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Fault diagnosis of Pakistan Research Reactor-2 with data-driven techniques

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ABSTRACT

In nuclear reactors, safety is of prime importance in their operation. Fault detection and isolation (FDI) methods are making their applications to improve safety, reliability and availability of nuclear reactors. Among various FDI techniques, data-driven techniques are best suited for fault diagnosis of nuclear reactors because process data is available to sensors, both in normal operation and under faulty conditions. Among data-driven techniques, principle component analysis (PCA) and Fisher discriminant analysis (FDA) have been successfully applied to many industrial processes. In this paper, PCA and FDA are applied for fault detection and fault isolation in Pakistan Research Reactor-2 (PARR-2) for known faults of control rod withdrawal and external reactivity insertion. PCA model is developed using training data set obtained during normal operation of PARR-2. It is then applied to test data set collected from the reactor during control rod withdrawal fault and external reactivity insertion fault. Likewise, FDA model is constructed for the above mentioned faults using the training data set and applied to the test data for fault isolation. The results demonstrate that PCA is successful in detection of both the faults. Additionally, FDA not only detects faults, but it is also successful in isolation/localization of the two faults in PARR-2.

1. Introduction

With depletion in conventional energy resources, scientists and engineers are looking for alternate energy resources. Among these, nuclear energy has become a major contributor at 10.9 percent, fourth behind coal at 40.4 percent, natural gas at 22.5 percent, and hydro-power at 16.2 percent worldwide (International Energy Agency, 2014). Nuclear energy is not only cheap but also environment friendly. Compared to conventional energy resources, where major cost in energy production is fuel cost, in nuclear energy 73 percent of cost is incurred on operation and maintenance (Hashemian, 2011). It has been shown that the operation and maintenance cost, and therefore the per unit energy cost, can be significantly reduced by introducing modern fault diagnosis methods to the nuclear power plants. In addition to economics, safety of nuclear reactors is of utmost importance. The safety and reliability of nuclear reactor got national concern during the Three Mile Island incident of 1979 (Zhao, 2005). During that incident, operators were faced with a large number of alarms coupled with conflicting indications. The operators were unable to recognize and prioritize the alarms and indications efficiently, thus complicating the recovery procedures. So, this has drawn the attention of researchers towards the development of fault diagnosis methods for safe and reliable operation of nuclear reactors (Park and Seong, 2002; Bartlett and Uhrig, 1992; Ohga and Seki, 1993).

The classical approach used for fault diagnosis in nuclear reactors is by hardware redundancy, that is, multiple sensors are utilized to measure the same quantity and a voting scheme gives the information of faulty sensor. However, hardware redundancy can not be added to other components of nuclear reactor. Therefore, to detect faults in these components, limit checking is performed, the measurements are monitored to see if these are within pre-defined limits, in case the measurements exceed the bounds, that implies the presence of some fault. Limit checking technique has the disadvantage that fault is only detected if it grows enough to cause some variable to exceed its bound. This disadvantage may be overcome by incorporating modern and more advanced fault diagnosis techniques which are based on software/analytical redundancy. In many industrial processes, the hardware redundancy is replaced by analytical redundancy which not only increases efficiency of fault diagnosis scheme but also reduces the cost. However, for safety critical processes, like nuclear reactors, software redundancy based fault diagnosis techniques should

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be used in complementary with hardware redundancy based techniques.

Major and well-established software redundancy methods that are used for fault detection and isolation (FDI) include analytical model-based, knowledge-based and data driven techniques. In analytical-model based technique, a mathematical model is obtained, usually by using the first principles, to represent normal behavior of system to be monitored. A residual is then generated by comparing observed behavior of actual system with the predicted behavior from the mathematical model. A nonzero residual signal gives the information about occurrence of fault(s) in the system (Abid, 2010). These techniques are only applicable to small systems which can be accurately modeled. In knowledge-based techniques, model is constructed from qualitative information about the system. Like, analytical model-based techniques, knowledge-based FDI techniques have limited applications to large industrial systems because extensive information is required to construct qualitative model which is cumbersome (Chiang et al., 2001). In contrast, data-driven techniques are more convenient and efficient because there we have to monitor the input–output information from sensors without going into details of the system. Therefore, data-driven techniques are well suited for fault diagnosis of large industrial systems. Among the most studied data driven methods are artificial neural networks (ANN), genetic algorithms (GA), multivariate statistical techniques including support vector machines (SVM), principle component analysis (PCA) and Fisher discriminant analysis (Elshenawy et al., 2009; Isermann, 2006; Chiang et al., 2001; Ding et al., 2014).

