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Design of comprehensive diagnosis system in nuclear power plant

Wei Li, Min-jun Peng *, Ming Yang, Geng-lei Xia, Hang Wang, Nan Jiang, Zhan-guo Ma

Fundamental Science on Nuclear Safety and Simulation Technology Laboratory, Harbin Engineering University, Harbin, China

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ABSTRACT

Safe operation of a nuclear power plant (NPP) is affected by the following two main factors in addition to the human factors in practice: one is the instruments, namely the condition of the sensors; the other is the systems and components. In this paper, a comprehensive diagnosis system (CDS) for NPP is developed based on these two factors. Thus the developed CDS mainly consists of two continuous parts: firstly it is the monitoring of sensors, and then it is the diagnosis of components and subsystems in a NPP. Based on the verified measurements of sensors, the monitoring results of components and subsystems can be guaranteed. Auto-associative kernel regression (AAKR) and sequential probability ratio test (SPRT) are combined to monitor the condition of sensors. If anomaly is detected, it is to reconstruct the measurements of faulty sensors, and the verified measurements are transmitted to the following step of CDS: the diagnosis of components and subsystems. A qualitative analysis method is applied in the diagnosis of components and subsystems based on the verified sensor measurements. Simulations of fault detection and identification on the sensors and components in reactor coolant system of Qinshan NPP are carried out, and the results demonstrate the effectiveness of the proposed CDS.

1. Introduction

With the increasing requirements for safety and economy in a nuclear power plant (NPP), operation support system (OSS) has been one of the focus researching fields in nuclear industries. Some international companies involved in nuclear power such as Westinghouse Corporation, Mitsubishi, General Electric Company etc. all have proposed research projects on the new generation of OSS (Ma and Jiang, 2011). Condition monitoring and fault diagnosis, namely the known fault detection and diagnosis (FDD) are important parts of OSS in a NPP. Compared with conventional fossil power industries whose main cost concentrate on the fuel cost, over 70% of the cost in a NPP is on the operation and maintenance (Hashemian, 2011). Thus one objective of the OSS in a NPP is to reduce the operation and maintenance cost.

The performance of instruments in a NPP may degrade over time, leading to problems such as drift and bias (Hashemian, 2004). Thus, instruments have to be calibrated periodically which often needs to shutdown the system or takes the instruments out of service. However, experience shows that less than 5% of conventional calibrations are even necessary (Hines and Seibert, 2006). Not only do the unnecessary calibrations decrease the economy obviously, but also the reliability of an instrument may be adversely affected by manual periodic maintenance. Therefore, a condition-based maintenance (CBM) schedule is proposed. In order to achieve CBM, online monitoring of sensors is required. Meanwhile, the operating condition of systems and components is also of significant of importance to the safe and economic operation of a NPP. If a fault in systems or components can be detected at the early stage, then the FDD system can prevent the faulty event developing into an accident. Thus FDD system used in a NPP can not only help on the sensor calibrations, but also can detect the failures in systems and components at the early stage. As a result, both the reliability and economy of a NPP can be enhanced with the application of FDD system (Richard et al., 1997).

The methods used for FDD in the literature can be classified into three categories: analytical model-based methods, qualitative model-based methods, and data-driven methods (Farhan et al., 2016). The analytical model-based methods usually require a mathematical model to represent the behavior of the concerned system, and FDD process is implemented by checking the consistency between the measured behavior and the model predicted behavior. If the residuals are nonzero values, it is indicated that some failures have occurred in the monitored system (Abid, 2010; Isermann, 2006). And in order to obtain better isolation of faults, some special models have been designed to magnify the residuals (Li and Shah, 2002; Li and Jiang, 2004). In practice, the application of the analytical model-based methods are very limited

* Corresponding author.
E-mail addresses: success870323@126.com (W. Li), heupmj@163.com (M.-j. Peng).

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due to the precise mathematical models are usually difficult to develop for a complex system. In contrast, data-driven methods are more suitable to implement FDD in a comprehensive industrial system from this perspective. Since when FDD process is carried out, only operating sensor measurements from the monitored system are required without going into the details of the system. Residuals are generated between the actual measurements and the predicted values by the data-driven model, and statistical test is then implemented on the residuals to execute FDD. In the past few decades, a lot of work has been done on this kind of method, mainly consist of artificial neural network (ANN), support vector machines (SVM), partial least squares (PLS), principal component analysis (PCA), multivariate state estimation technique (MSET), auto-associative kernel regression (AAKR), Fisher discriminant analysis (FDA) and their variants (Santosh et al., 2009; Garvey and Hines, 2006; Farhan et al., 2016; Upadhyaya et al., 2003; Ding, 2014). In qualitative model-based methods, a qualitative relationship is applied to represent the behavior of the monitored system which is different from the quantitative computation in an analytical model-based method. Thus compared with analytical model-based method, it is representative of the convenient implementation. In the literature, Fuzzy logic, expert systems, genetic algorithms and signed directed graph (SDG) are the common used qualitative model-based methods.

