Automatic Power Control for Daily Load-following Operation using Model Predictive Control Method

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1. Introduction

Under the circumstances that nuclear power occupies more than 50%, nuclear power plants are required to be operated on load-following operation in order to make the effective management of electric grid system and enhanced responsiveness to rapid changes in power demand.

Conventional reactors such as the OPR1000 and APR1400 have a regulating system that controls the average temperature of the reactor core relation to the reference temperature. This conventional method has the advantages of proven technology and ease of implementation. However, this method is unsuitable for controlling the axial power shape, particularly the load-following operation. Accordingly, this paper reports on the development of a model predictive control method which is able to control the reactor power and the axial shape index.

The purpose of this study is to analyze the behavior of nuclear reactor power and the axial power shape by using a model predictive control method when the power is increased and decreased for a daily load-following operation. The study confirms that deviations in the axial shape index (ASI) are within the operating limit.

2. Methodology

2.1 Method of Generalized Predictive Control

The method of model predictive control [1] originated in the late seventies and has developed considerably since then. There are many applications of predictive control successfully in use at the current time, not only in the process industry but also applications to the control of other processes. This study uses the generalized predictive control method. The basic idea of generalized predictive control is to calculate a sequence of future control signals in such a way that it minimizes a multistage cost function defined over a prediction horizon. The index to be optimized is the expectation of a quadratic function measuring the distance between the predicted system output and a predicted reference sequence over the horizon plus a quadratic function measuring the control effort.

Controller auto-regressive integrated moving-average(CARIMA) model is used to formulate generalized predictive control. A CARIMA model for two outputs and two inputs is expressed as

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

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

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

where $A(z^{-1})$ and $B(z^{-1})$ represent polynomial matrices.

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

$$J(N_1, N_2, N_3) = \sum_{j=N_1}^{N_2} \delta(j)[y(t+j|t) - w(t+j)]^2 + \sum_{j=1}^{N_3} \lambda(j)[\Delta u(t+j-1)]^2 \qquad \text{(Eq. 2)}$$

The objective of generalized predictive control is to compute the future control sequence u(t), u(t+1) and this objective is accomplished by minimizing $J(N_1, N_2, N_3)$. The future control inputs, which are the control rod positions, are obtained as follows:

$$u = (G^T G + \lambda I)^{-1} G^T (w - f) \qquad \text{(Eq. 3)}$$

2.2 Method of Model Parametric Identification

The proposed generalized predictive control method needs appropriate parameters of the model. The parameters of the model are usually obtained by optimizing a function that measures how well the model, with a particular set of parameters, fits the existing input-output data. When process variables are perturbed by a transient nature, such as a nuclear reactor, the identification problem is interpreted as a parameter estimation problem, which is expressed in terms of following. Parameter estimation equation:

$$z_k = \theta \Phi_k \qquad \text{(Eq. 4)}$$

where Θ is the vector of the parameters to be estimated, Φ_k is a vector of the past input and output measures, and z_k is a vector of the latest output measures. The multivariable CARIMA model described by Eq. 1 can easily be expressed as equation Eq. 4. That is, Θ,Φ_k can be expressed as follows:

$$\Theta = [A_1\ A_2\ \cdots\ A_{na}\ A_{na+1}\ B_0\ B_1\ \cdots\ B_{nb}]$$

$$\Phi_k = [-y(t-1) - y(t-2) \cdots - y(t-na)(t-nb)$$

$$\Delta u(t-1)\Delta u(t-2) \cdots \Delta(t-nb)]^T \qquad \text{(Eq. 5)}$$

The parameters are identified with the aid of a least squares identification algorithm.

3. Simulation Procedure

Methods of generalized predictive control and real time model identification are coded in standard C language as a model predictive controller. Model predictive controller has the ability to interface with the code of a nuclear plant system (namely the KISPAC-1D code) which was developed for the analysis of performance related design basis events with one-dimensional reactor core model. The simulation procedure as follows: the KISPAC-1D code generates power, ASI and two control rod positions. The latter are divided into two control rod positions of part strength and full strength. The model predictive controller then calculates the optimized control rod positions every second by using methods of plant model parametric identification and generalized predictive control.

