Monitoring and diagnosis of equipment faults

Equipment faults and the associated plant upsets, which can result in reduced power production, thermal cycling, and protection system challenges, are a fact of life for commercial reactors. Operator response is symptom-based, requires scanning many instruments and alarms, and may not identify the fault. Automated diagnosis can help speed things up.

Plant equipment faults and grid upset events, including those that presently result in transients that challenge the protection system, might be better managed through the use of advanced operator aids. There are clear safety and economic advantages if the probability that an upset will lead to an unplanned shutdown can be reduced or if the plant response to an upset can be mitigated such that transient-induced thermal stresses are reduced. Presently an operator's response to events is driven by paper-based procedures: a sensor sends a signal to an alarm panel in the main control room; after consulting written procedures operators adjust controls to rectify the fault.

But a more informed operator working with procedures that are executed in a semi-automated manner, according to the process flow of (i) sensor fault identification to (ii) component fault identification to a (iii) realignment control action by control algorithms, has the potential to stabilize the plant in a more timely and precise manner and thereby avert a shutdown or temper transient-induced thermal fatigue.

The Computer Operator Support System (COSS) is a concept that has been proposed for providing the operator with new capabilities to handle such events (see also 'A Computerized Operator Support System Prototype,' by K. Thomas, R. Boring, R. Lew et. al., INL/EXT-13-29651, September 17, 2013). The COSS is envisioned as collection of technologies to assist operators in monitoring overall plant performance and making timely, informed decisions on appropriate control actions. The COSS does not replace the operator, but aids him or her by providing rapid assessments, computations, and recommendations to reduce workload and augment operator judgment and decision-making during fast-moving, complex events. The functions provided by a COSS require technologies for sensor validation and component fault diagnosis.

Objectives

The overarching issue for sensor validation technologies is a false alarm rate that is sometimes considered troublesome by those who have worked in the field. We have determined that contributing factors include inability to perform extrapolation, inability to operate with data where plant dynamics have been excited, and absence of guidelines for how the measurement vector should be composed and for what constitutes an appropriate set of training data to ensure the physical behaviour of the system is adequately captured.

The objective of the sensor validation work then is to develop methods with the ability to:

- Detect sensor output drift or failure due to sensor degradation
- Correct the sensor output until such time as the sensor can be either re-calibrated or replaced, such as during a planned shutdown, recognizing that sensors are not readily accessible for maintenance during operation
- Address the above root causes of false alarms by including the ability to extrapolate, work with dynamic data, and have a sound basis for how to compose the measurement vector.

The issue for the fault diagnosis technologies is the complexity of the problem and how it can be best approached. The most apparent approach might be a delineation of all possible faults and a procedure for finding a match with the observed sensor data. But this leaves open the possibility that a fault has been overlooked, and requires a unique hardwired set of faults for each system.

The objective of the fault diagnosis work then is to develop methods with the ability to:

- Reason the origin of a fault from sensor data without requiring *a priori* a list of all possible faults and combinations thereof (a so-called event driven approach)
- Be sufficiently general in approach that the heart of the algorithm does not need to be reworked with each new application.

The approach to accomplishing the objectives outlined above involves a combination of methods development and assessment by simulation on a test platform. The three main elements in this approach are described below.

Signal validation. The shortcomings of existing algorithms identified above are addressed by first considering the case of the Multivariate State Estimation Technique (MSET), an algorithm that has seen great commercial success. It is found in the oil and gas industries, aerospace industries, and the electric power generation industries. Yet, based on open literature descriptions of the methods of MSET, the algorithm does not appear to address the issues of extrapolation, dynamic data, and basis for composing the measurement vector. An inspection of the methods of MSET suggested that the absence of consideration for the properties of the equations that describe the physical systems monitored accounts for its drawbacks.