Although, a lot of work has been carried out for fault diagnosis of many industrial processes, including aerospace industry, chemical industry, automobile industry, etc., and modern fault diagnosis techniques are successfully applied (see, for example, Isermann (2011), Liu et al. (2014), and Schwung et al. (2015)), only a little attention has been paid to diagnosis of nuclear reactors. There are only a few manuscripts addressing the application of modern fault diagnosis techniques for nuclear reactor. Since it is hard to obtain a detailed and accurate model for nuclear power systems, a limited number of publications are available on model-based FDI for nuclear reactors (Ablay and Aldemir, 2013; Pang and Xia, 2014; Singer et al., 1997). Data-driven techniques are more suitable for fault diagnosis of nuclear reactors because heavy instrumentation is there to obtain input–output data. There are a few articles addressing the application of data-driven techniques for monitoring of nuclear reactors. Artificial neural networks (ANN) are applied for detection of a total instantaneous blockage fault of a sodium-cooled fast reactor in Martinez-Martinez et al. (2015) and to propose accident diagnosis advisory system for nuclear power plants in Lee et al. (2005). Distributed fault diagnosis system in nuclear power plants, based on fuzzy neural network and data fusion, is proposed in Yong-kuo et al. (2013) and its efficiency is improved in Liu et al. (2014). Three types of sensor fault signals were simulated using modified ensemble empirical mode decomposition and probabilistic neural network in Yu et al. (2015). Application of genetic algorithms for fault diagnosis of nuclear power plants is proposed in Yangping et al. (2000), the simulations are carried out on nuclear power plant simulator data to detect several faults by observing 62 sensors. Detection of sensor faults and component faults in nuclear power plants using SVM is presented in Zavaljevski and Gross (2000) and Liu et al., 2013). Application of PCA is applied to detect faults in nuclear power plants is studied in Dunia et al. (1996), Upadhyaya et al. (2003), Kaistha and Upadhyaya (2001), and Lu and Upadhyaya (2005). A comprehensive study of these approaches with relevance to nuclear power plants is presented in review paper (Ma and Jiang, 2011).

The contribution of this paper is application of data driven techniques for fault diagnosis of Pakistan Research Reactor-2 (PARR-2) which is a low power miniature neutron source research reactor. Detailed study is carried out to analyze possible faults in PARR-2. Real data is collected from available sensors in the reactor and two most commonly studied data driven techniques, that is, principle component analysis (PCA) and Fisher discriminant analysis (FDA) are applied for fault diagnosis of the reactor. Control rod (CR) withdrawal fault and external reactivity (ER) insertion fault are successfully detected by PCA. Furthermore, Fisher discriminant analysis (FDA) is successfully applied to detect and isolate the above mentioned faults in PARR-2. A very important feature of this manuscript is that fault diagnosis techniques are applied to data collected directly from PARR-2, compared to many other papers which are either based on simulations or on data collected from reactor simulators.

The paper is organized as follows. Section 2 describes Pakistan Research Reactor-2 (PARR-2), its characteristics and possible faults that may occur in the reactor. Review of FDI methods including analytical model-based approach, knowledge-based and data driven approach with particular focus on principle component analysis (PCA) and Fisher discriminant analysis (FDA) is presented in Section 3. In Section 4, PCA and FDA techniques are applied for fault diagnosis of PARR-2 and results are discussed. Section 5 presents a brief summary and concluding remarks for the paper.

2. Pakistan Research Reactor-2

Pakistan Research Reactor-2 (PARR-2) is a low power (30 kW) miniature neutron source reactor (MNSR), tank-in-pool type research facility. It is cooled, moderated and shielded by demineralized light water. The core is surrounded by beryllium (Be) reflector in order to minimize neutron leakage. It uses ninety percent enriched U-235 based fuel. It has 344 fuel rods and one central oval shaped rod made of cadmium which serves the purpose of control rod. The core is enclosed in aluminum vessel suspended in an underground pool as shown in Fig. 1. Long term reactivity compensation is achieved by increasing the thickness of top beryllium reflector. Reactor has ten irradiation sites, five of which are present inside the beryllium annulus while the others surround the reactor. These sites are assessed through pneumatic sample transfer tubes. Fission heat generated in the core is first removed by natural convection and then transferred to pool water, which serves as heat sink (Bokhari and Pervez, 2010; Mahmood et al., 2008).

The reactor has inherent safe characteristics of under moderated core array and low excess reactivity. Under-moderated design feature leads to negative temperature coefficient of reactivity, that is, reactivity decreases with increase in temperature (Iqbal et al.,

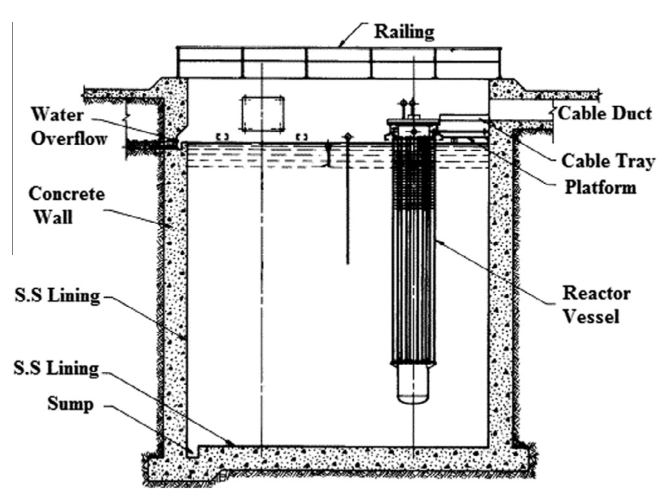

Fig. 1. PARR-2 core suspended in an underground pool (Iqbal et al., 2002).