The reference pattern of power change consists of a 25%/h power decrease and increase. That is, the power decreases from 100% to 50% in 2h after the signal of a power change starts. The power is then maintained at 50% for 6h. After that, the power increases to 100% for another 2h.

The operating conditions of the reactor core are as follows: the boron concentration is constant for 10h and the speed of the control rod position accelerates from a minimum of 0.05cm/s to a maximum of 1.27cm/s. In addition, the burnup is 500MWD/MTU.

4. Results

Figure 1 shows the powers and the ASI from 10s to 29,000s. The Ref_ASI is 0.00 and the Ref_power is the turbine power with a change rate of ±25%/h (±0.006944%/s). The MPC_power is the reactor power generated by the KISPAC-1D code with the model predictive controller. The average deviation of two powers is less than about 0.3% and the maximum deviation is about 2.48% at 7,201s. The maximum power deviation occurs when model predictive controller calculates the optimal control rod positions on the basis of the power and ASI; the ASI value reaches its greatest value at 7,201s.

After 23,000s, there is a gradual increase in power deviations. This decrease occurs because the control rods are inserted deeper than the required depth to compensate for any power defect. Power defects may be induced by such positive reactivity as the moderator temperature when the reactor power is decreased. Hence, there is no extra control rod to increase the reactor power after 2,300s.

Figure 2 shows how the control rod position changes in relation to the power change. The top position of all control rods is 381 cm and the bottom position is 0 cm. Between 7,201s and 21,601s, the control rod positions change even though the power remains unchanged. This phenomenon occurs when the decrease in power leads to an increase in the xenon concentration. In addition, the deviation of the ASI from Ref_ASI is within 0.7%, which is smaller than the operation limit. After 25,201s, all control rods are out.

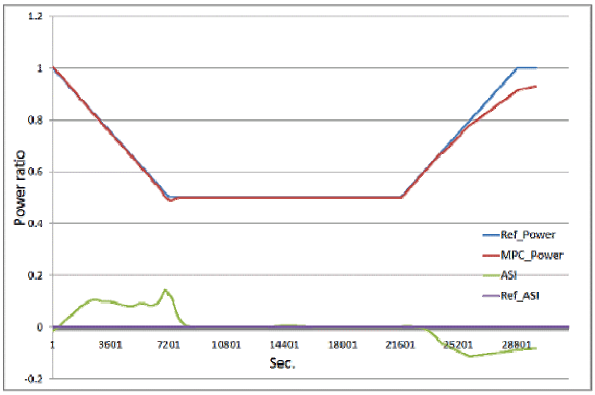

Fig. 1. The power and ASI of a power change simulation from 10s to 29,000s

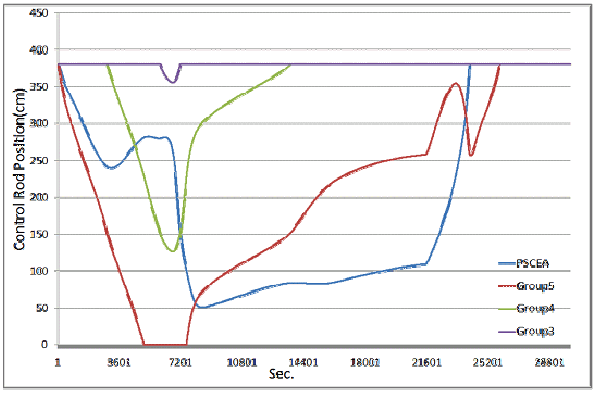

Fig. 2. The control rod position of power change simulation from 10s to 29,000s

5. Conclusion

The power change simulation for a daily load-following operation was performed with a real-time model of parametric identification and a generalized predictive control method. According to the simulation results, the power and the ASI are within the operating limits; however, it is not possible to return to 100% power from 50% power. This phenomenon is basically the problem of system dynamics rather than the control method.

Thus, future studies will focus on the use of changes in the boron concentration to compensate for power defects when power is decreased or increased. In addition, the weighting factors of the generalized predictive control method will be changed and sensitivity studies on the weighting factors will be performed to minimize deviations of the power and ASI during power changes.

REFERENCE

[1] Eduardo F. Camacho and Carlos Bordons, "Model Predictive Control", Springer, 2007.