Progress in Nuclear Energy 105 (2018) 42–50

Contents lists available at ScienceDirect

Progress in Nuclear Energy

journal homepage: www.elsevier.com/locate/pnucene

Knowledge base operator support system for nuclear power plant fault diagnosis

Abiodun Ayodeji[a,b], Yong-kuo Liu[a,*], Hong Xia[a]

[a] Fundamental Science on Nuclear Safety and Simulation Technology Laboratory, Harbin Engineering University, Harbin, Heilongjiang 150001, China
[b] Nuclear Power Plant Development Directorate, Nigeria Atomic Energy Commission, Abuja, Nigeria

ARTICLE INFO

Keywords:
Fault diagnosis
Recurrent neural network
Operator support system
Nuclear power plant

ABSTRACT

A high-tech, high-performance system such as the nuclear power plant needs a wide range of support for operators to efficiently operate the plant, interpret and manage the volume of information available, and detect and diagnose fault in a timely manner. Increasingly, application of artificial neural networks and its variants for fault detection and isolation has moved from toy examples to real-world systems. However, different network architectures respond to different data set in different ways, and the complex, dynamic, high background noise, overlapping patterns and non-linear characteristics of Nuclear Power Plants (NPP) requires a careful selection of a suitable neural network architecture that reflects these traits. This work presents a pilot scheme towards the development of a comprehensive knowledge base for the operator support system of the Chinese Qinshan II NPP, using Principal Component Analysis (PCA) and artificial neural networks. In this work, we utilize the PCA method for noise filtering in the pre-diagnostic stage, and evaluate the predictive/regression capability of two different recurrent neural networks – The Elman neural network and the Radial Basis Network – on a representative data from Qinshan II NPP. The process was validated using data from different fault scenarios simulated on a desktop Pressurized Water Reactor simulator, and the fault signatures were used as the input. The predictive outputs required are the location and sizes of the faults. The result shows that the Radial Basis network gives better prediction and diagnoses the faults faster than Elman neural network. Some of the important diagnostic results obtained from the networks are presented in this paper, and they serve as the pilot study for the development of knowledge base for the computerized NPP operator support system.

1. Introduction

In nuclear installations, Fault Detection and Isolation (FDI) and preventive maintenance are very important tasks. These tasks are important for several reasons: the release of even insignificant amount of radioactive material from the site can lead to not only economic and environmental impact, but also a substantive damage in goodwill and public confidence concerning the safe operation of the plant. Besides, the trans-boundary effect of negative public opinion in the event of a major release of radioactive material in a plant –such as in the case of Fukushima - could result in retrogressions in the nuclear industry.

Operator Support Systems (OSS) plays a crucial role in assisting operators in decision making during abnormal transient and process disturbances, by actively displaying the status of the plant and recording events, time of occurrence and suggesting relevant actions. It presents necessary and sufficient information on time to the plant operator to take appropriate actions to mitigate abnormal situations (Santosh et al., 2003). However, a knowledge base is a fundamental necessity to the development of an effective OSS to assist operators in problem-solving, learning, decision making, forecasting, and maintenance planning, and in generating feasible options for actions. In addition, the peculiar nature of NPPs and the volume of information available to the operator demand an extensive knowledge base with considerable breadth and depth. Hence, developing a knowledge base for OSS would assist the plant operators to diagnose fault quicker and take mission critical decision on time for continuing safe operation of the plant. A considerable number of research have gone into computerized support systems which act in advisory role for nuclear plant operators (Boring et al., 2015, Thomas et al., 2013). Thomas et al. (2013), details the fault management capability of the existing operator advisory system and their limitations, and the knowledge-based functions required from an operator such as estimating the type, location and size of cracks based on available plant information. To further aid the cognitive activities of operators, Yoshikawa and Zhang (2014) proposes a quantitative and qualitative approach to evaluate the cognitive information flows in nuclear plant diagnosis tasks. However,

* Corresponding author.
E-mail address: lyk08@126.com (Y.-k. Liu).

https://doi.org/10.1016/j.pnucene.2017.12.013
Received 6 June 2017; Received in revised form 22 November 2017; Accepted 26 December 2017
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some of these approaches does not possess the flexibility of data–driven method, and have no proposed suggestions on practical application in a real plant.

FDI, as applied in NPP has many facets. One of the most important facets is the early detection of small, incipient faults in plant's components and during transients. The classical first principle, fault diagnosis approaches for nonlinear complex dynamic system like NPP has a number of limitations. One, its applications have been limited to highly abstracted demonstrations. Another is the presence of large mismatch and uncertainties in the linearization of the non-linear model that does not satisfactorily represent the physical plant. Moreover, on the account of the nuclear plants' inherent complexity, it is difficult to establish a quantitative physical model of nuclear power plant. Besides, it is known that NPP has many transient states, as a result of its complexity. Modeling these states using state space representation is quite difficult, and the data-driven methodology provides a very quick means of fault detection.

