Automatic Control of Reactor Temperature and Power Distribution for a Daily Load-following Operation

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1. Introduction

An automatic control method of reactor power and power distribution was developed for a daily load-following operation of APR1400 [1]. This method used a model predictive control (MPC) methodology having second-order plant data. And it utilized a reactor power ratio and axial shape index as control variables. However, the reactor regulating system of APR1400 is operated by the difference between the average temperature of the reactor core and the reference temperature, which is proportional to the turbine load. Thus, this paper reports on the model predictive control methodology using fourth-order plant data and a reactor temperature instead of the reactor power shape.

The purpose of this study is to develop a revised automatic controller and analyze the behavior of the nuclear reactor temperature (Tavg) and the axial shape index (ASI) using the MPC method during a daily load-following operation.

2. Methodology

2.1 Method of Generalized Predictive Control

The generalized predictive control (GPC) method [2], which is a model predictive control method, is used for a daily load-following operation. The controller auto-regressive integrated moving-average (CARIMA) model is used to formulate generalized predictive control.

$$A(z^{-1})y(t) = B(z^{-1})u(t-1) \qquad \text{Eq. (1)}$$

$$A(z^{-1}) = I_{n\times n} + A_1 z^{-1} + A_2 z^{-2} + \cdots + A_{na} z^{-na}$$

$$B(z^{-1}) = B_0 + B_1 z^{-1} + B_2 z^{-2} + \cdots + B_{nb} z^{-nb}$$

$A(z^{-1})$ and $B(z^{-1})$ represent multivariable polynomial matrices. $A(z^{-1})$ polynomials are control variables such as a reactor temperature and ASI. $B(z^{-1})$ polynomials are manipulated variables such as full strength control element assembly (FSCEA) and part strength control element assembly (PSCEA). z^{-1} is the backward shift operator that means past data. In this study, fourth-order plant data of $A(z^{-1})$ and $B(z^{-1})$ are used from (t-4) time to (t-1) time.

The generalized predictive control method involves the application of a control sequence that minimizes the multistage cost function of the following equation:

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

The prediction of y(t+j|t) can be expressed in condensed form as Gu plus f. Thus, Eq. (2) can be rewritten as below.

$$J = (Gu + f - w)^T R(Gu + f - w) + u^T Q u \qquad \text{Eq. (3)}$$

If there are no constraints, the optimum manipulated values can be expressed as Eq. (4)

$$u = (G^T R G + Q)^{-1} G^T R(w - f) \qquad \text{Eq. (4)}$$

2.2 Method of Model Parameter Estimation

The generalized predictive control method needs the appropriate parameters of a plant model. The parameters are usually obtained by optimizing a function that measures how well the model fits the existing input-output data. The multivariable CARIMA model described by Eq. (1) can easily be expressed as Eq. (5). That is, the parameter estimation equation using the CARIMA model is

$$\hat{y}(t+j) = \theta^T(t) \cdot \varphi(t) \qquad \text{Eq. (5)}$$

$$\theta^T(t) = [A_1(t)A_2(t)\cdots A_{na}(t)B_0(t)B_1(t)\cdots B_{nb}(t)]$$

$$\varphi^T(t) = \begin{bmatrix} -y(t) - y(t-1) - y(t-na+1)\Delta u(t)\Delta u(-1) \\ \cdots \Delta u(t-nb) \end{bmatrix}$$

where θ^T is the vector of the parameters to be estimated, $\varphi(t)$ is a vector of the past input and output measures, and $\hat{y}(t+j)$ is a vector of the latest output measures. The parameter vector $\theta(t)$ is estimated with the aid of a recursive least-squares method as follows:

$$\theta(t) = \theta(t-1) + \Sigma(t)\varphi(-1)\left[y(t) - \theta^T(t-1)\varphi(t-1)\right]$$

$$\Sigma(t) = \Sigma(t-1) - \frac{\Sigma(t-1)\varphi(t-1)\varphi^T(t-1)\Sigma(t-1)}{\lambda(t) + \varphi^T(t-1)\Sigma(t-1)\varphi(t-1)}$$

2.3 Automatic Controller

Two methods of GPC and model estimation are coded using standard C programming language, respectively. These codes are coupled as an automatic controller that is capable of receiving and processing control rod positions, Tavg and the ASI from the KISPAC-1D code.

