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Method of a Daily Load-following Operation for APR+

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1. Introduction

In order to manipulate a nuclear power plant (NPP) on a daily load-following operation, it should be considered that a reactor average temperature, which is closely related to the reactor power level, and an axial power distribution are controlled within limited operation conditions. In present, however, Advanced Power Reactor Plus (APR+)[1] does not have the capability to automatically control the axial power distribution. Therefore, in this paper, two kinds of control methods are developed using reactor control rods for controlling the reactor average temperature and the axial power distribution. The first is a Model Predictive Control (MPC) method aimed for controlling reactor power. So, an existing average temperature method was substituted with this method. The second is a logical control method which adjusts the axial power distribution. And these methods were combined as an automatic controller for a daily load-following operation and numerical simulation was performed using it.

2. Methodology

2.1 Method of Controlling Reactor Average Temperature

The Generalized Predictive Control (GPC) [2-4] method was used for controlling a reactor average temperature. GPC method proposed by Clarke et al. has become one of the most popular MPC methods in both industry and academia. GPC uses a Controller Auto-Regressive Integrated Moving–Average (CARIMA) model for a Single-Input Single-Output (SISO) process. A CARIMA model can be expressed as

$$A(z^{-1})y(t) = B(z^{-1})u(t-1) + \frac{1}{\Delta}C(z^{-1})e(t) \quad (1)$$

where $A(z^{-1})$, $B(z^{-1})$ and $C(z^{-1})$ are polynomials in the backward shift operator z^{-1}.

$$A(z^{-1}) = 1 + A_1 z^{-1} + A_2 z^{-2} + \cdots + A_{n_a} z^{-n_a}$$
$$B(z^{-1}) = B_0 + B_1 z^{-1} + B_2 z^{-2} + \cdots + B_{n_b} z^{-n_b}$$
$$C(z^{-1}) = 1 + C_1 z^{-1} + C_2 z^{-2} + \cdots + C_{n_c} z^{-n_c}$$

The operator Δ is defined as $\Delta = 1 - z^{-1}$. The variables $y(t)$ and $u(t)$are the output and control sequences of the plant and $e(t)$ is a zero mean white noise. For simplicity, the C polynomial is chosen to be 1.

The objective of GPC method is to compute the future control sequence u(t), u(t+1), … in such a way that the future plant output is driven close to a future set-point. This is accomplished by minimizing cost function as below.

$$J(N_1, N_2) = \sum_{j=N_1}^{N_2} R[\hat{y}(t+j\,|\,t) - w(t+j)]^2 + \sum_{j=N_1}^{N_2} Q[\Delta u(t+j-1)]^2 \quad (2)$$

$\hat{y}(t+j\,|t)$ is an optimum j step ahead prediction of the system output on data up to time t. N_1 and N_2 are the minimum and maximum prediction horizons and w(t + j) is a future set-point or reference sequence for the output. R and Q are positive definite weighting variables. In this study, reactor average temperatures and control rod positions are applied to y(t) and u(t) respectively. Using this cost function, we calculate optimized control rod positions of Full Strength Control Element Assemblies (FSCEAs) for reaching a future set-point of a reactor average temperature.

2.2 Method of Controlling Axial Power Distribution

In order to change power level related to a reactor average temperature for a daily load-following operation, FSCEAs are inserted and withdrawn to bring the reactor average temperature close to a set-point. In addition, axial power distribution is changed due to the movement of FSCEAs. For instance, when control rods are located at the upper of half reactor core, reactor power shape is axially bottom skew. And power shape is axially top skew if upper control rods of half reactor core are withdrawn. In addition to the movement of control rods, Xenon-135 concentrations, which are affected by power level, also change axial power shape because Xenon-135 has a strong neutron capture cross section.

APR+ has also a Part Strength Control Element Assembly (PSCEA) besides FSCEAs. So, in this study, the control algorithm that only adjusts axial power distribution using a PSCEA is developed because FSCEAs are controlled only in order to manipulate power level. The concept of this algorithm is to control top skew power shape. That is, when axial power shape leans toward the top of reactor core, a PSCEA is inserted and if it doesn't, a PSCEA is withdrawn. This concept is based on the phenomenon that axial power shape gradually leans toward the top of the reactor core according to the burn-up. In this algorithm, a PSCEA moves from the top to the half of reactor core. The reason why the maximum inserted position is determined as the half of reactor core is to effectively control axial power distribution. The key algorithm is shown in Table 1.

