U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

Clean. Reliable. Nuclear.

Process-Constrained Data Analytics for Sensor Assignment and Calibration

Advanced Sensors and Instrumentation Annual Webinar

October 29, November 5, November 12 , 2020

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Project Overview

- Goal
  - Determine the minimum sensor set required to diagnose equipment degradation (sensors/components) in a system in a nuclear facility
- Objectives
  - Solve using data analytics and physics-based methods
  - Deploy in an industry setting to solve a meaningful O&M problem
- Participants (2020)
  - Richard Vilim – Argonne; Xcel Energy; University of Michigan
- Schedule
  - Y1: Develop Method and Algorithms and Engage a Nuclear Utility
  - Y2: Perform Sensitivity Studies on an Application Selected by Nuclear Utility
  - Y3: Install at Utility Site for Their Assessment

Summary of accomplishments (FY20)

- Deliverables
  - R. B. Vilim, T. Nguyen, H. Wang and R. Ponciroli, “Description of Sensor Assignment Optimization Method as Deployed on a Multi-Node Cluster”, March 31, 2020.
  - R. B. Vilim, T. Nguyen and R. Ponciroli, “Performance Results for Sensor Calibration Method”, August 31, 2020.
  - R. V. Vilim, “Second Annual Progress Report on Process-Constrained Data Analytics for Sensor Assignment”, September 30, 2020
- Journal Paper
  - T. Nguyen and R.B. Vilim, “A Probabilistic Model-Based Diagnosis Framework for Fault Detection and System Monitoring in Nuclear Power Plants,” Annals of Nuclear Energy, August 2020.
- Patents
  - Three patent applications are being written

Summary of accomplishments (FY20)

- Extended Algorithms and Methods
  - Added uncertainty treatment to automated reasoning algorithm
- Added Pump/Motor/Bearing Models to Component Library
  - Centrifugal pump, synchronous induction motor, and shaft bearing model added to PRO-AID library
- Validated Methods Using Blind Data from Utility Partner
  - Received FW pump normal operation data and blind fault data
  - Successfully diagnosed sensor biases superposed on plant measurements
  - successfully diagnosed blind faults
- Deployed Cluster-Based Executable for Sensor Assignment
  - Delivered executable to University of Michigan for subcontract task
  - Started software quality assurance upgrade

Technology Impact (1/3)

- Advancement of state of the art for nuclear application
  - Improves the reliability of nuclear plant health monitoring technology by including physics-based information as an adjunct to sensor data
  - Increases situational awareness among plant engineering staff by providing early identification of equipment degradation
  - Improves plant efficiency by providing a technical basis for determining when scheduled maintenance is unnecessary and can be bypassed
  - Facilitates the new paradigm of a remote monitoring center aimed at improving overall efficiency of a utility's nuclear fleet
  - Provides a techno-economic basis for designing the plant health-monitoring sensor set for an advanced reactor

Technology Impact (2/3)

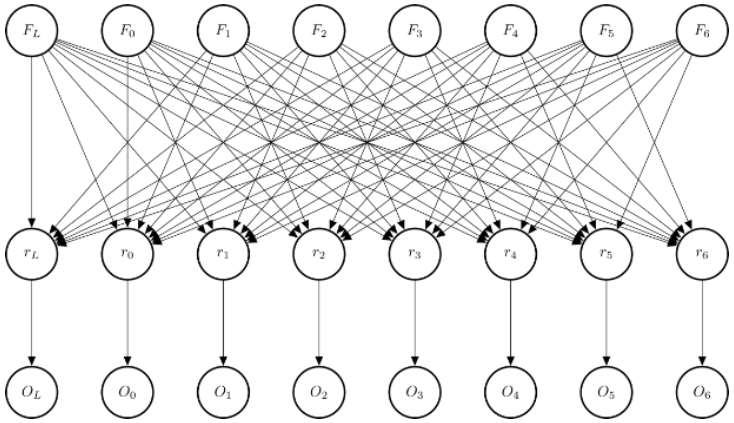
- Support for the DOE-NE research mission
  - Improves the economic competitiveness of nuclear power by reducing O&M costs
  - Leverages national laboratory expertise to advance commercial sector capability
  - Improves U.S. energy security through development of science-based technology that furthers the viability of nuclear power for electricity production
- Impacts the nuclear industry
  - Targets improved O&M efficiency in the current fleet with evaluation underway by two U.S. utilities in coordination with a U.S. energy services company

Technology Impact (3/3)

- Commercialization
  - Presently in early phase evaluation/adoption by two utilities developing remote monitoring centers
  - A U.S. nuclear energy service company has committed to adopting (industry partner on TCF awards) the method as a front-end plugin to maintenance optimization and asset management tools they are developing through EPRI sponsorship
  - Proceeding with three patent applications to protect U.S. taxpayer investment