Hence, in this work signal validation is approached using a conservation-law-based representation of the physical system being monitored to guide methods development. This is a set of ordinary differential equations

Table 1: Relevant computer operator support system functions

Step	COSS Function
Detection:	Detect a plant anomaly before an operator would notice it. This could actually be in the noise-level of the instrument signal and long before it would be noticeable as a parameter trend or reach an alarm set point.
Validation:	Determine whether an apparent fault is real or caused by sensor failure by cross-checking related sensor readings and calculating whether the sensor in question is reading correctly.
Diagnosis:	Determine what type of fault would explain the values of the related sensors once they had been validated as reading correctly. The plant system model is compared to the validated readings of the actual plant to precisely locate the point of deviation from expected behaviour. The COSS could provide a graphical depiction of the fault to the operator for quick comprehension of the nature of the situation.

and includes representation of the actuators that drive the system and sensors that are used to observe it. This model does not need to be known in detail, but an understanding of its general structure is needed for developing a robust data-driven model. Conditions that the training data must satisfy are identified. In principle, our newly-developed data-driven Algorithm for Transient Multivariable Sensor Estimation (AFTR-MSET) requires only one instance of a transient observation during training.

Component Fault Diagnosis. A basis exists for performing fault diagnosis according to the above objectives. The confluence-based diagnosis method uses the conservation laws written as equations to detect fault-induced deviations and reason as to their origin. The reasoning approach does not require an *a priori* list of potential faults while the reasoning process is based on a set of rules that encapsulate the conservation laws. Detection and diagnosis are based on variable process trends and do not depend on explicit statement of process engineering parameters (for example, heat transfer area or heat transfer coefficient). The only application-specific information needed is the Piping and Instrument Diagram.

Test Platform. A software-based test platform is under development to support simulation-based testing and assessment of sensor validation and component fault diagnosis algorithms. The test platform links the algorithms that implement the methods with dynamic simulation data generated for plant systems ranging from those at the individual-component level all the way up to the whole-plant level. This platform will facilitate testing of algorithm performance for a wide range of parameters including sensor noise properties, sensor and component fault severity, sensor set diversity, training data range, monitored vector value with respect to the latter, and deviations in plant behaviour from assumptions made while developing the methods and implementing them as algorithms.

Validation of sensor readings

A nuclear power plant (NPP) has a large number of sensors which monitor temperature, pressure and flow rate of the process fluid. Sensors undergo physical degradation, a process accelerated by harsh environments, which results in their readings deviating from the calibration curve. Some of the early signs of sensor malfunction can take the form of a lagging response caused by increase of the sensor time constant. Other early indications of sensor malfunction may consist of occasional erratic output due to loose sensor component contacts. Conventional maintenance for inaccessible sensors consists of off-line integrity evaluation and recalibration or replacement. This approach does not result in timely detection of sensor degradation because inspection has to wait for scheduled process shut-downs. Such shutdowns are scheduled infrequently because of loss of revenue during plant down times. On-line sensor monitoring aims to (i) detect early signs of sensor malfunction thus enabling predictive maintenance, and (ii) provide corrected sensor readout until the time when the sensor is physically recalibrated.

During on-line monitoring, the underlying physical process variables' input to sensors are not known directly and can only be inferred. When the plant is in steady state, sensor readings do not normally change over time, except for noise-induced variability. A reading will change only if the plant undergoes an operational transient, or if the sensor malfunctions. Therefore, the main challenge for on-line monitoring involves making a decision if (i) the observed change in sensor reading is caused by a normal operational process transient and the sensor response is consistent with the calibration curve, or (ii) the observed change in sensor reading is caused by malfunction and the sensor response is inconsistent with the calibration curve.

Methods for sensor validation and equipment fault diagnoses that represent improvements on the state-of-the-art have been developed. Associated algorithms have been implemented in software.

