Progress in Nuclear Energy 106 (2018) 300–315

Contents lists available at ScienceDirect

Progress in Nuclear Energy

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

Optimal placement of fixed in-core detectors for Tehran Research Reactor using information theory

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ARTICLE INFO

Keywords:
Research reactor
Fixed in-core detectors
Optimal placement
Information theory
Entropy

ABSTRACT

Monitoring of neutron flux distribution is very important in safe operation of both research reactors and nuclear power plants. Most challenging issue in design and implementation of online flux mapping systems is to determine optimal locations of the detectors. Optimal placement of the detectors for flux reconstruction should extract maximum information from reactor states, while information duplication is avoided. Information theory is one of the most effective methods for sensor placement optimization, and it is based on entropy (Shannon function) which is defined by probability of sensor measurements. Objective function of optimization using information theory could be defined by (1) minimizing mutual information between each pair of sensors, while maximizing total entropy, or (2) maximizing total entropy, while common information is minimum achievable by defining joint probabilities (proposed algorithm by this paper). In this paper, optimal location of fixed in-core self-powered detectors for Tehran research reactor is determined by both of the information-based methods. The results of both methods indicate that the proposed algorithm (Method 2) has superior performance in comparison to Method 1 (adopted from literature), and results in more informative placement of same number of detectors. This optimal placement reduces costs in construction, implementation, operation, and maintenance of the fixed in-core detectors of the online flux mapping system for Tehran research reactor.

1. Introduction

Monitoring distribution of core power is one of the important issues in safety of research reactors and nuclear power plants. Neutron flux (or power) distribution is a fundamental parameter for assessment of safety margins in operation of a reactor (Peng et al., 2014). Power Peaking Factor (PPF), Departure from Nucleate Boiling Ratio (DNBR), and Axial Offset (AO) are the safety-related parameters calculated using distributions of the neutron flux. During normal operation of a reactor, neutron flux distribution is continuously changing due to movement of control rods, fuel burn-up, temperature and power feedbacks, etc., and its theoretical equation does not exist. Also, place of favorite events in the core may not have coincidence with the detector locations. Therefore, to determine safety-related parameters, it is required to reconstruct the flux distribution in the reactor core using limited number of fixed in-core detectors. 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). The reconstructed neutron flux can be used for sensor calibrations, or for optimization of fuel burn-up. Also, estimation of global parameters such as core power by OFM systems is very useful especially for Pressurized Heavy Water Reactors (PHWR) which have large core and loose neutron flux coupling (Mishra et al., 2012a). In addition, neutron flux reconstruction in research reactors is very important for designing experiments and improvement of reactor efficiency. Nowadays, most of OFM systems are implemented using Self-Powered Neutron Detectors (SPND), because of low cost and suitable dimensions.

Nonetheless, the number of sensors in any surveillance system is limited by economic considerations, mechanical constrains, maintenance cost, etc. (Krause et al., 2006). Hence, the optimal configuration/location should be employed. Optimization of sensors' placement in different applications is usually performed for one of these reasons (Basseville et al., 1986): (1) State reconstruction, (2) State estimation, (3) Parameter identification, and (4) Failure detection. Main objective in optimization of state reconstruction systems is to minimize the uncertainty of estimated parameters in the locations without a priori direct measurement (Alfonso et al., 2009). Placing sensors in the locations

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

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

https://doi.org/10.1016/j.pnucene.2018.03.012
Received 27 May 2017; Received in revised form 10 February 2018; Accepted 12 March 2018

9	E.B	GR	GR	GR	E.B	GR
8	SFE 0.93	CFE-RR 18.40	SFE 16.04	CFE-SR2 47.81	SFE 11.78	SFE 5.08
7	SFE 20.14	SFE 31.46	SFE 11.81	SFE 48.62	SFE 39.21	SFE 12.88
6	SFE 7.89	CFE-SR1 59.54	SFE 45.05	E.B	CFE-SR3 38.06	SFE 8.48
5	SFE 31.56	SFE 35.99	SFE 49.92	SFE 40.02	SFE 31.40	SFE 5.02
4	SFE 17.25	SFE 22.48	CFE-SR4 54.77	SFE 55.66	SFE 22.15	E.B
3	SFE 3.19	SFE 10.83	SFE 24.89	E.B	SFE 0.0	GR
2	GR	GR	E.B	GR	GR	GR
1	GR	GR	GR	GR	GR	GR
	A	B	C	D	E	F

SFE: STANDARD FUEL ELEMENT   **CFE**: CONTROL FUEL ELEMENT
GR-BOX: GRAPHITE BOX   **E.B**: EMPTY BOX
SR: SHIM SAFETY ROD   **RR**: REGULATING ROD

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

which have almost constant values in different states, provides little information. Also, nearby sensors may provide same or very similar information. Therefore, placement of sensors should be optimized to maximize information in sensor measurements and to avoid duplication of same information (Park and Lim, 2015). Information theory is one of the methods to deal with the optimization of sensors' placement. In the literature, mutual information of each pair of sensors and total correlation of all sensors are employed to eliminate common information problem. However, it is obvious that the elimination of second order mutual information does not necessarily lead to the complete independence of the provided information by all sensors, as some dependence could remain hidden in triplet sensor mutual information or its higher orders. In this paper, an algorithm is proposed for defining multiple joint probability in way that common information is minimized between the probabilities. 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.

