Progress in Nuclear Energy 85 (2015) 17–27

Contents lists available at ScienceDirect

Progress in Nuclear Energy

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

Estimation of relative power distribution and power peaking factor in a VVER-1000 reactor core using artificial neural networks

Ahmad Pirouzmand*, Morteza Kazem Dehdashti

Department of Nuclear Engineering, School of Mechanical Engineering, Shiraz University, Shiraz, Iran

ARTICLE INFO

Article history:
Received 12 February 2015
Received in revised form
28 April 2015
Accepted 1 June 2015
Available online 10 June 2015

Keywords:
Real-time monitoring system
Relative power distribution (RPD)
Power peaking factor (PPF)
Artificial neural networks (ANNs)
Ex-core neutron detectors
MCNPX code

ABSTRACT

Designing a computational tool to predict in real-time neutronic parameters of a VVER-1000 reactor core such as axial and radial relative power distributions (RPDs) and power peaking factor (PPF) based on an artificial neural network (ANN) framework is presented in this paper. The method utilizes ex-core neutron detector signals, some core parameters data, and a neural network to setup a real-time monitoring system for RPD and PPF predictions. To detect the hottest fuel assemblies (FAs), the radial RPD in the core is first monitored and then the axial relative power of those FAs is screened to detect the PPF in the core. To achieve this, two hundred reactor operation states with different power density distributions are obtained by positioning the control rods in different configurations. Then a multilayer perceptron (MLP) neural network is trained by applying a set of experimental and calculated data for each core state. The experimental data are core parameters such as control rods position, coolant inlet temperature, power level and signal of ex-core neutron detectors taken from Bushehr nuclear power plant (BNPP) for each operation state. The RPD and PPF for each corresponding state are calculated using a validated model developed in MCNPX 2.7 code. The results of this study indicate that the RPD and PPF can be determined through a neural network having in input the position of control rods, the power level, the coolant inlet temperature, the boric acid concentration, the effective days of reactor operation, and the signal of ex-core neutron detectors, accurately. Also, the sensitivity study of the ANN response to different selection of input parameters illustrates that the signal of ex-core neutron detector plays an important role in the ANN prediction accuracy.

1. Introduction

An accurate prediction on the neutronic parameters of a nuclear reactor core is a major design concept for both economic and safety reasons. Development of economically beneficial and safe operation requires more accurate, comprehensive and real-time analysis of the neutronic parameters (IAEA, 2005). Various safety requirements imposed on the fuel pellets and fuel clad barriers such as the LPD[1] and the DNBR[2] play an important role in protection and monitoring systems. To confirm that these requirements are not violated during the reactor operation a real-time monitoring system is required (Wang et al., 2003). The changes in reactor core power distribution are usually monitored by detecting the neutron flux density via the protection system which uses in-core and ex-core neutron detectors signals. Early monitoring of the reactor power distribution and power peaking factor measurements are performed by miniature fission chamber neutron detectors installed in the in-core instrument channels and the calculation of the power distribution is carried out using a series of neutron flux data. However, utilizing the in-core neutron detectors to compute the power distribution and the other real-time parameters accurately is faced with some difficulties. Core size, high temperature, high pressure and proposing some special materials into the core are limitations of using in-core detectors in some cases (Bae et al., 2009). The purpose of developing an ex-core instrumentation system for advanced reactors, including VVER-1000 reactors, is to increase the safety and efficiency of the nuclear power plant

---

* Corresponding author.
E-mail address: pirouzm@shirazu.ac.ir (A. Pirouzmand).

[1] Local power density.

[2] Departure from nucleate boiling ratio.

http://dx.doi.org/10.1016/j.pnucene.2015.06.001
0149-1970/

operation by increasing the response speed, reliability and accuracy of the operational monitoring system.

The central objective of this study is to predict the radial and axial RPDs[3] and PPF[4] in a VVER1000 reactor core using measured signals of the reactor coolant system, the ex-core neutron detectors, the power level, and the control rods position. Studying the complex relationship among the power distribution variation, core neutron flux change and the ex-core neutron detector response reveals that artificial neural networks (ANNs[5]) can properly fit the complex nonlinear correlation of these aspects. ANNs allow modeling complex systems without requiring an explicit knowledge or formulation of the relationship that exist among the variables and constitute an alternative to structured models or empirical correlations (Hassoun, 2003). ANNs have been successfully applied to different applications in nuclear engineering from nuclear reactor dynamics simulation to the PPF estimation and the 3D power distribution prediction (Pirouzmand and Hadad, 2011a,b; Hadad and Pirouzmand, 2007; Tanabe and Yamamoto, 1993; Nae et al., 2004; Mary et al., 2006; Montes and Francois, 2009; Xia et al., 2013). This work proposes a method based on the artificial neural network technique to predict the radial and axial RPDs and PPF accurately in real-time. To verify this method, a series of experimental data taken from the Bushehr nuclear power plant (BNPP[6]) are used. All of these parameters are deduced from the core variables such as the signal of ex-core detectors, the position of control rods, the power level, the coolant inlet temperature, and the boric acid concentration.