Table 1. Key Algorithm of a PSCEA's Movement

Axial Shape Index (ASI*)conditions	PSCEA Action
Logic : True or False {Abs(Target_ASI – Present_ASI) > 0.015 & (Target_ASI – Present_ASI) > 0.0 & Present_ASI < 0.0}	True : ->Insertion False : ->Withdrawal

$$* \, ASI = \frac{FZBOT - FZTOP}{FZBOT + FZTOP}$$

FZBOT : power in the bottom half of the core
FZTOP : power in the top half of the core

3. Simulation Procedure on a Daily Load-following Operation

For a simulation of a daily load-following operation, KISPAC-1D code [5] is used. The reason why KISPAC-1D code is selected is that it generates one-dimensional power distribution as well as reactor average temperature (Tavg). And reactor average temperature and axial power distribution control method are coded using standard C programming language and they are coupled as an automatic controller. Detailed numerical simulation procedure on a daily load-following operation is as the following.

At first, the control method of reactor temperature using GPC method receives initial Tavg as an input and generates optimized FSCEA's positions. And, at the same time, the new position of a PSCEA is also determined by the control algorithm of axial power distribution. Then, the KISPAC-1D code receives the positions of FSCEAs and a PSCEA and recalculates a new Tavg and ASI. These procedures are repeated every 10^{th} second.

4. Results

During a daily load-following operation, at first, the power level decreases from 100% to 50% in two hours and is maintained at 50% for six hours. After that, the power level increases to 100% for another two hours. During the simulation, especially, constant Tavg program is used in order to reduce the movement of control rods. So, target Tavg has a constant value of 308.9℃ between 100% and 75% power level.

Fig. 1 shows average temperatures and power levels during a daily load-following operation. Although there are some differences between Target_Tavg and Present_Tavg, Present_Tavg is controlled well by GPC method because the deviations are acceptable.

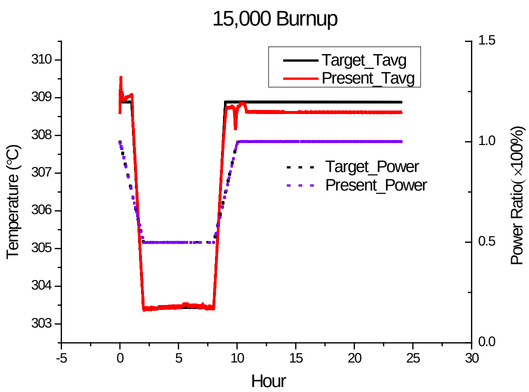

Fig. 1. Temperature and Power Ratio

Fig. 2 shows that FSCEAs and a PSCEA are inserted and withdrawn in order to control Tavg and axial power distribution. Through Fig. 2, it is confirmed that a PSCEA is inserted if the logic of Table 1 is true and withdrawn if it is not. And the deviations between Target_ASI and Present_ASI are less than 0.015 which is set-point at the algorithm of a PSCEA's movement.

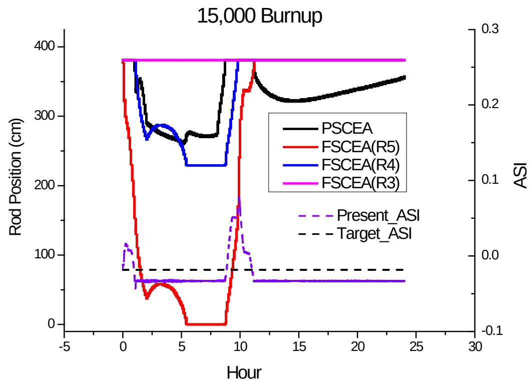

Fig. 2. Control Rod Positions and ASI

5. Conclusion

In this study, an automatic controller using the control methods both reactor average temperature and axial power distribution has been developed for a daily load-following operation of APR+. Through the simulation results, we confirmed that reactor average temperature and power level were properly controlled and axial power distribution was also restricted within the given condition. In conclusion, the developed automatic controller is suitable for a daily load-following operation of APR+.

Acknowledgment

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REFERENCE

[1]APR+ Stand Safety Analysis Report, Korea Hydro & Nuclear Power co., Ltd.

[2]Eduardo F. Camacho and Carlos Bordons, Model Predictive Control, Springer, 2007, p. 127-142.

[3] W.H. Kwon and A. E. Pearson, A Modified Quadratic Cost Problem and Feedback Stabilization of a Linear System, IEEE Trans. Automatic Control, 22, p. 838(1977).

[4]Man Gyun Na, Sun Ho Shin, and Whee Cheol Kim, A Model Predictive Controller for Nuclear Reactor Power, J. Korean Nucl. Soc.,35,p.399 (2003).

[5] Development of the KISPAC-1D Code for the Application to the Performance Analysis of the Korea Next Generation Reactor, KOPEC/TR/99-008, 1999.