Diagnosis of component faults

Diagnosing an equipment fault differs in a fundamental way from diagnosing a sensor fault. A degraded sensor output can be detected using the analytic methods above, without the need for complex reasoning. Only a representation for the normal operating state of the system is needed. An equipment fault, on the other hand, involves a redirection of mass, energy, or momentum as a consequence of a physical change in the system from normal. For fault diagnosis to proceed there needs to be some reasoning process that can relate observed changes in process variables back to a physical change in the system.

A method that meets the criterion above ("'PRODIAG' A Process-Independent Transient Diagnostic System – I: Theoretical Concepts" by J. Reifman and T.Y.C. Wei, *Nuclear Science and Engineering*, 131, 329-347, 1999) is summarized here. The method, implemented as the computer code PRODIAG, was developed to perform automated diagnosis of faults in nuclear power plants. Data from plant sensors are sampled periodically and trends are compared against the steady-state condition to determine if an anomaly exists. If an anomaly is detected, the code attempts to identify the cause through a reasoning process that involves rules that relate faults to sensor trends combined with knowledge of how plant components are connected.

The method is property that components in thermal-hydraulic systems act as sources or sinks of the conserved quantities of mass, energy, and momentum. Then, if a change in the characteristics of a component resulting from a fault is marked by a unique imbalance in the conserved quantities, one has a basis for fault diagnosis. In PRODIAG imbalances in conserved quantities are detected using sensor readings. An imbalance is matched against a priori derived categories of imbalances for the component with each category representing a generic fault for that component. Since the number of component types in a thermal-hydraulic system is limited (for example, valve, tank, compressor, heat exchanger) and there are a limited number of imbalance categories for each component type, there are a relatively small number of possibilities that can account for the observed behaviour of the faulted system.

The reasoning process in PRODIAG uses qualitative physics to relate sensor readings to a fault type in a component. The trends of process variables—increasing, decreasing, or unchanged—identify the category of imbalance and from that the type of fault. A qualitative approach transforms complex time histories of numerical values into a simpler representation. This permits generalization in place of having to consider the fine detail of a sensor signal trace.

The reasoning from process variable symptoms back to identification of fault type is performed in three steps:

1. The **physical rules database** (PRD) maps qualitative trends in process variable values (for example, increasing temperature or decreasing pressure) for a component into imbalance types among the three conservation equations. The imbalance is assumed to arise from abnormal operation resulting from a change in the component (that is, a fault).
2. The **component classification dictionary** (CCD) maps for a particular component type each possible imbalance type and the generic fault that could give rise to the imbalance. For example, a filter exhibiting an increasing trend in momentum loss but no change in mass or energy balance signals a plugged filter.
3. The **piping and instrumentation database** (PIDB) contains, for a process, the components and their interconnections and the sensors and their location with respect to components. It is