2. VVER-1000 ex-core nuclear measurement system

Using geometric symmetry, the VVER-1000 reactor core can be segmented into six regions in which each one contain 28 fuel assemblies (FAs[7]). As long as the neutron flux of each segment is obtained, the axial RPD[8] of the core can be calculated in certain conditions. When the reactor core operates at hot zero power each segment can be viewed as a neutron source and the neutron leakage from each segment is almost constant that is monitored by ex-core neutron detectors. The escaped neutrons can cross over the surrounding segments, the reflective layer, and the pressure vessel and finally reach to the ex-core detectors. Meanwhile, the count of the detector is the superposition of the neutrons leaked from each segment. Therefore, a correspondent relationship would exist between the measured data and the neutron flux density value of each segment. In addition, there is a strong correlation for neutron flux between each segment, especially between adjacent ones. Also, the change of the neutron flux in one segment interacts neighboring segments as well as remote segments. The ex-core neutron detector is extremely sensitive to the neutron flux change of the peripheral segment. Consequently, the change of the core neutron flux distribution can be deduced from the count rate of the ex-core neutron detectors (Xia et al., 2013).

The ex-core neutron detectors of the VVER-1000 reactor together with the corresponding electronic systems can monitor the core neutron leakage under power operation within the range of (10^{-9} to 120) % rated power. In addition, the ex-core measurement system provides some critical core parameters such as reactor period over the range of (10–500) seconds, reactivity, monitoring of neutron flux during start-up of reactor and reactor core loading (refueling). Fig. 1 shows the ex-core neutron detectors arrangement around the core in instrumentation and control (I&C[9]) channels. There are provided 15 neutron detector channels in the biological shield with different measuring level. Measuring level is divided into three groups involves start-up, working and source ranges. Table 1 shows the arrangement of sensors in channels in reactor's concrete shield over the core perimeter in two sets of equipment. The detectors are located at different vertical levels. The main task of the ex-core nuclear measurement system is to alarm timely during steady power operation and active the shutdown system when it is needed by monitoring the neutron flux (AEOI, 2007). This research addresses the RPD and PPF predictions from the ex-core measurement system in 1/6 core symmetry. Here, the signal of one neutron detector is used for the neural networks training, validation and testing.

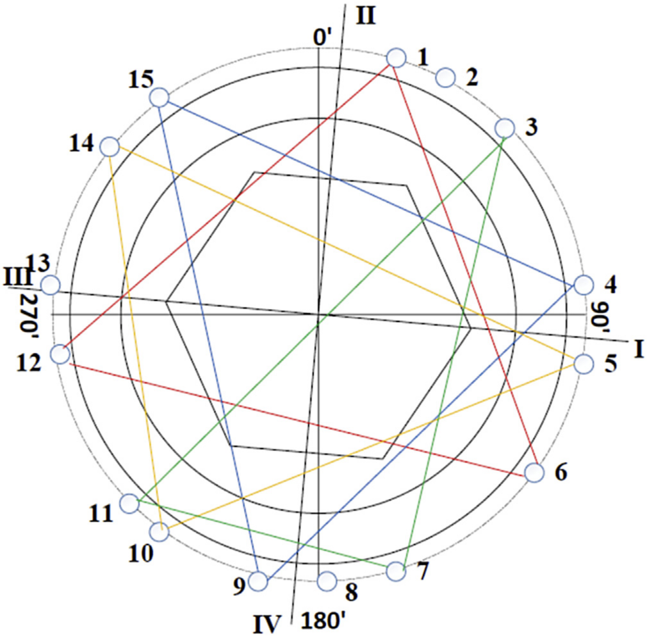

Fig. 1. Diagram of detection unit arrangement in I&C channels (AEOI, 2007).

Table 1
Arrangement of sensors in channels in reactor concrete shield over the core perimeter (AEOI, 2007).

Channel number	Purpose of the channel
1, 6, 12	First set of equipment, start-up and working ranges
4, 9, 15	Second set of equipment, start-up and working ranges
3, 7, 11	First set of equipment, source range
5, 10, 14	Second set of equipment, source range
9	First set of equipment of physical start-up
2, 13	Second set of equipment of physical start-up
13	Redundant channel for equipment of the first set
8	Redundant channel for equipment of the second set

3. MCNPX model

A Monte Carlo method does not solve an explicit equation like a deterministic code; it rather calculates the solutions by simulating

---

[3] Relative power distributions.

[4] Power peaking factor.

[5] Artificial neural networks.

[6] Bushehr nuclear power plant.

[7] Fuel assemblies.

[8] Relative power distribution.

[9] Instrumentation and control.