Legacy plants used to rely on probabilistic method such as fault trees, event trees, Bayesian network and Markov chain (causal reasoning) for fault diagnosis. However, the probabilistic approach to nuclear plant fault diagnosis are very mechanical, time consuming and highly subjective. They rely heavily on the expert knowledge of the reactor operations and configuration to have a usable model. In addition, they are prone to error, and cannot be easily updated, as finding a priori probability is still problematic. Modern diagnosis tasks discard these approaches in favor of either acoustic/signal processing method, chemical method or the innovative data-driven method, which is the subject of this paper. Increasingly, application of neural networks and its variants for FDI has moved from toy examples to real-world systems. Recently, the diagnostic tasks in OSS are being performed with the help of Artificial Neural Networks (ANNs), by operating on a large knowledge base, which is developed by collecting the plant's time-dependent transient data from the system. Improvements in the application of ANN for identification of dynamic events is as a result of a number of reasons: the ANNs characteristics of adaptive learning, generalization ability, fault tolerance, robustness to noisy data, and parallel processing ability (Roverso, 2000).

In analyzing a complex system using ANN, the main concern for diagnostic engineer is how to choose appropriate network architecture and (non-linear) function to represent the overall output from the neurons. Besides, the No-Free-Lunch theorem for neural network learning algorithms (Wolpert, 1996) states that no completely general-purpose learning algorithm (by extension, architecture) exists - that is, for every learning model there is a data distribution on which it will fare poorly - somewhat further justify the need to test the architectures and select the optimum approach for the OSS knowledge base. Many functions and methods for selecting suitable network have been researched and well documented in the literature. However, there is no consensus on any single approach, and it is still widely believed that network selection result from experimental trial and error. Meanwhile, some of the widely use data-driven approaches are the Gaussian radial basis neural network, applied to the problem of identifying nuclear accidents in a Pressurized Water Reactor (PWR) nuclear power plant (Venkat et al., 2003). A distributed fault diagnostic strategy with BP neural network has been used for local diagnosis for subsystems (Gomes and Medeiros, 2015). Also, Gottlieb et al. (2006) presented a study on transient identification using support vector machines in nuclear power plants. Principal Component Analysis (PCA) methodology has also been used for pattern recognition using a case study of Bruce B zone-control level oscillations in CANDU reactors by Elnara and Hossam (2014). Liu et al. (2013) developed a fault diagnosis expert system for nuclear power plants using data fusion and fuzzy neural network for single and multiple fault diagnosis. Lind and Zhang (2014) studied the application of multi-layer flow model in a PWR primary system and a primary heat transfer system of the Fast Breeder Reactor (FBR). Liu et al. (2017) also proposed the integration of Elmann neural network and signed directed graph (SDG) for fault recognition. The SDG model was used for fault identification while fault size was estimated with the neural network, based on features selected with principal component analysis.

In most linear systems, simple limit checking approach works efficiently for steady state processes, but in a dynamic closed-loop process where operation changes are compensated automatically, the limit value based approach works if the changes in the process are larger (Patton et al., 2002). However, large process parameter change usually transcends the boundary of incipient fault diagnosis, as large changes usually indicate component failure or accident scenario, which is almost always obvious to the operator. This explains the difficulty faced by fault monitoring engineers, first in using simple methods for a dynamic system, and secondly in misdiagnosing or leaving entirely the realm of fault diagnosis to accident analysis.

Following the success of the 300 MW Qinshan I NPP full scope simulator developed by Harbin Engineering University, this research serves as a necessary foundation for building a comprehensive knowledge base for the advanced Qinshan II NPP operator support system. This work serves dual purposes: on one hand, we developed a process for the implementation of a knowledge base for the operator support system for Qinshan II NPP, based on the research work of Santosh et al. (2003) and on the other hand, we evaluated the performance of the two most popular recurrent neural networks used for non-linear dynamic systems, on the representative data derived from the simulation of the 600 MW Qinshan II NPP. That is, we determined the optimum neural network architecture necessary to build a comprehensive knowledge base for the operator support system of Qinshan II NPP. This work compares the predictive result of the two main recurrent neural network architecture, the Elman, and the Radial basis network, for predicting the severity and location of incipient faults in different parts of the plant. As a pilot study, a spectrum of break sizes and incipient fault in different locations are analyzed to assess the performance of the neural network architectures.

This work is arranged as follows: the first section provides the theoretical background for this research. The second section explains the methodology while the third section presents our experimental results. In the fourth section, we discussed the result and conclude the research work.

2. Methodology

2.1. Theory of the knowledge-based fault diagnosis

The proposed method uses the hybrid of Principal Component Analysis (PCA) and Artificial Neural Networks (ANN) for fault diagnosis. In the application of ANN for diagnostic tasks, the choice of the input sequence is of paramount importance. Besides, the specific characteristics of the data from NPP – such as high measurement noise resulting from sensor drift and radiation effects on measuring equipment - could affect the modeling accuracy and generalization ability of ANN. To estimate the predictive ability of ANN to a specific representative data from NPP, two different Recurrent Neural Networks (RNN) was considered in this work, and their performance was evaluated, based on the data obtained from the simulation of Qinshan II NPP. In this research, PCA was applied to the input data, for feature extraction, dimensionality reduction, noise filtering and data cleaning. The purpose is to select the most informative predictive variable sequences (principal components). Then we experiment with Elman Neural Network (ENN) and Radial Basis Function Network (RBFN), to determine the generalization capability and the network architecture suitable for the task of fault identification on a representative data from simulated Qinshan II NPP.

2.2. Noise filtering and feature extraction with PCA

NPP operations are characterize by disturbances, noise in

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