3. Simulation condition and procedure

The key of the load-following operation is to control the axial power distribution within the operation limits while the reactor power follows the target power. In APR1400, control rods and soluble boron are used as the means for the daily load-following operation. Therefore, in this paper, control rods and a simplified boron scenario are used for the daily load-following operation of APR1400. KISPAC-1D code is used. Detailed simulation conditions are given in Table 1.

Table 1. Simulation conditions for the daily load-following operation

Core thermal power	3983 MWth
Core burn-up	500 MWD/MTU
KISPAC-1D operation time	0 ~ 43210 sec.
TBN power change(%) Simplified boron scenario(ppm)	100 - 50 - 50 - 100 1125-1090-1090-1125
Rates of TBN power change (MPC target temp.)	±25 %/h (±15˚F)
Operation limit(Tavg/ASI)	±2˚F / ±0.27

The automatic controller receives Tavg, ASI and positions of the PSCEA and FSCEA from the KISPAC-1D code. Using them, the automatic controller generates optimized control rod positions in control horizons and then, the first positions of PSCEA and FSCEA are used for next time step. The KISPAC-1D code receives optimized positions and calculates a new Tavg and ASI. These procedures are repeated every second.

4. Results

The temperature, power and ASI from 0s to 43,210s are shown in Figure 1 and 2. The MPC_temp, MPC_pow and MPC_ASI are the results generated by the KISPAC-1D code using the automatic controller. The values of the targets and the MPC results such as temperature and power are nearly the same. The ASI values are between +0.5 and -0.5. The ASI fluctuates because the automatic controller prioritizes temperature control due to the temperature weighting factor. According to the power decrease of the turbine, in Figure 2, the automatic controller inserts control rods from All Rod Out(ARO) in order to match the changing Tavg. Thus, the axial power shape leans toward the bottom of the core from 10s to 1,700s because the control rods are located at the top half of the core. However, after 1700s, the axial power distribution gradually flattens. Generally, during a simulation, the automatic controller properly controls the Tavg and the ASI.

Figure 3 indicates how the control rod position changes in relation to the power changes. The control rod positions are withdrawn and inserted even though the reactor average temperature remains unchanged between 7,200s and 28,800s. This phenomenon is caused by changes of boron and xenon concentration.

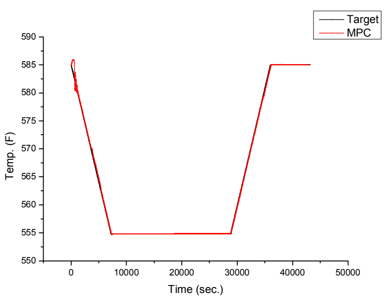

Fig. 1. Changes of reactor average temperature every second

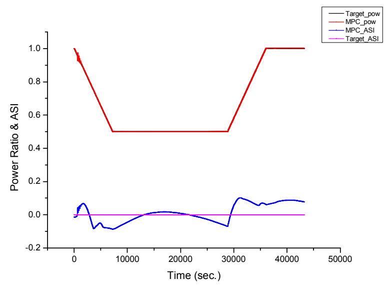

Fig. 2. The comparison of target values with simulation results using the automatic controller every second

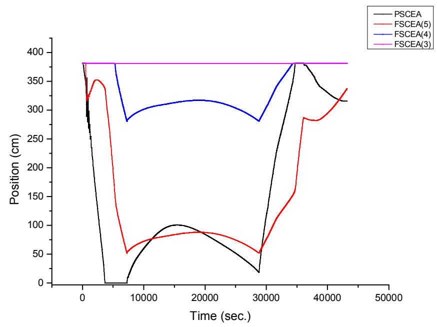

Fig. 3. Changes of control rod positions every second

5. Conclusion

A new automatic controller was developed for controlling Tavg and ASI. And a numerical simulation for a daily load-following operation was performed with the automatic controller. According to the simulation results, the Tavg and ASI were within the operating limits during a daily load-following operation. These results confirmed that the new automatic controller is suitable for the daily load-following operation of APR1400.

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