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Smart sensing of the axial power and offset in NPPs using GMDH method

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ABSTRACT

The status of nuclear power plants' conditions must be checked to avoid initial events which may eventually lead to accidents. Axial power and axial offset (AO) are key parameters which are usually used to state 3-dimensional core power peaking, in the form of a practical parameter. Group method of data handling (GMDH) has a wide range of applications. Here, a GMDH is used and modified as an efficient method to predict the axial power and AO of the reactor core as well as fuel assemblies. In this paper, axial power offset of the whole reactor core is reconstructed by using in-core detectors. By using the developed GMDH algorithm, the optimum relationship between the independent in-core detector signals and the dependent variables, the core axial power and AO, is determined. Two separate sets of big data are prepared and analyzed. The first set includes power at each of 24 axial nodes at different core states. The second set is similar to the first set except as it also contains fuel assembly data.

1. Introduction

Group method of data handling (GMDH) as a tool for forecasting future trends has been used in various fields. Zhang et al. (2012) and Khemchandani et al. (2009), for example, used GMDH for financial time series forecasting. Huang and Shih (2002), on the other hand, applied GMDH to enhance the performance of fuzzy modeling for short-term load forecast applications. It has also been used for the identification of physical laws, short-term and long-term stepwise forecasting, etc. (Ivakhnenko and Ivakhnenko, 1995; Madala and Ivakhnenko, 1994). This paper will describe how the GMDH can be used for predicting some of the most important control parameters in nuclear power plant (NPP) systems. In this work, GMDH is also applied for the first time to the whole reactor core.

The status of NPP conditions must be checked to avoid initial events which can eventually lead to accidents such as loss of coolant accident (LOCA) and steam generator tube rupture (SGTR). In particular, axial power distribution and Axial Offset (AO) are very important data for operators of an NPP. To monitor in-core power distributions in pressurized water reactors (PWRs), the axial power profile reconstruction using in-core detector signals is essential. Currently, the Core Operating Limit Supervisory System (COLSS) uses fifth-order Fourier series expansion to reconstruct axial power shapes, which is known to have relatively large errors for the saddle, top- and bottom-skewed shapes (Park and Shin, 2014). Operators usually use the COLSS to understand the real core state in order to take appropriate action. The fifth-order Fourier series is widely used to reconstruct power distribution corresponding to in-core neutron detectors. In et al. (1991) used the cubic spline synthesis for OPR1000/APR1400 NPP. A stochastic method, the alternating conditional expectation algorithm was applied by Lee et al. (1999). In addition, Park and Shin (2014) used the GMDH algorithm to reconstruct 20-node axial fuel power shapes from five in-core detector power measurements. They used axial power as an input and output of the GMDH method. However, they focused on the fuel assembly level calculations instead of the core level calculations.

Moreover, any change in control rod position can affect the time-space xenon oscillation which in turn induces large local power peaking. Axial offset (AO) is a key parameter which is usually used to state three-dimensional core power peaking, in the form of a practical parameter. Here, the GMDH is adopted and employed as an efficient method to predict axial power and the AO of the reactor core as well as fuel assemblies at different core conditions. Although the AO can be calculated after the axial power has been reconstructed, we propose to directly predict the AO from the detector signals so as to avoid the impacts of the possible biases in the reconstructed axial power shape. In addition, by using

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the in-core detector signals instead of the ex-core detector signals to predict the AO, it is expected the results can be more precise and accurate, which is a great potential advantage for the core protection and monitoring systems that might improve the operation margin. Although the AO is an integral parameter, there is no information loss since the AO is treated as an additional independent parameter besides the axial power distribution.

Among all kinds of soft-computing methods, the GMDH is a heuristic self-organizing modeling technology. The GMDH algorithm was first introduced and applied by (Ivakhnenko, 1970) to solve high-order regression polynomials. As stated earlier, the GMDH has a wide range of applications, but the basic idea which is hidden in such methods is to build a multilayer feedforward network structure. Starting from the input layer, new candidate models are generated in every layer. New candidate models can be made by combining two models of the previous layer. Finally, utilizing some external criteria, the middle candidate models can be evaluated and selected (Ivakhnenko, 1976; Sarychev, 1990; Xiao et al., 2009). Our main goal in this paper is to find an optimum relation between the in-core detector signals and the dependent variables, the axial power and the AO.

2. Basic definitions and datasets

2.1. Definition of axial offset in a NPP

Local power peaking factor has two main components, the radial and axial power peaking factors. Radial power peaking can be flattened by loading pattern optimization while the axial power peaking factor continues to change by perturbation caused by control rod movement. The AO is routinely used to present core power peaking. It is defined as

$$AO = \frac{P_{top} - P_{bot}}{P_{top} + P_{bot}}, \tag{1}$$

Where P_{top}, P_{bot} state the fraction of thermal power generated in the top and bottom of the reactor core, respectively. In other words, AO is a way to represent the axial power peaking of the reactor core.

