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Adapting plant measurement data to improve hardware fault detection performance in pressurised water reactors

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ABSTRACT

With the fairly recent adoption of digital control and instrumentation systems in the nuclear industry a lot of research now focus on the development expert fault identification systems. The fault identification systems enable detecting early onset faults of fault causes which allows maintenance planning on the equipment showing signs of deterioration or failure. This includes valve and leaks and small cracks in steam generator tubes usually detected by means of ultrasonic inspection.

Detecting faults early during transient operation in NPPs is problematic due to the absence of a reliable reference to compare plant measurements with during transients. The distributed application of control systems operating independently to keep the plant operating within the safe operating boundaries complicates the problem since the control systems would not only operate to reduce the effect of transient disturbances but fault disturbances as well.

This paper provides a method to adapt the plant measurements that isolates the control actions on the fault and re-introduces it into the measurement data, thereby improving plant diagnostic performance.

1. Introduction

All online plant diagnostic approaches rely on the availability of a reference to compare the measured plant output to. With the use of plant training simulators in the nuclear industry since the 1980s and the continual improvement of computational speed and mathematical modelling methods, with increasing processing speed and improving model accuracies a full scope engineering simulator running in real time becomes the ideal reference to indicate faulty plant behaviour and degradation of plant hardware.

With this availability and advances in nuclear power plant simulation technology, a research project was initiated to make use of simulators to provide a deterministic dynamic reference for in-transient fault detection (Cilliers et al., 2011).

The primary objectives of the research were to:

1. Develop an early fault detection system by using real time simulators of nuclear power plants, continuously monitoring and comparing simulated measurement data and control outputs of the model reference adaptive control negative feedback system with the actual measured data and control outputs from the plant. The fault detection system should detect small faults that would normally go undetected as well as detect faults during plant operating transients.
2. Develop a fault characterisation method, making use of measured and simulated data together with the actual and simulated control system response. The fault characterisation system should provide information on the magnitude and location of the fault.
3. Develop a control and protection framework that allows NPP licensing within the existing licensing framework, but is still able to uncover the benefits of expert control and protection systems.

This paper introduces a section of the first objective, with following papers presenting the second and third objectives.

Petersen and McFarlane (2004) define the requirements for process fault detection and diagnosis as the following:

- the availability of well defined, accurate first principles models (with any modelling errors also suitably represented),
- clearly identified fault modes and models to represent these, and
- appropriately located sensors (often with levels of redundancy).

We have found these requirements to also be generic requirements applicable to the fault identification system developed as part of this research.

Plant diagnostics in the Instrumentation and Control discipline has been researched and developed over the last 40 years with various methods of providing dynamic reference models. In 1976, Willsky (1976) examined statistical techniques for the detection

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of failures in dynamic systems revealing key concepts, similarities and differences in problem formulations, system structures, and performance. Specifically, they discussed the problem of detecting abrupt changes in dynamic systems.

Chen and Howell (2001) notes that statistical and learning methods are fast and do not require a plant model, but are comparatively brittle because they cannot handle situations that are not explicitly anticipated. The 'brittleness' referred to makes the implementation of heuristic methods particularly problematic in the nuclear industry where deterministic proof of system dependability is required.

Simani and Fantuzzi (2000) notes that Fault Detection Systems have been widely developed during recent years with model-based methods, fault tree approaches and pattern recognition techniques amongst the most common methodologies utilised in such tasks with neural networks used in Fault detection problems for model approximation and pattern recognition.

Iserman (2004) presented an introduction into the fault detection field by describing how model-based methods of fault detection were developed by using input and output signals and applying dynamic process models. These methods are based on amongst others, parameter estimation, parity equations or state observers. Also signal model approaches were developed with goal is to generate several symptoms indicating the difference between nominal and faulty status. Based on different symptoms fault diagnosis procedures follow, determining the fault by applying classification or inference methods.

