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Determination of control rod positions during fuel life-cycle using fixed in-core Self-Powered Neutron Detectors of Tehran Research Reactor

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A B S T R A C T

This paper deals with reconstruction of reactor states from measurements of fixed in-core Self-Powered Neutron Detectors (SPNDs) by Artificial Neural Networks (ANNs). Reactor states are defined by position of the control rods and burn-up of the fuel for Tehran Research Reactor. Position of control rods during fuel life-cycle should be monitored, because of their strong impact on neutron flux distributions and operational safety margins of the reactor. In the literature, position of control rods is reconstructed using axial distributions of neutron flux measured by in-core detectors in the vicinity of the control rods. In this research, ANNs are employed to determine position of the control rods and burn-up of the fuel, using 2D neutron flux measurements of the previously optimized SPNDs at central elevation of the reactor core. Also, sensitivity studies are performed on mapping performance of the ANNs with different architectures and training algorithms. The results indicate that a specific architecture of feed-forward neural networks, which are trained by Bayesian regularization back-propagation algorithm, has the best performance for the reactor states reconstruction. In addition, noise resistance capability of the developed ANN is evaluated with noisy data sets. The developed neural network has satisfactory noise resistance response, especially when trained by noisy data sets.

1. Introduction

Reconstruction of neutron flux across the reactor core can be used for calculation and monitoring of safety-related parameters, sensor calibrations, optimization of fuel burn-up, etc. (Dias and Silva, 2016; Peng et al., 2014). Neutron flux distribution is continuously subjected to change during normal operation of a reactor, due to movement of control rods, fuel burn-up, etc. For reconstruction of neutron flux distributions, on-line or off-line approaches may be employed. For example, neutron activation techniques can be used for off-line measurement in different locations of the reactor core for fitting neutron flux distribution (Chiesa et al., 2015). Core monitoring and control systems in nuclear reactors usually include a sub-system for On-line Flux Mapping (OFM), e.g. BEACON[1] (Boyd and Miller, 1996) and GNF-ARGOS[2] (Tojo et al., 2008). Estimation of global parameters such as core power by OFM systems is very useful, especially for Pressurized Heavy Water Reactors (PHWR), which have a large core and loose neutron flux coupling (Mishra et al., 2012). In addition, OFM systems in research reactors can be employed for designing experiments and improvement of reactor efficiency. Nowadays, most of OFM systems implemented are using Self-Powered Neutron Detectors (SPND) (Lee and Kim, 2003; Pomerantz et al., 2002). SPNDs consist of an inner electrode (emitter), surrounded by insulation and an outer electrode (collector) with coaxial structure (El-Badry and Hassan, 2003). Inner electrode, which typically is made from Rh, V, Co, Ag, Pt, or Hf, emits beta particles by absorbing neutrons (El-Badry and Hassan, 2003; Wanno et al., 1999).

Because of strong impact of control rods on neutron flux distributions, OFM systems can also be used for monitoring position of control rods (Peng et al., 2017). Monitoring position of control rods is usually performed by specialized instruments installed in nuclear reactors (Akatsuka and Kodama, 2009; Zhang et al., 2013). Up to now, different approaches such as Levenberg-Marquardt algorithm (Li et al., 2010), Artificial Neural Networks (ANNs) (Andersson et al., 2003; Garis et al., 1998), Group Method of Data Handling (GMDH) (Peng et al., 2015) are employed to reconstruct position of control rods using axial distributions of neutron flux measured by in-core detectors in the vicinity of the control rods.

This paper presents a methodology based on ANNs to determine position of the control rods and burn-up of the fuel, using 2D neutron

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[1] Best Estimate Analysis of Core Operations – Nuclear.

[2] A core monitoring system for Boiling Water Reactors (BWR).

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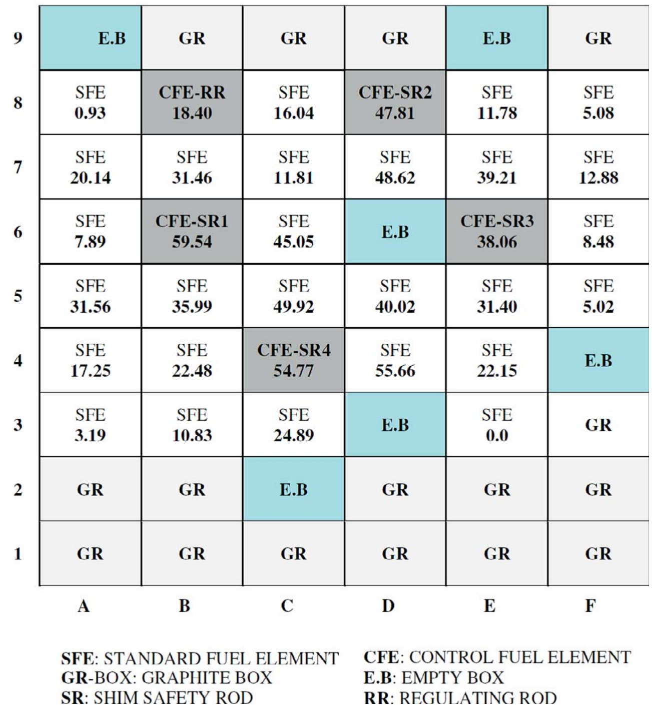

Fig. 1. TRR core configuration (Lashkari et al., 2013).

