal

A direct relationship is not observed between the vibration and the pressure signals. These characteristics will be studied in the further. STFT of one of the motor current shows strong frequency relationship with the pressure signal (corresponding to the rotor frequency).

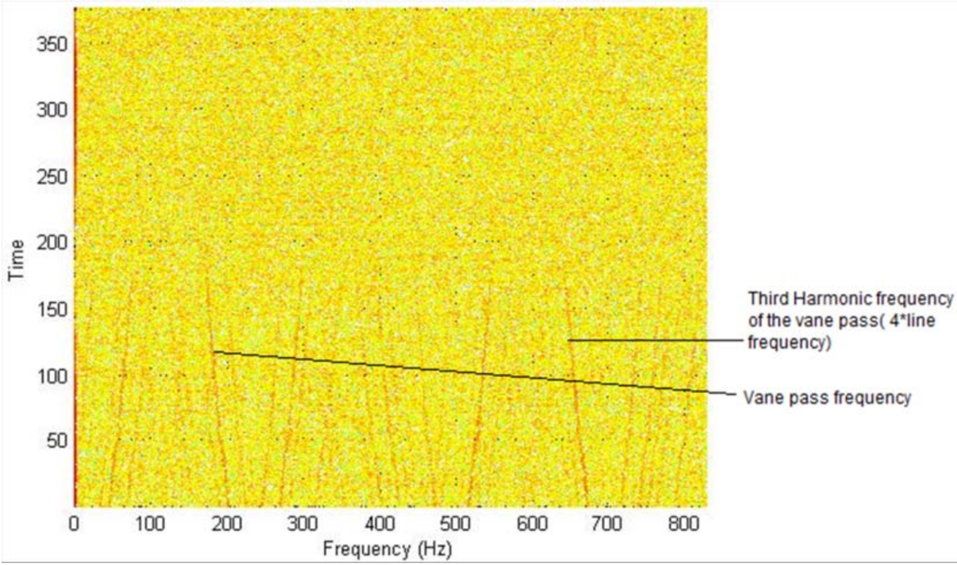


Figure 6: STFT of pressure signal

4. Concluding Remarks

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 small modular reactors. Preliminary results show a strong relationship between motor current and process variables such as flow and pressure. The continuing work in signal analysis involves the use of auto- regression time-series modeling of wide-band data. These models will be generated based on different operating conditions (motor frequency), and will be used to diagnose any discrepancy observed by running tests on the various motor frequencies, and checking if the power spectra show the shift in the frequencies. This modeling technique will help to find the time block where anomalous events would occur. The relationship between the motor current in the time domain and pressure spectrum information from the auto-regression (AR) model would determine if characteristics in the pressure signal could be deduced from the information in the motor current signature. Any change in the motor frequency shows up in the current signal. Development of auto-regression models is expected to illustrate that the change in the motor frequency would show up in the spectral peaks derived from the AR model. Future research includes the processing of non-stationary signals using the Hilbert-Huang transform (Huang et al, 1998).

Acknowledgments

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References

Clayton D and Wood R.T., December 2011, “The role of I&C technology in enabling the deployment of small modular reactors,” Nuclear News, Vol. 54, No. 13, pp. 42-47,.

Huang N.E., et al., 1998, “The empirical mode decomposition and the Hilbert transformation for nonlinear and non-stationary time series analysis,” Proc. Roy. Soc. London, Vol. 454, pp. 903-995.

Sharp M, 2012, *Prognostic Approaches Using Transient Monitoring Methods*, PhD Dissertation, University of Tennessee, Knoxville.

Upadhyaya B.R. and Perillo S.R.P., May 2011, *Multi-modular Integral Pressurized Water Reactor Control and Operational Reconfiguration for a Flow Control Loop.* Final Report prepared for the U.S. Dept. of Energy, University of Tennessee, Vol. 5, Report No. DE-FG07-07ID14895/UTNE/2011-7.

Upadhyaya B.R., Hines J.W., Damiano B., *et al.*, September 2012, *In-situ Condition Monitoring of Components in Small Modular Reactors Using Process and Electrical Signature Analysis*, Annual Report, NEUP-2011-3212-Annual-2012, University of Tennessee.