The development of steady state Fault Detection Systems making use of the steady state references to detect control operation deviations in the nuclear industry has been done since 2000 with Chen and Howell (2001) commenting:

> Little has been written about distributing diagnostic tasks presumably because traditionally, the diagnostic engineer's view of feedback control is that it complicates, rather than aids, diagnostic reasoning. Feedback control adds to the complexity of fault detection in process plants by masking measurement deviations that might indicate a fault.

Also, Hamelin and Sauter (2000) realised that most of the developed algorithms make many idealised assumptions such as steady state conditions which are very often not satisfied, since in reality the system parameters may either be uncertain or time dependent, resulting in a mismatch between the actual system and the associated mathematical model used for reference. They state that even though the problem of uncertain parameters is of crucial importance to the industrial implementation of fault detection methods, it has however received little attention with only a handful of works so far devoted to it. Hamelin and Sauter (2000) also state that future developments should concern the incorporation of the proposed approach into a closed-loop system stating that: "Clearly, in a closed-loop system, the controller gain will also have an effect on the residual output."

This fault masking effect is compounded during expected plant transients when the various control systems are operating to the return the plant to steady state. The fault masking effect of the control system prevents makes plant diagnostics very difficult when small slow acting faults occur.

To address the fault masking effect of the feedback control system, not only are the measurements and simulated measurements compared, but also the simulated and actual control operations. With the primary objective being to improve plant performance and fault detection dependability, a secondary benefit was achieved when early onset faults are detected while the control system manages to mask the fault completely. These faults often take a long time to develop large enough for conventional plant protection systems to detect the fault condition.

The benefits from detecting early onset faults are the ability to execute online maintenance on the affective systems when possible or plan maintenance on these systems during outages. This results in increased uptimes as well as the reduction of efficiency losses due to faults.

This was also used by Roy et al. (1998) who developed a fault characterisation system to address the need to have improved predictive maintenance techniques in an operating plant. Guidance into the methodology came from one of the earliest applications of state estimation based fault detection methods in nuclear plants. Roy et al.'s (1998) primary objective was to provide an early warning to the human operator regarding the failing health of control equipment, in the process averting major breakdown with its associated large plant downtime.

2. Fault masking by the control system

It is important to keep in mind that the purpose of the control system is to control the output of the nuclear plant, thus continuously providing control variables to steer the plant to reach the reference value. The only reasonable method of control in nuclear plants is closed-loop negative feedback control as opposed to an open-loop system as depicted in Fig. 1. The closed-loop is depicted in Fig. 2 using a block diagram. A block diagram representation of the system relationships is prevalent in control system engineering. The control diagrams are analysed in the 's' domain, this allows analysing steady state and transient conditions in state-change domain, rather than the time domain. This is used to model linear time-invariant systems and responses as a function of the input and output (transfer function) of the system.

The closed-loop control system compares output values with a reference. This reference indicates a desired value, and the difference between the reference and measured values is used to set the control variable. This is not done to raise alarms or identify faults; in fact, the difference between the reference and the measured value is expected, since the reference value is set to the value the operator wants the plant to reach.

With:

- $R(s)$ representing the reference the output is compared to,
- $C_p(s)$ representing the control system,
- $P_p(s)$ representing the plant,
- $S_p(s)$ representing the sensor or measurement equipment, and
- $E_p(s)$ represents the error between the reference value and the output from the measurement equipment.

In the case of the Model Reference Adaptive Control (MRAC) system introduced by Whitaker in 1958, the plant is controlled to follow a reference model provided by a lookup table. The reference value $R(s)$ would change to allow various plant conditions. In many cases, such a variable reference is used with the reference value sourced from a lookup table, as in the case of a typical Generation II PWR we consider in this research. When the reference is changed the control system should follow to produce an output as close as possible to the reference. Analysing the feedback control loop confirms this:

$$E_p(s) = R(s) - S_p(s)Y_p(s) \tag{1}$$

and

$$Y_p(s) = C_p(s)P_p(s)E_p(s) \tag{2}$$

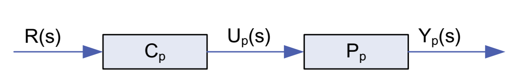

Fig. 1. Open- loop system.