2.2. Data sets

The GMDH neural network develops on a data set. The data set includes independent variables $\mathbf{X}(x_1, x_2, \ldots, x_m)$ and one dependent variable $\mathbf{y}$. For example, OPR-1000 has fixed in-core rhodium detectors installed at the 45 fuel assembly sites in five axial levels. Figs. 1 and 2 show the radial and axial positions of in-core neutron detectors of the OPR-1000 reactor. Using these 225 (45×5) detector signals which come from the data acquisition system (DAS), COLSS reconstructs 24-node axial power to evaluate the DNBR (Departure from Nucleate Boiling Ratio) and LHT (Linear Heat Rate). The in-core neutron detectors (self-powered neutron detectors) are placed at 38.1, 114.3, 190.5, 266.7 and 342.9 cm from the bottom of the reactor.

In order to train the developed GMDH, there has to be enough number of data sets of simulated or measured detector signals and reactor AOs. The data set is obtained from SIMULATE-3 calculations (SIMULATE-3, 2009) for a number of reactor core conditions. Table 1 shows 45 different sets of data at different cycle burnups and different control rod positions. In other words, there are 45 scenarios which include three restarting burnup points at BOC, MOC, and EOC. All of the control rods are withdrawn at first, and selected control banks are inserted at a given time. For example, case 1 starts at 0GWd/MT. All control banks are inserted to half of the rod insertion limit (RIL, same as core height), and they are withdrawn after 1 h.

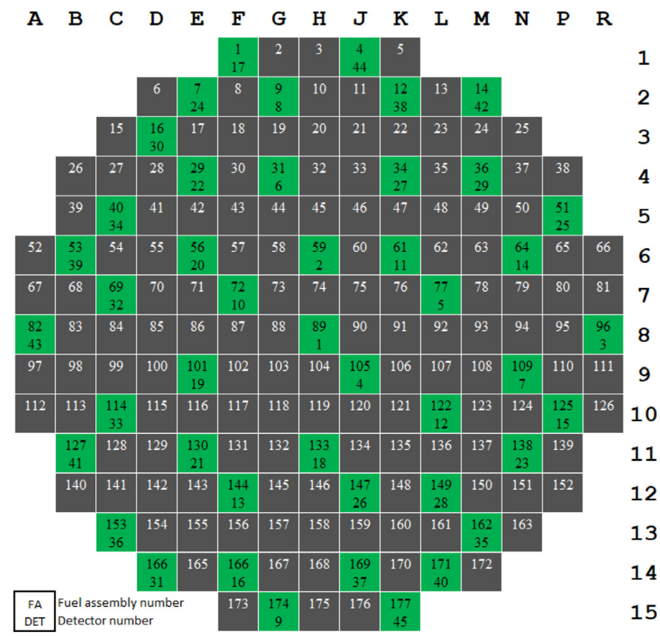

Fig. 1. Radial positioning of the self-powered neutron detector at OPR-1000.

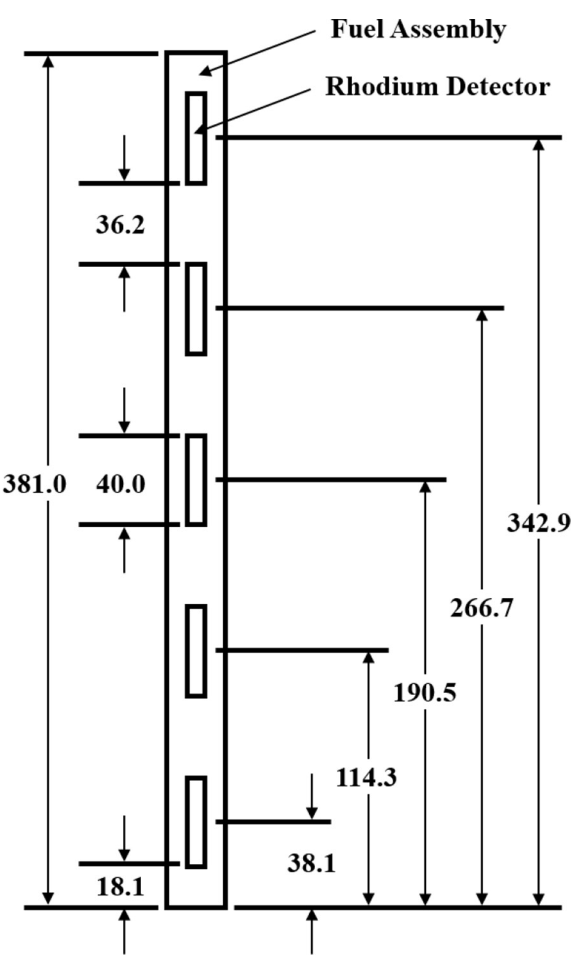

Fig. 2. Axial positioning of the self-powered neutron detector.

The OPR-1000 core uses 73 control element assemblies (CEAs) which consist of three kinds of control rods: regulating banks (R1, R2, R3, R4, R5) for power control, partial strength (PS) for AO