VVER-1000 REACTOR CORE MONITORING USING EX-CORE NEUTRON DETECTORS AND NEURAL NETWORKS

Ahmad Pirouzmand *[1], Morteza Kazem Dehdashti [2]

[1]Department of Nuclear Engineering, School of Mechanical Engineering, Shiraz University, Shiraz, Iran

Abstract

This paper proposes a method, based on the artificial neural network technique, to predict the radial and axial relative power and power peaking factor accurately in real time. The method utilizes ex-core neutron detector signals, some core parameter data, and neural network to set up a real time monitoring system for reactor's relative power distribution. In order to detect hottest fuel assemblies, we first monitor radial relative power in the core and then screen the axial relative power of those fuel assemblies. To achieve this goal, several reactor states with different power density distribution are obtained by positioning the control rods in different configurations. Then, a multilayer perceptron (MLP) neural networks utilizing a set of data, consist of experimental and calculated data for each core state, is trained. The experimental data are core parameters such as control rods position, coolant inlet temperature, power level and signal of ex-core detectors taken from BUSHEHR nuclear power plant (BNPP) for each core state. The reactor relative power distribution and power peaking factor for each corresponding state are calculated using a validated model in MCNPX 2.7 code. The results of this study indicates that the power peaking factor can be determined through a neural network having as input the position of control rods, core inlet temperature, power level, and signal of ex-core detectors, accurately.

1. Introduction

The monitoring of some core parameters are prerequisite for the operation of nuclear power reactors. It is vital to be ensured that various safety limits imposes on the fuel pellets and fuel clad barriers, such as the local power density (LPD) and the departure from the nucleate boiling ratio (DNBR) which play an important role in the protection and monitoring systems, is not violated during the reactor's operation [1]. The changes of reactor core power distribution are usually monitored by detecting the neutron flux density. The measurement system using in-core and ex-core neutron detectors signal. Early monitoring of the reactor power distribution and the power peaking factor measuring utilized miniature fission chamber neutron detectors which installed in the in-core instrument channels, and the power distribution is computed with the help of a series of neutron flux data. Although there are some problems using in-core neutron detectors to compute the power distribution and other parameters in real-time and accurately. Core size, high temperature, high pressure and some special materials proposes in core are limitations of using in-core detectors in some cases [2]. The objective of this paper is to predict the relative radial and axial power distributions and power peaking factor in the VVER1000 reactor core using measured signals of the reactor coolant system, ex-core neutron detectors, and control rods position. By studying the complex relationship between the power distribution change, core neutron flux change and ex-core neutron detector response, we find out that artificial neural networks (ANNs) could fit complex nonlinear function of these aspects. Artificial neural networks allow modelling 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 [3]. ANNs have been successfully applied for the power peaking factor estimation and the power distribution prediction [3-7]., Herein to verify the validity of this method, a series of experimental data from BNPP are used. All of these parameters are usually inferred from primary system variables such as the signals from ex-core detectors, position of control rods, power level, coolant inlet temperature, and boric acid concentration [8].

2. VVER-1000 Ex-Core Nuclear Measurement System

VVER-1000 reactor core can be divided into similar 60^0 symmetry each one contain 28 hexagonal segments (fuel assemblies). As long as the neutron flux of each segment is determined, the distribution of the core axial and radial relative power can be calculated for each core state. 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. These escaped neutrons can cross over the surrounding segments, the reflective layer, and the pressure vessel and then reach to the ex-core detectors. Meanwhile, the count of the detector is the superposition of the leaked neutrons from each segment. Therefore, a correspondence relationship between the ex-core detector signal and the neutron flux density values of each segment exists. In addition, a strong correlation between each segment for the neutron flux, especially between adjacent segments, happens. 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 [5]. The neutron detector outside of the VVER-1000 reactor together with the matched electronic systems can monitor the core's neutron leakage under power operation within the range of (10^{-9}-120) % of rated power. In addition ex-core measurement system provides some critical core parameters such as reactor period over the range of (10-500) seconds, reactivity, monitoring of the neutron flux during start-up of the reactor and the reactor core loading (refuelling), etc.. Fig.1 shows the neutron ex-core detectors arranged around the core. There are provided 15 neutron detector channels in the biological shield with different measuring level. Measuring levels are divided to three groups, consist of start-up, operation and source ranges. The channels 1, 6, and 12 measure the neutron leakage during the start-up and operation range, the channels 3, 7, and 11 are used during source range, and the channels 4, 9, 15, 2, and 13 are utilized during the source range. The detectors are located in 3 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. This research investigated the relative power distribution prediction from the ex-core measurement system in 1/6 core symmetry. Three signals from an operation type neutron detector are used for the neural networks training, validation and test. The signals have been measured during the first cycle of BNPP operation [8].