Comparing the foregoing three categories of FDD methods, data-driven and qualitative model-based methods are commonly used in process industries due to their great maneuverability and practicability (Ma and Jiang, 2011). A lot of studies involved in the applications of data-driven and qualitative techniques in various industries have been done in the literature. Similarly, these techniques are also investigated in nuclear industries because of their advantages. Tang adopted qualitative analysis to diagnosis the component faults in high temperature gas-cooled reactor (Tang et al., 2006). A multilevel flow model (MFM) was developed to implement alarm analysis and fault diagnosis for the systems and components in a NPP by Yang (Yang et al., 2011). SDG method was combined with expert system by Wu, and the developed diagnosis system was applied to the fault detection and identification of a typical failure in a NPP (Wu, 2016). MSET and ANN methods have been combined in the SmartSignal system which was developed by the General Electric Co. to implement FDD processes for instruments in a NPP (SmartSignal, 2010). A process evaluation and analysis system called PEANO was developed on the basis of Halden project, and it was used for online monitoring of sensors in a NPP (Fantoni, 2005).

In the previous work, it can be seen that most of FDD methods proposed by the researchers either are applied only to the sensors or only to the components and systems in a NPP. However as we all know, the safe operation of a NPP is not only affected by the condition of sensors, but also affected by the condition of components and subsystems in the NPP. Thus, one contribution of the paper is the proposal of a comprehensive diagnosis system (CDS) for a NPP which does not only include the FDD of sensors, but also the FDD of components and subsystems in a NPP is covered.

The mentioned advantages of data-driven and qualitative methods are also suitable for the implementation of FDD processes in a NPP. Meanwhile, the disadvantages of analytical model-based methods are also existed in the nuclear industries, since the NPP is quite a large and complex system that there are enormous difficulties to build its mathematical models for sensors, components and subsystems. On the other hand, with the wide application of I&C system in a NPP, more and more sensors are applied and more operating information can be conveniently obtained. In this context, it is very beneficial to adopt data-driven methods to implement FDD for sensors. A study conducted by Hines et al. concluded that the simplicity of data-driven techniques and the tractability of their uncertainty calculations could favor them for acceptance by regulatory bodies (Hines et al.). Because of this reason, auto-associative kernel regression (AAKR) method is adopted for sensor FDD according to its relative simplicity and individual strong points in this paper. Meanwhile considering the black-box model and the non-explanation of data-driven methods, a qualitative analysis method which is based on the qualitative conservation equations of the subsystems in a NPP is applied to the FDD of components and subsystems in this paper. It is because the interpretability of the FDD results for components and subsystems is much required than that for sensors in a NPP. And in this way, a monitoring result which is explicable can be made by the FDD system before any actions are taken by the NPP operators. Thus another contribution of this paper is the combined application of data-driven and qualitative techniques for the FDD of sensors, components and subsystems in a NPP.

Thus, in the proposed CDS in this paper, AAKR based on data-driven methods is used to carry out the FDD for sensors, and the residuals generated by AAKR model are analyzed by the sequential probability ratio test (SPRT); a qualitative analysis method is applied to the FDD of components and subsystems in a NPP. In this way, sensor measurements are verified firstly and then the guaranteed measurements are conveyed to the next step of CDS: the FDD of components and subsystems in a NPP. As a result, not only are the condition of sensors realized on-line monitoring, but also the influence of faulty sensors to the subsequent FDD of subsystems and components are eliminated. Only in this way, the proposed CDS can be called a complete diagnosis system for a NPP.

The paper is organized as follows. Section 2 describes the proposed CDS in this paper which includes the condition monitoring of sensors based on AAKR method as well as the FDD of components and subsystems based on a qualitative analysis method in a NPP. Section 3 shows the simulation results of the proposed CDS in Qinshan NPP, the FDD procedures of sensors, components and subsystems with proposed CDS are demonstrated in the reactor coolant system (RCS) of Qinshan NPP. A brief summary and discussion are given in the last section.

2. Design of the CDS in a NPP

As described previously, the proposed CDS consists of two parts since the failures in sensors and components may influence each other when it comes to the fault diagnosis of a NPP. Firstly it is the condition monitoring of sensors. If any anomaly is detected in a sensor, it is required to reconstruct the measurements of a faulty sensor. Then the reconstructed values are used to the diagnosis of components and subsystems in the NPP. And only in this way can the following diagnosis results for subsystems and components be guaranteed. The specific procedures of CDS are described as follows.

2.1. Condition monitoring of sensors

The operating condition of sensors are affected by a variety of factors, meanwhile the failure types of sensors are also various. Usually the sensor failures can be classified into the following categories based on the failure symptoms: fixed deviation, drift, accuracy decline and complete failure (Andre, 2012). The first step of FDD for sensors is to separate the monitored sensors into different groups in accordance with the subsystem where the sensors work. For instance we can select all sensors in chemical and volume control system (CVCS) as a group and all sensors in component cooling water system (CCWS) as another group. Different monitoring models for different sensor groups are developed respectively. And all these condition monitoring models are running in parallel to