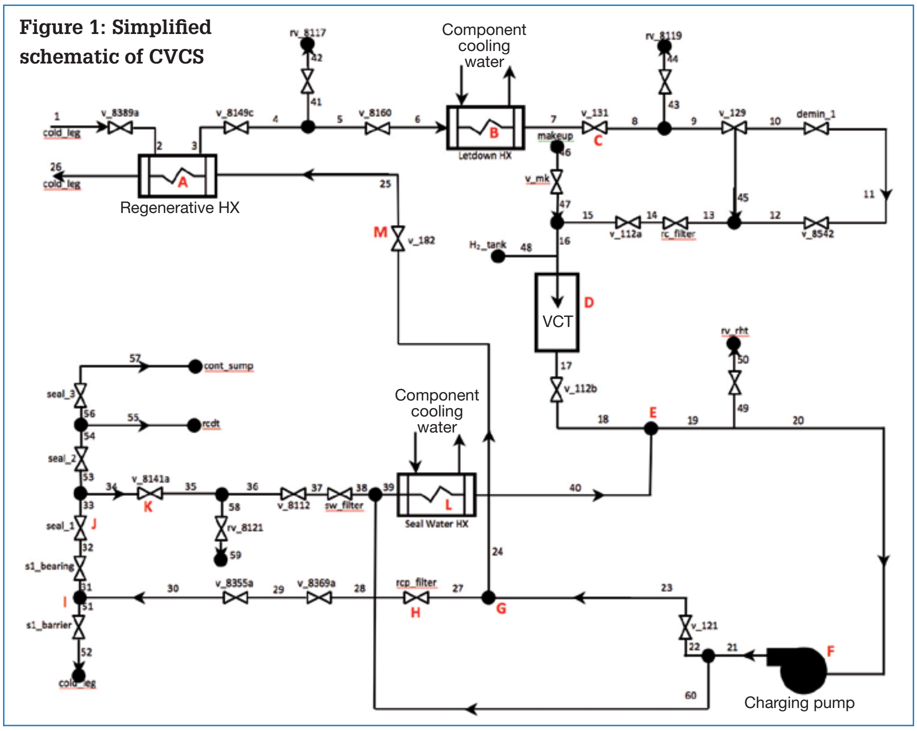


Figure 1: Simplified schematic of CVCS

generated from the Process Piping and Instrumentation Diagram (PID). The PIDB provides process specific information that allows for the PRD rules to be applied component by component. It provides the identity of each component so that the CCD can be used to associate an observed conservation imbalance for a component with a fault in the component.

Because only this third step requires process specific information, the three-step procedure can be implemented in a manner that makes it highly portable across plants.

Recently the implementation of the automated reasoning algorithms and the software methods of PRODIAG were brought up to state-of-the-art standards.

Dynamic simulation models

Models were developed for a typical sensor (resistance temperature detector), heat exchanger (tube and shell and printed circuit), and for an engineered system (PWR chemical and volume control system; see below). Proof-of-principle tests were performed using simulation data generated from these models. The algorithms performed as intended and had the properties predicted by theory.

A one-dimensional systems code model was developed for the chemical and volume control system (CVCS) of a Westinghouse pressurized water reactor (PWR). This model is used to simulate the dynamic response of the CVCS to equipment faults such as heat exchanger leaks, pump failures, seal failures, pressure relief valve leaks and filter blockages. The data generated by the simulation is used to test the AFTR-MSET and PRODIAG algorithms.

The CVCS is designed to provide the following services to the reactor coolant system (RCS):

a. Maintenance of programmed water level in the pressurizer, that is, maintain required level inventory in the RCS
b. Maintenance of seal-water injection flow to the reactor coolant pumps
c. Control of reactor coolant water chemistry conditions, activity level, soluble chemical neutron absorber concentration, and makeup
d. Emergency core cooling (part of the system is shared with emergency core cooling system)
e. Provide means for filling, draining, and pressure testing of the RCS.

A simplified schematic of the CVCS is shown in Figure 1, where several components/subsystems can be identified: regenerative heat exchanger (A), letdown heat exchanger (B), seal water heat exchanger (L), reactor volume control tanks (D), charging pump (F). Other relevant subsystems, such as the reactor coolant purification and chemistry control system, the reactor makeup control system and the boron thermal regeneration system were not explicitly modelled and are simply represented by valves representing the concentrated pressure drops associated to these systems from the point of view of the RCS circulating water.

Demonstration platform

The computer system architecture is centred on the Experimental Physics and Industrial Control System (EPICS) software package. EPICS is a set of software tools and applications for developing distributed control systems. EPICS provides a general treatment of 1) databases for storing process variable values from the different engineering simulation codes, 2) communication channels through which these codes exchange values over the network, and 3) graphical user interfaces (GUI) through which values are displayed and through which operator input is