3. MCNPX Model

A VVER-1000 reactor core model is designed and developed by MCNPX 2.7 code. The model contains all physical core components in real reactor operation conditions. Different tallies are considered in this model to calculate the axial and radial relative power distributions. All fuel rods (material and clad), water channels, guide channels and control rods are divided to ten axial nodes for considering the effect of coolant temperature and density distribution on the core axial relative power calculation. The relative power distribution is affected by major factors such as: the time of operation, the coolant inlet temperature, the control rod groups' position, the power level, the boric acid concentration, and etc. The MCNPX model is validated against BNPP FSAR and neutron album data during the first fuel cycle. The calculation is carried out for the first fuel cycle from 0.00 to 293 days with variation in the control rods position, the boric acid concentration, the power level, and the coolant inlet temperature. Table 1 presents some part of the MCNPX model results are compared with BNPP neutron album data. In this table T_{eff}, T_{in}, H_{10}, P, C_{bc}, K_q, K_v, N_k, and N_z are the time of reactor operation, the core inlet temperature, the position of control rods group 10, the power level, the boric acid concentration, the radial and axial power peaking factors, the FA number, and the core axial level, respectively. Also Fig. 2 illustrates the radial and axial relative power distributions. As shown there is a very good comparison between the MCNPX model results and BNPP neutron album data.

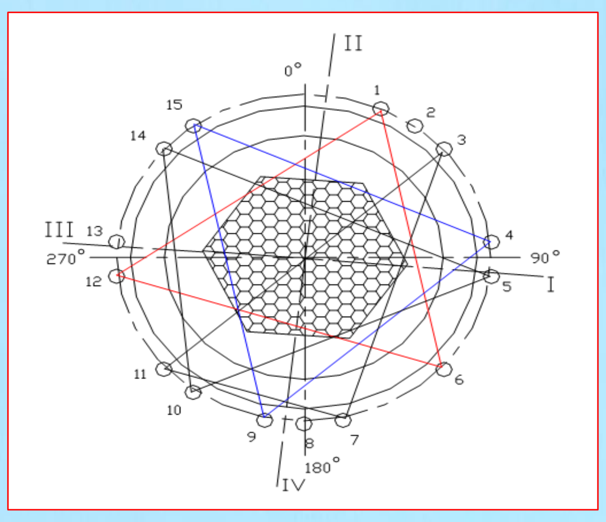

***Figure** 1. Diagram of detection unit arrangement in I&C channels* [8] ●

***Table1**.The calculated MCNPX model results compared with BNPP neutron album data.*

					BNPP neutron album		MCNPX Model	
T_{eff} [day]	T_{in} [^oC]	H10%	P [MW]	C_{bc} [g/kg]	K_q [relative, N_k]	K_v [relative, N_k,N_z]	K_q [relative ,N_k]	K_v [relative ,N_k,N_z]
0.00	280.5	60	150	6.83	1.42 25	2.07 25 5	1.42 25	2.07 25 5
1.00	282.8	60	750	6.04	1.34 21	1.90 21 4	1.34 21	1.90 21 4
5.00	284.4	70	1200	5.60	1.29 21	1.78 21 5	1.29 21	1.78 21 5
10.00	285.5	80	1500	5.36	1.26 21	1.71 21 5	1.26 21	1.71 21 5
20.00	288.3	80	2250	4.95	1.22 21	1.66 21 4	1.22 21	1.66 21 4
40.00	288.3	80	2250	4.74	1.22 1	1.60 1 5	1.22 1	1.60 1 5
80.00	291.0	90	3000	3.93	1.24 1	1.45 3 4	1.24 1	1.44 3 4
100.00	291.0	90	3000	3.58	1.22 3	1.39 3 3	1.21 3	1.39 3 3
200.00	291.0	90	3000	1.76	1.17 3	1.31 3 2	1.17 3	1.31 3 2
260.00	291.0	90	3000	0.63	1.15 3	1.31 15 2	1.14 3	1.31 15 2
293.82	291.0	90	3000	0.00	1.14 3	1.30 15 2	1.14 3	1.29 15 2

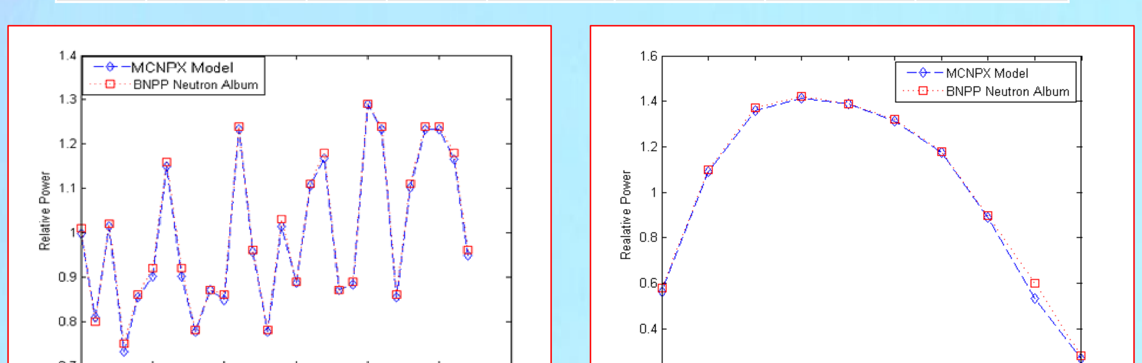

Figure 2. Comparison of the MCNPX model results with BNPP neutron album (a) radial and (b) axial relative power.