In optimization of sensors' placement, defined objective (cost) function should be maximized (or minimized). Optimization processes are mostly based on heuristic algorithms such as Genetic Algorithm (Chapot et al., 1999), Cross Entropy (de Moura Meneses and Schirru, 2015), Ant Colonies Optimization (Machado and Schirru, 2002), Particle Swarm Optimization (Meneses et al., 2009), Simulated Annealing (Barati, 2014), Artificial Bee Colony (de Oliveira and Schirru, 2011), Population Based Incremental Learning (Caldas and Schirru, 2008), etc. to find global maximum (or minimum) without sticking in local maxima (or minima). In this paper, methods to define the objective functions are mainly focused and compared.

The rest of this paper is arranged as follows. In Section 2, various methods to define an objective function for optimization of sensors' placement are discussed and compared. Then, an algorithm based on information theory is proposed to overcome the weaknesses of pervious methods. In Section 3, optimal placement of different number of fixed in-core detectors for Tehran Research Reactor (TRR) is determined using two methods based on information theory, and the performance of these methods are discussed and compared. Finally, Section 4 includes a brief summary and conclusion.

2. Methods to determine optimal placement of sensors

Methods to optimize the location of sensors can be categorized in (1) Minimizing error of state reconstructions, (2) Variance-based methods, and (3) Entropy-based methods (Information theory). In following subsections, advantages/disadvantages of these methods are discussed, and finally, an algorithm is proposed to overcome the weaknesses of the previous methods.

2.1. Methods based on minimizing error of state reconstruction

The objective of optimization in these methods is to minimize error of estimated parameters (reconstructed state) by changing number or location of the sensors placed in the reactor core (Mishra et al., 2012b; Upadhyaya and Li, 2011). In the optimizing process, other constrains for new arrangements should be considered as well as minimizing the

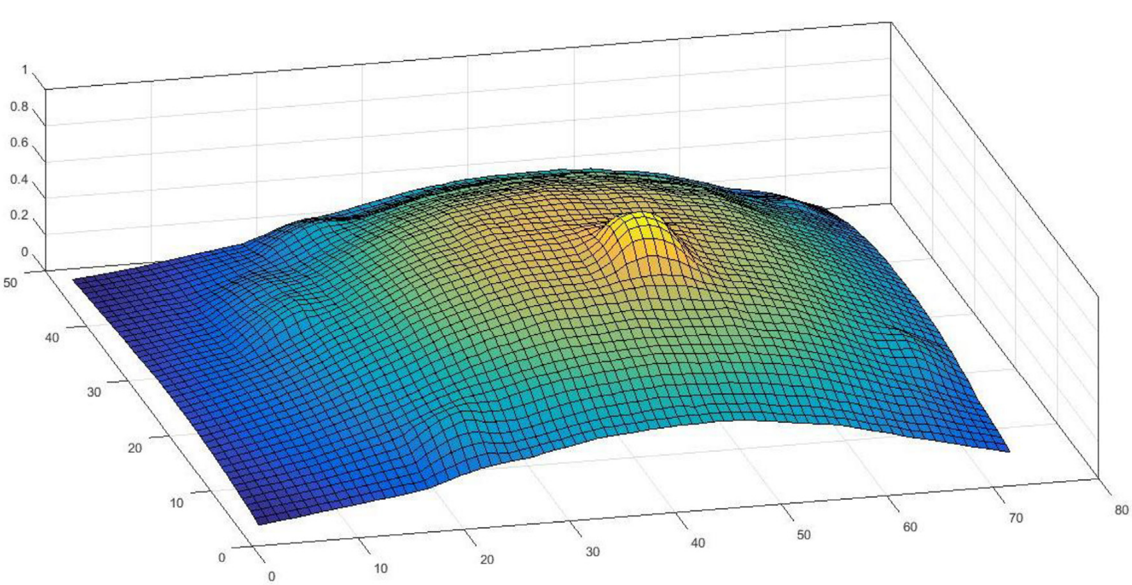

Fig. 2. Neutron flux distribution in TRR core for fully taken out control rods.