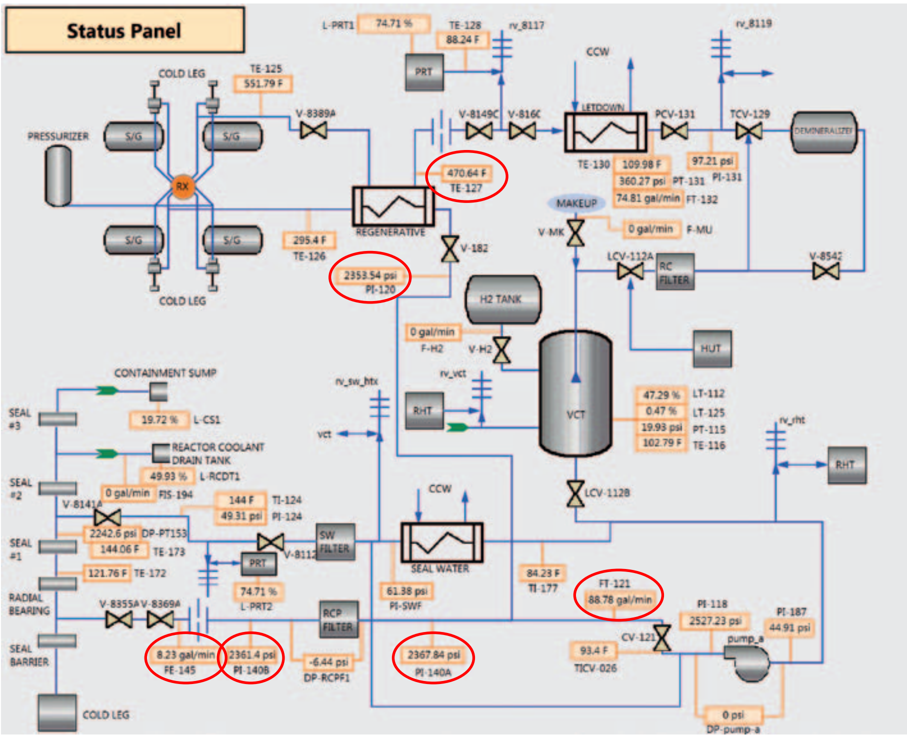


Figure 2: New CSS BOY graphical user interface for the CVCS. Sensors with plots in Fig. 4 circled

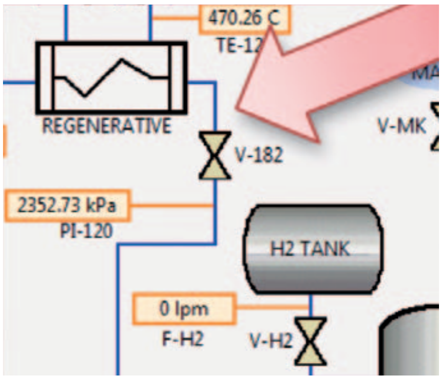


Figure 3: Charging line leak location

accepted.

A visual representation during a fault diagnosis session is provided to the user through a GUI. In the case of fault diagnosis for the CVCS, this takes the form of a schematic of the CVCS, including the display of sensor values as they change throughout the simulation. The current GUI was prepared based on Control System Studio (CSS) framework. Control System Studio is an Eclipse RCP (Rich Client Platform) application. It was originally developed to provide GUI support for the EPICS program. The GUI development package BOY (Best OPI Yet) was used to construct the operator panels. BOY is an operator interface (OPI) editor and runtime graphical user interface that provides for construction graphic representations, and associating the database data. Powerful OPIs can be developed by configuring graphic control panels, connecting to databases, and implementing dynamic rules and scripts.

Significant events that occur throughout the evaluation of PRODIAG will instantiate a response that is viewed through the CSS BOY Graphical User Interface. For example, if there is an issue or a notification connected with pump a shown in Figure 2, then the resulting screen would highlight this component.

A separate bridge program was written that provides inter-process communication with the EPICS database and the plant simulator.

Component fault diagnosis

Verification and validation studies were performed for the new PRODIAG code. This involved re-running the 20 distinct fault cases defined at the time the code was originally developed. These cases involved introducing faults into the CVCS of the simulator of the (PWR) Braidwood Nuclear Power Plant and having PRODIAG operate on the resulting sensor readings. The test data in these 20 cases represent transient conditions for a range of postulated failure conditions in the CVCS.