Accomplishment #1 – Developed Algorithms and Methods

- Automated reasoning algorithm extended to include uncertainty treatment

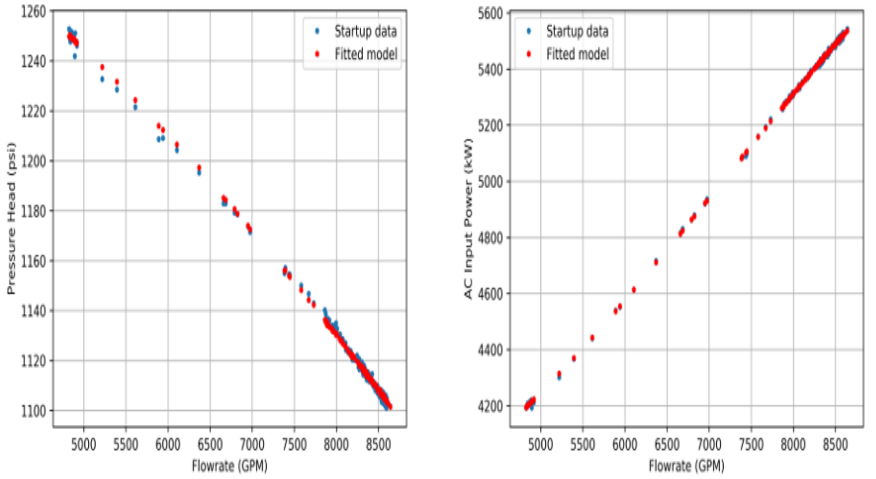


- Sensor assignment algorithm developed and programmed

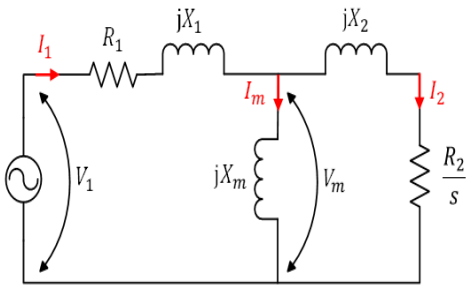
```
//Pseudo code for finding sensor set that yields optimal maintenance
// and asset management scheduling strategy
while     //iterate on sensor set
      spawn sensor_set
      generate virtual_sensors      // Subtasks 1.2 and 1.3
      generate Current_Likelihood_Component_Faults      // Subtask 2.2
      while      //Subtask 2.5
            spawn PM_schedules
            evaluate maintenance_asset_cost_function
      exit_if maintenance_asset_cost_function < epsn
exit_if maintenance_asset_cost_function < epsn
print cost, sensor set, PM schedules
end
```

Accomplishment #2 – Developed Component-Library Models

- First-principles models for generic nuclear plant components were developed
  - Centrifugal pump, synchronous induction motor, shaft bearing
  - Added to the component library of the PRO-AID engineering-system health-monitoring code



Centrifugal Pump Performance Maps



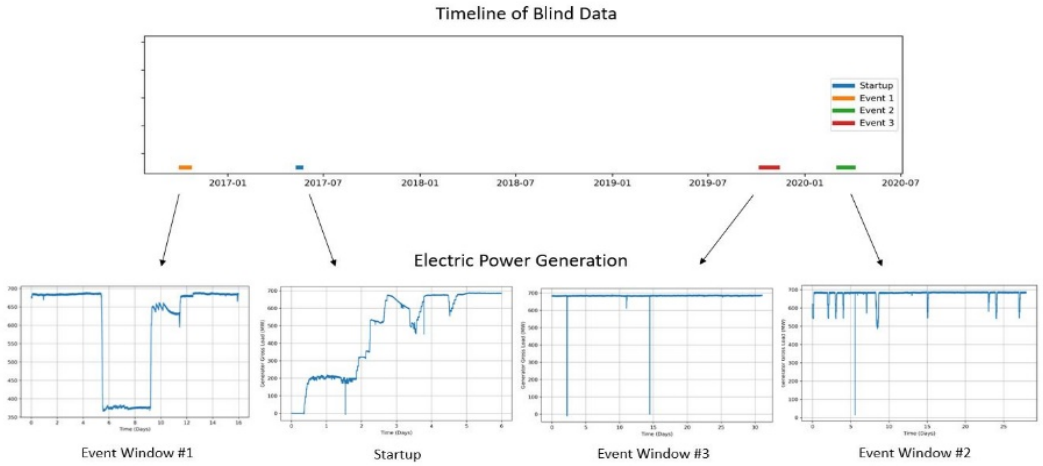
Variable	Description
V_1	Stator phase supply voltage (V)
I_1	Stator phase current (A)
I_2	Rotor phase current (A)
I_m	Magnetizing current (A)
$s = \frac{n_s - n_r}{n_r}$	Slip ($-$)
n_r	Rotor speed (rpm)

