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# Optimization of the worth shape of axially variable strength control rods with simulation optimization methodology for the power maneuvering of pressurized water reactors

Ung-Soo Kim*, Poong-Hyun Seong[1]

*Department of Nuclear and Quantum Engineering, Korea Advanced Institute of Science and Technology, 373-1, Guseong-Dong, Yuseong-Gu, Daejeon 305-701, South Korea*

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**Abstract**

In this research, the optimization of the worth shape of axially variable strength control rods (AVSCRs) is performed to provide optimal performance to the AVSCRs for the power maneuvering of PWRs. The optimization objective is minimizing axial offset (AO) violation of target boundaries during the power maneuvering, and the objective functions for the optimization are relationships between AO variation and axial worth shape of the AVSCRs. However, in this case, an analytic objective function does not exist, and the response for input can only be evaluated by computer simulation. Therefore, a simulation optimization methodology is used. The response surface methodology (RSM) is adopted and objective functions are evaluated with a typical 100-50-100%, 2-6-2-14 h pattern of daily load-follow power maneuvering using reactor simulation code. The optimization result shows that the optimized AVSCRs have good performance on the AO control. The violation of the AO target boundary during the power maneuvering is minimized, and consequently the AO is regulated well within the AO target band during the power maneuvering.


## 1. Introduction

During the power maneuvering of a nuclear power plant, the reactor core is in a transient state induced by transient effects of xenon. The reactivity change that causes change in reactor power makes variation of xenon concentration and axial distribution, and a change in xenon axial distribution causes xenon oscillation, which makes the reactor able to reach an uncontrollable state or trip. Therefore, in order to prevent a xenon oscillation, maintaining the axial power distribution within some prescribed range is required during the power maneuvering. The axial power distributions in a reactor are represented by a variable called axial offset (AO).

$$\mathrm{AO} = \frac{P_{\mathrm{T}} - P_{\mathrm{B}}}{P_{\mathrm{T}} + P_{\mathrm{B}}}$$

where $P_{\mathrm{T}}$ is the power in the top half of the core, $P_{\mathrm{B}}$ is the power in the bottom half of the core.

This is simply the normalized difference between the power in the top half of the core and the power in the bottom half of the core. However, the reactivity change using the existing mechanisms has difficulties in maintaining this AO within the prescribed range. In a previous study, therefore, axially variable

* Corresponding author. Tel.: +82-42-869-3860; fax: +82-42-869-3810.
*E-mail addresses:* uskim@kaist.ac.kr (U.-S. Kim), phseong@kaist.ac.kr (P.-H. Seong).
[1] Tel.: +82-42-869-3820; fax: +82-42-869-3810.

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strength control rods (AVSCRs) are suggested, and lower shifted worth control rods (LSWCRs) are devised as a kind of AVSCRs to mitigate variation of axial power distribution during the power maneuvering. Through this work, the utilities of LSWCRs are identified such that these rods have good characteristics for controlling the AO during the power maneuvering of PWRs, and the power maneuvering without reactivity compensation by change of boron concentration is accomplished (Kim and Seong, 2003).

However, the objectives of developing these LSWCRs were showing feasibility for the use of control rods that have axially varying worth shape, and the LSWCRs were developed intuitively as a kind of AVSCRs. Therefore, in this work, the optimization of the worth shape of the AVSCRs is performed to find optimal worth shape that provides the AVSCRs with optimal performance for the power maneuvering of PWRs. The suggested AVSCRs are axially three-sectioned control rods that are divided into three sections which have different strengths in relation to each other. The optimization objective is minimizing AO violation of target boundaries during the power maneuvering, and the objective functions for the optimization are relationships between AO variation and axial worth shape of the AVSCRs. However, in this case, an analytic objective function does not exist, and the response for input can only be evaluated by computer simulation using reactor simulation code. Therefore, a simulation optimization methodology is used. A simulation optimization problem is an optimization problem where the objective function and some constraints are responses that can only be evaluated by computer simulation.

## 2. Simulation optimization

When the mathematical model of a system is studied using simulation, it is called a simulation model. System behavior at specific values of input variables is evaluated by running the simulation model for a fixed period of time. A simulation experiment can be defined as a test or a series of tests in which meaningful changes are made to the input variables of a simulation model so that we may observe and identify the reasons for changes in the output variables. The process of finding the best input variable value from among all possibilities without explicitly evaluating each possibility is simulation optimization (Carson and Maria, 1997). Simply stated, a simulation optimization problem is an optimization problem where the objective function (objective functions, in case of a multi-criteria problem) and/or some constraints are responses that can only be evaluated by computer simulation.

The major issues that simulation optimization addresses are as follows: First, there does not exist an analytical expression of the objective function or the constraints. This eliminates the possibility of differentiation or exact calculation of local gradients. Second, the objective functions and constraints are stochastic functions of the deterministic decision variables. This presents a major problem in the estimation of even approximate local derivatives. Finally, computer simulation programs are much more expensive to run than evaluating analytical functions. This makes the efficiency of the optimization algorithms more crucial.

There are advantages in using simulation in optimization that can be exploited. In particular: First, the complexity of the system being modeled does not significantly affect the performance of the optimization process. Second, for stochastic systems, the variance of the response is controllable by various output analysis techniques. Finally, where structural optimization of systems is considered, simulation provides an advantage that is often not possible in classical optimization procedures. Here, by employing appropriate techniques, the objective function or constraint can be changed from one iteration to another to reflect alternative design for the system (Azadivar, 1999).

The formulation of simulation optimization problems is often done for maximization or minimization of the expected value of the objective function of the system. A general simulation model comprises $n$ input variables $(x_1, x_2, \ldots, x_n)$ and $m$ output variables $(f_1(\boldsymbol{x}), f_2(\boldsymbol{x}), \ldots, f_m(\boldsymbol{x}))$ or $(y_1, y_2, \ldots, y_m)$ as shown in Fig. 1. Simulation optimization entails finding optimal settings of the input variables, i.e. values of $x_1, x_2, \ldots, x_n$, which optimize the output variables.

A simulation optimization model is displayed in Fig. 2. The output of a simulation model is used by an optimization strategy to provide feedback on the progress of the search for the optimal solution. This in turn guides further input to the simulation model.

Simulation optimization methodologies are classified into the six major categories as follows: The first