Table 1
Control rods insertion for the flux distributions in Fig. 2.

Rod	SR1	SR2	SR3	SR4	RR
Nominal insertion (%)	39	39	39	39	50

flux measurements of the fixed in-core SPNDs installed at central elevation of the reactor core. This methodology has been developed in the framework of a research project to develop an OFM system for Tehran Research Reactor (TRR). The OFM system of TRR will be able to reconstruct 2D neutron flux distribution across the reactor core using measurements of SPNDs. This research project consists of three steps: (1) Optimal placement of SPNDs in the reactor core using information theory, to provide maximum independent measurements (Terman and Khalafi, 2017), (2) Mapping measurements of the SPNDs to a reactor state defined by position of the control rods and burn-up of the fuel (this paper), and (3) Reconstructing neutron flux distribution of a specific reactor state by combining harmonics of different base states using Flux Synthesis Method (FSM) (Hong et al., 2005; Kulesza, 2011).

The rest of this paper is arranged as follows. In Section 2, a brief description about TRR and neutronic modeling of the reactor core is presented. In Section 3, configuration of fixed in-core SPNDs in TRR core is presented. The number and placement of the SPNDs were previously optimized by information theory. In Section 4, reactor states (position of control rods and burn-up of the fuel) are reconstructed by ANNs using measurements of the SPNDs. Also, some sensitivity studies are performed on mapping performance of ANNs with various architectures and training algorithms, to develop the best reconstruction model. In addition, noise resistance capability of the developed ANN is evaluated with noisy data sets. Finally, Section 5 includes a brief summary and conclusion.

2. Development of a data set of detector measurements by MCNP code

The Tehran Research Reactor (TRR) is a 5 MW, thermal, light-water, pool-type reactor, built by the U.S. in Iran. Originally, this reactor was designed and operated with High Enriched Uranium (HEU), which is now converted to Low Enriched Uranium (LEU), plate type fuels. This reactor uses 4 Safety Rods (SR), each having a worth around 3 dollars, for long-term reactivity compensation and safety purposes and 1 Regulation Rod (RR), worth less than 1 dollar, for the purpose of power level fine tuning. The core configuration of this reactor is shown in Fig. 1 (Lashkari et al., 2013).

The version of MCNP neutronic code which is used to obtain neutron flux distributions, is MCNPX2.7E (Pelowitz et al., 2011). As a compromise between statistical errors and runtime, we have used 20,000 particles per cycle, 50 inactive cycles, and 200 active cycles in the criticality mode. The active region of the core has been meshed using 1 (cm) × 1 (cm) squares, only in the x-y plane using the TMESH card.

Neutron flux distribution is calculated by MCNPX2.7E code (Pelowitz et al., 2011) for 3312 meshes (72*46) of 2048 reactor states, which are generated by different positions of 5 control rods and fuel burn-ups. Neutron flux distribution in the TRR core for a specific configuration of the control rods (Table 1) at beginning of cycle[3] and end of cycle[4] 100 MWD of the fuel are illustrated in Fig. 2(a) and (b), respectively.

3. Optimum number and placement of in-core SPNDs of TRR

The number of sensors in any surveillance system is limited by economic considerations, mechanical constraints, maintenance cost, etc. (Krause et al., 2006). Hence, maximum capacity of each sensor should be employed. Placing sensors in the locations which have almost constant values in different states, provides a little information. Also, nearby sensors may provide same or very similar information. Therefore, placement of sensors should be optimized to maximize information in measurements and to avoid duplication of same information (Park and Lim, 2015).

For an OFM system, which reconstructs neutron flux all over the reactor core, it is vital to optimize placement of fixed in-core detectors to decrease economic cost and increase efficiency of the system. Information theory (Shannon, 1948) is the best method to deal with the optimization of sensors placement (Ainslie et al., 2009; Krause et al., 2008).Information content in a random variable, $X = \{x_1, x_2, ..., x_n\}$, with the probability of occurrences $\{p(x_1), p(x_2), ..., p(x_n)\}$ can be defined by entropy or Shannon function, $H(X)$, (Shannon, 1948):

$$H(\mathrm{X}) = \sum_{i=1}^{n} p(x_i)\log_2\frac{1}{p(x_i)} \tag{1}$$

Entropy of a random variable is a measure of uncertainties about occurrence of the possible outcomes. Entropy is not related to value of the variable, and it is calculated using probability distributions. Occurrence of the events with higher probabilities leads to less information in comparison with occurrence of the events with lower probabilities. $H(\mathrm{X})$ is a positive-definitive function for all $p(x_i) \in [0,1]$ and has the maximum value, when probability distribution is uniform (Yeung, 2008).

After defining the objective function of the optimization, information content of the measurements should be maximized by gradient-based or heuristic methods. Implementation of heuristic methods such as Genetic Algorithm (GA) lead to a better convergence to a global maximum in comparison to gradient-based methods, while avoiding to stick in local maximums. Therefore, GA optimization is selected to maximize information (entropy) of SPNDs measurements in TRR (Terman and Khalafi, 2017).

Table 2 shows the share of information can be extracted by optimal placement of different number of SPNDs. It can be concluded that, by

[3] BOC.
[4] EOC.