4.Results

In this study multi-layer perceptron neural networks with two and three hidden layers and various number of neuron in each layer are investigated to choose the best network topology. One hundred and eighty samples from the MCNPX model and experimental data are used to train, validate and test the networks. The network inputs are three signals from the ex-core detectors (RR_{ex}, ARR_{ex}, and S_{ex}), the control rod groups position (CR10, CR9, and CR8), the inlet temperature(T_i), the effective days of reactor operation (T), the boric acid concentration (C_{bc}), and the power level (P). The outputs of network are the radial and axial power peaking factors for 28 FAs in the ten axial layers. The performance of the networks to estimate the relative power distribution is summarized in Table 2. This table shows the topologies and the calculated root mean square (RMS) errors during the training process. For the MLP neural networks, the average root mean square error is 0.00592. The minimum RMS is 0.000723 for case 4, therefore for further investigation case 4 is chosen.

Also Fig. 3 shows the regression fraction for case 4. The validation and test errors after training are tabulated in Table 3 for case 4.

***Table2**.Topologies and root mean square errors of MLP networks*

	Topology (Number of neuron)	Root mean square error	Regression fraction
Case1	(5,10)	0.0111	0.9374
Case2	(3,10,10)	0.0095	0.9337
Case3	(7,10,10)	0.0052	0.9276
Case4	(9,11,10)	0.0007	0.9827
Case5	(15,10)	0.0029	0.9789

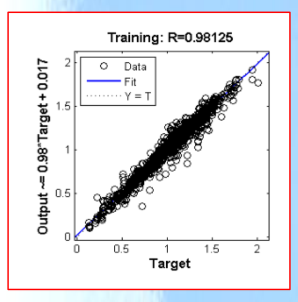

***Figure 3.** Prediction of RPD by network case 4*

***Table 3.**The validation and test errors for case 4*

Topology	Validation error	Testing error
Case 4 (9,11,10)	0.03211	0.01034

***Table 4.** Comparison of ANN prediction with BNPP neutron album data*

BNPP neutron album		ANN prediction		Error %	
Radial relative power N_k	Axial relative power	Radial relative power N_k	Axial relative power	Axial	Radial
1.41 27	0.2758	1.41 27	0.2788	1.08%	0.0%
	0.7216		0.7109	1.4%	
	1.0856		1.0766	0.82%	
	1.2088		1.1897	1.5%	
	1.4101		1.3979	0.86%	
	1.7775		1.7568	1.1%	
	2.1395		2.1187	0.97%	
	2.2011		2.2186	0.79%	
	1.8566		1.8662	0.51%	
	1.4291		1.4356	0.45%	

Table4 presents the MLP network's real-time prediction and BNPP neutron album data for the hottest fuel assembly, CR10=0%, CR9=20%, CR8=70%, T=5, T_i=291, P=40% and C_{bc}=4.89. As shown the maximum value of radial power peaking factor (1.41) occurs in FA number 27. Also the predicted axial power peaking factors are comparable with the true value. The radial relative power distribution for 1/6 core symmetry is shown in Fig. 4.

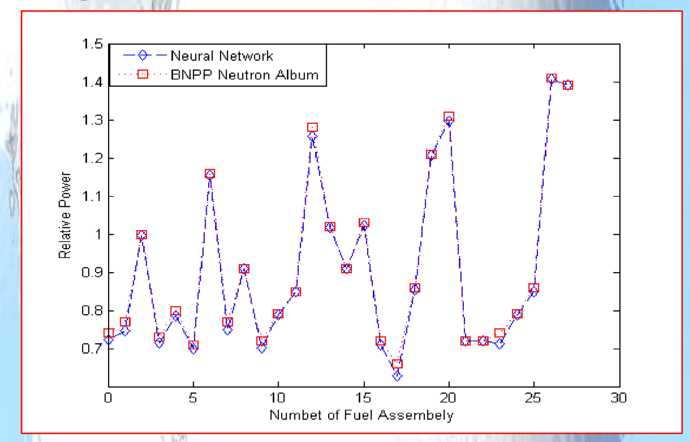

***Figure 4** Prediction of radial RPD by ANN*

5. Conclusion

This paper introduced a model for the prediction of VVER1000 relative power distribution based on the artificial neural networks, a series of experimental reactor operation data, and MCNPX code results, which can be incorporated to reactor protection system. The experimental data are core parameters such as control rods position, coolant inlet temperature, power level and signal of ex-core detectors taken from B nuclear power plant (BNPP) for each core state. The reactor relative power distribution and power peaking factor for each corresponding state were calculated using a validated model in MCNPX 2.7 code. The artificial neural network technique was chosen to develop the monitoring system due to its ability in solving complex and non-linear problems in real time. Different ANN topologies were examined for choosing the best architecture. The results of this study indicates that the power peaking factor can be determined through the MLP neural networks having as input the position of control rods, the core inlet temperature, the power level, and the signal of ex-core detectors, accurately.

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