The results were divided into component failures and piping failures. Of the 15 cases of component failure, in 13 cases the two PRODIAG versions performed the same, and in one case the new system produced a better prediction, and in another case it produced a worse prediction. Of the 12 cases of piping failure, in three cases the two PRODIAG versions performed the same, in three cases the new system performed better and in six cases the new system accurately identified the fault, but to a less precise degree than the old system. (This last result is related to the post-rule processor, which is still undergoing development).

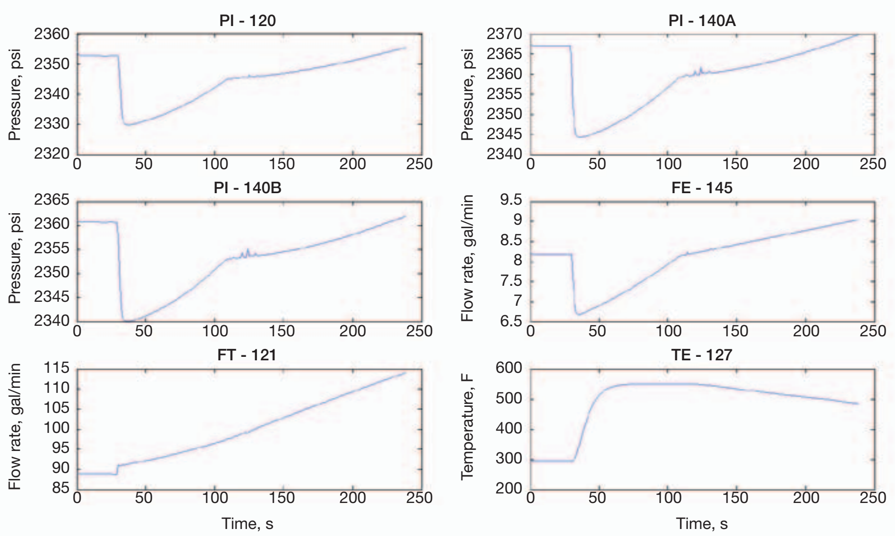
The diagnostic reasoning that underlies PRODIAG is illustrated by considering in greater detail one of the 20 fault cases simulated. The case considered is CV25-45 which involves a charging line leak inside containment located upstream of the regenerative heat exchanger as indicated in Figure 3.

Figure 4 shows the plots versus time of the relevant process variables in response to the fault. One should refer to Figure 2 to view the location of the six (circled) sensors whose readings are plotted in Figure 4. The leak causes an immediate pressure drop in the charging line pressure as sensed by pressure sensors PI-120, PI-140A, and PI-140B. There is as expected an increase mass flow rate upstream of the leak as measured by FT-121. And downstream of the leak there is as expected a decrease in mass flow rate as measured by FE-145. The decrease in flow rate in the regenerative heat exchanger cold side causes an increase in the hot side outlet temperature as measured by TE-127. However, due to thermal inertia, this temperature change is delayed.

The sequence that unfolds as PRODIAG performs its diagnosis is as follows. The diagnosis starts when during the transient the value FE-145 reaches the primary threshold causing the {P,W} time window to open. This causes trends of the other sensor to be set based on the secondary thresholds. Then through exhaustive rules firing, the trends of the unfilled variables are deduced via Q and CV rules, and transport rules. As a result, a pool of candidate diagnostic results is made. Subsequently, post-processing rules are applied to narrow down the most relevant diagnosis. The diagnostic result appears in red in the GUI display and correctly locates the leak to the affected section of piping.

Future work will examine the sensitivity of algorithm performance to parameters such as number and types of sensors, degree of sensor degradation, severity of equipment faults, magnitude of sensor noise, and method improvements. ■

Figure 4: Process variable plots for Case CV25-45



About the authors

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