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Correlating hardware fault detection information from distributed control systems to isolate and diagnose a fault in pressurised water reactors

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ABSTRACT

Early fault identification systems enable detecting and diagnosing early onset faults or fault causes which allow 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.

We have shown (Cilliers and Mulder, 2012) that detecting faults early during transient operation in NPPs is possible when coupled with a reliable reference to compare plant measurements with during transients. The problem introduced by the distributed application of control systems operating independently to keep the plant operating within the safe operating boundaries was solved by re-introducing the fault information it into the measurement data, thereby improving plant diagnostic performance.

This paper introduces the use of improved fault detection information received from all distributed systems in the plant control system and correlating the information to not only detect the fault but also to diagnose it based on the location and magnitude of the fault cause.

1. Introduction

With the 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; Cilliers and Mulder, 2012).

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 the second objective, with a following paper presenting the third.

Owing to the use of distributed control systems in nuclear plants, the same fault will affect a number of plant measurements during which the affected control systems will operate to counteract the effect of the fault on the system. The plant diagnostic system re-introduces this fault effect into the relevant measurement information (Cilliers and Mulder, 2012). As a result, the fault is detected early in more than one system, each system revealing something about the nature and possible cause of the fault.

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

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".

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We have shown that the fault masking problem described here can be overcome by re-introducing the fault information into the measurement data in an open loop (Cilliers and Mulder, 2012). The use of distributed diagnostics now becomes possible.

Once a fault is detected in a system, a trip can be initiated to shut the plant down and to keep it safe, whilst being able to characterise the detected fault to assist in repairing the plant. The characterisation of a fault could vary from indicating the sub-system in which the fault is located, to indicating the magnitude and spatial location of the fault.

Roy et al. (1998) 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's 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. Further, an attempt was made to identify subcomponent faults, so as to carry out fault event sequencing and root cause analysis. They state that most fault detection and characterisation algorithms proposed up to 2000 have been essentially limited to the detection and identification of global faults in a system and so, a further step to this would be to develop fault identification methods for identifying subcomponent faults in equipment, resulting in improved fault localisation and providing better predictive maintenance aids.

The method used by Roy et al. (1998) is shown to be very effective to characterise faults although still being limited to only being able to identify faults during steady state conditions. The fault identification system developed in this research aims to detect and characterise faults during transient or operational mode change conditions when a plant tends to be exposed to higher stresses than under steady state conditions.

In other research Cheon et al. (1993) made use of neural networks to process alarms to aid in the diagnosis of nuclear power plants, while a lot of work has been done to detect and locate faulty sensors in plants, such as the work done by Dorr et al. (2007) and Ming et al. (2006). The research in this paper does not intend to detect faulty sensors although it could potentially aid in locating such faults.

As recently as 2008, Yan et al. (2008) developed a distributed fault identification system with the objective to address problems arising from the models that typically exhibit complex nonlinearity and compensates for the effects of the faults on the residuals that are hidden owing to noise, both of which can prevent an deterministic solution. The noise referred to in this case can also be equivalent to disturbances due to operational mode changes which makes this method come close to identifying faults during transient states of the plant although this is not shown.

To realise the proposed system Yan et al. (2008) made use of a fault tracking approximator to detect and identify system faults. A network of distributed estimators is constructed where the fault tracking approximator based on an iterative learning algorithm is embedded into each estimator. Compared with a neural network-based fault identification scheme, the approach proved to be more efficient although still based on approximation schemes that are very difficult to license in the nuclear industry.

Similar to Yan et al. (2008) approach, Hadad et al. (2008) used neural networks to detect and characterise faults occurring in the Russian VVER pressurised water reactor. Ming et al. (2006) made use of a hybrid approach to diagnose faults with neural networks. Ferrari et al. (2008) designed a fault isolation scheme in an input–output discrete-time framework and derived detectability and characterising properties making is of analytical methods.

In 2010 Villez et al. (2010) initiated a project to integrate diverse fault detection systems and automation into closed loop supervisory control systems to reduce the human interaction when a fault is detected. The integration approach in their research requires new control paradigms to be created which would make the nuclear licensing of the new systems difficult.

In the chemical process industry, Chilin et al. (2010, 2012) focuses their research on monitoring and reconfiguration of distributed model predictive control systems. Here the focus is not to detect and isolate faults, but rather to adapt the distributed control parameters of the control systems to maintain system stability when actuator faults occur.

Also in the process control industry a similar approach to this research was taken by Frank and Ding (1997) with the aim to research and design a residual generator that eliminates effect of process input signals and other disturbances, evaluate the results and where elimination of process input signals and disturbances are not fully possible, to optimise the process to achieve approximate results. In this case the reference model is created by estimating outputs of the process. The evaluation of the results is done by fuzzy logic. Similar work was also surveyed by Frank (1990). Although this research provides clear guidance to the problem at hand as well as the methodology to approach the problem, the nature of the nuclear industry requires that deterministic systems are used in both the reference model as well as the evaluation of the results.

The nuclear industry is in a unique situation in having access to first principle simulation models, developed and improved over the last 30 years that can be used as a reliable reference model in fault detection systems.

The system described in this research is deterministic in nature and makes use of conventional nuclear plant protection philosophies. This results in pragmatic fault identification system that can easily be adopted into any existing or new nuclear power plant protection approach.

1.1. Fault characterisation

For fault characterisation, it is possible to combine the isolated fault information from various measurements inside the plant and to correlate this information with various typical plant faults. This would identify the fault with an increasing level of certainty as the fault effects unfold over time and this information becomes available to the real-time system. The system does this in the following sequence:

1. The system detects that various control systems are behaving unexpectedly (Cilliers and Mulder, 2012).
2. The fault effect is reintroduced into the measurement data of each affected control system (Cilliers and Mulder, 2012).
3. The adapted measurements drift away from the expected measurements beyond the conventional trip set point and a fault is detected (Cilliers and Mulder, 2012).
4. The unexpected behaviour is characterised by matching the behaviour with the known behaviour of certain fault categories.
5. The fault is characterised further, as the behaviour trend is identified.
6. The location of the fault is found by combining the measurement equipment that indicated the fault with the location and cause becoming more accurate as the fault is detected in other subsystems.
7. The magnitude of the fault is calculated from the magnitude of the variation from the expected transient.

The first three stages deals with detecting a fault condition early while the operating point has not yet shown any movement due to the fault condition as described by Cilliers and Mulder (2012). The following stages deals with fault characterisation or fault diagno-