Parameters	Description
R_1	Stator leakage reactance (Ω)
X_1	Stator leakage reactance (Ω)
R_2	Rotor resistance at standstill (Ω)
X_2	Rotor leakage reactance (Ω)
X_m	Magnetizing reactance (Ω)
n_s	Synchronous speed (rpm)

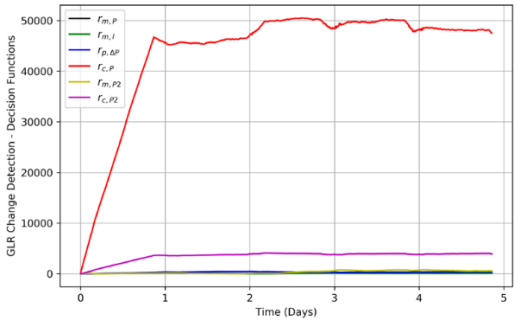
Synchronous Induction Motor Equivalent Circuit

Accomplishment #3 – Validated Methods Using Blind Data from Utility Partner

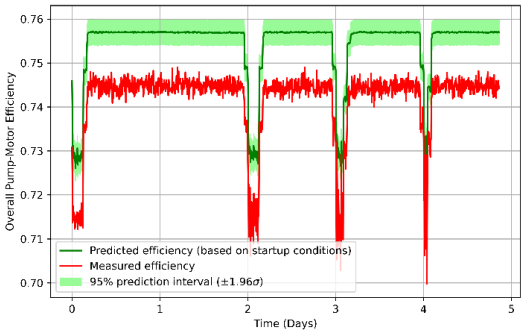
- Received FW pump/motor normal operation data and blind fault data



- Successfully diagnosed sensor biases superposed on plant measurements
- Successfully diagnosed blind faults

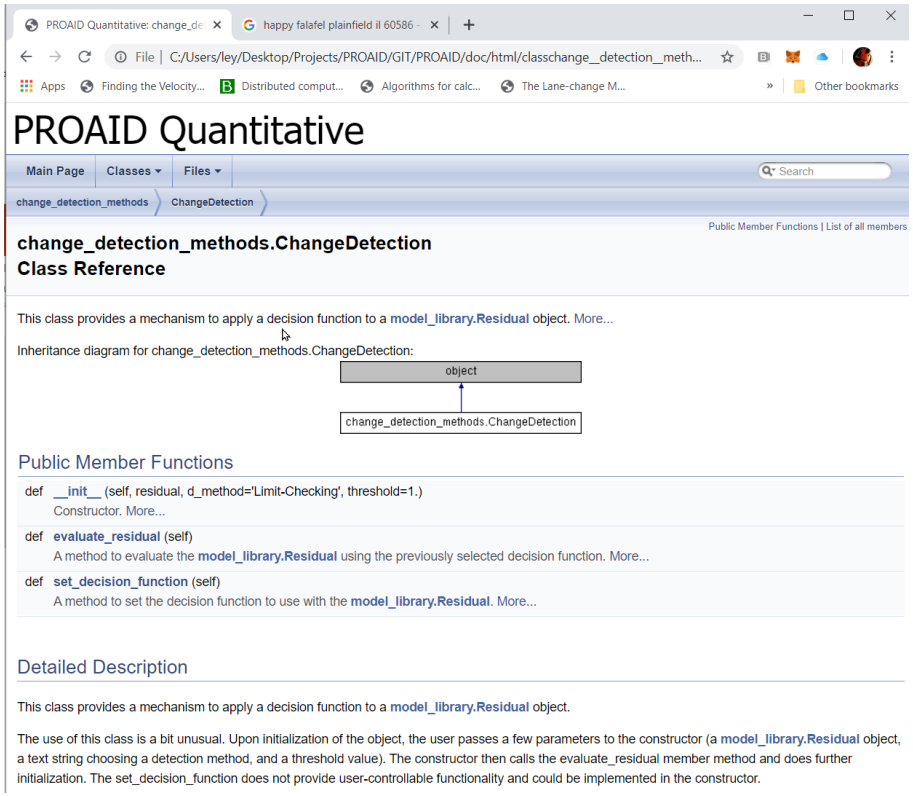


Diagnosis of feedwater pump bearing degradation



Accomplishment #4 – Release of Cluster-Based Executable

- Brought in software engineer to help with life-cycle management of PRO-AID code
- Developed and delivered cluster-based alpha version of PRO-AID code for use by Univ. of Michigan



Conclusion

- Algorithm and methods work was largely completed
  - Uncertainty treatment added
  - Component models added
- Validated algorithms and methods for feed water pump use case in collaboration by partnering utility
  - Successfully diagnosed sensor bias errors superposed on normal operating plant data
  - Successfully diagnosed blind faults in three plant event cases
- Released an alpha version of the code for use in sensor assignment problem
- Contact Information
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