Transactions of the Korean Nuclear Society Autumn Meeting
Jeju, Korea, October 21-22, 2010

Numerical Simulation of Daily Load Follow Operation for APR1000 using KISPAC-1D

Yu Sun Choi
Korea Electric Power Research Institute, 65 Munji-ro Munji-dong, Yuseong-gu, Daejeon 305-380
yschoi@kepri.re.kr

1. Introduction

Model predictive control has proved to be an efficient control strategy as a powerful tool for the control of industrial process systems.[1-4] A model predictive control (MPC) method is applied to APR1000 reactor as a power controller for power level and axial power distribution controls with boron concentration control logics. In this paper, daily load follow operations are numerically simulated by KISPAC-1D at EOC for APR1000.[5]

2. Methodology

The main idea of MPC algorithms is to solve an optimization problem in order to find the control vector trajectory that optimizes the cost function over a future prediction horizon. With the idea, MPC method is applied to minimize control rod moving distance in daily load follow operation for APR1000.

2.1 Model Definition

The reactor dynamics is described by the controlled auto-regressive and integrated moving average (CARIMA) model and the predicted outputs can be derived as a function of past values of inputs and outputs and of future control signals.

$$A(q^{-1})y(t) = B(q^{-1})\Delta u(t-1) + C(q^{-1})\xi(t) \quad (1)$$

where $y \in R^n$ is the output(n=the number of outputs), $\Delta u \in R^n$ is the control input change between two neighboring time steps(m=the number of inputs), $\xi \in R^n$ is a stochastic noise vector sequence with zero mean value, $A(q^{-1})$ is monic matrix, $B(q^{-1})$ is n x m polynomial in the backward shift operator q^{-1}..

2.2 Cost Function

The control strategy minimizes a weighted sum of square predictive future errors and square control signal increments. In order to achieve fast responses and prevent excessive effort, a performance index for deriving an optimal input is represented by following quadratic function:

$$J = \frac{1}{2}\sum_{j=1}^{N}\left(\hat{y}(t+j\,|\,t) - w(t+j)\right)^T Q\left(y(t+j\,|\,t) - w(t+j)\right) + \frac{1}{2}\sum_{j=1}^{M}\Delta u(t+j-1)^T R \Delta u(t+j-1), \quad (2)$$

subject to constraints

$$\begin{cases} \hat{y}(t+N+i) = w(t+N+i), & i = 1,\cdots,L \\ \Delta u(t+j-1) = 0, & j > M \quad (M < N) \end{cases}$$

where $\hat{y}(t+j\,|\,t)$ is an optimum j-step-ahead optimal prediction of the system output (power level) based on data up to time t. The vector, w, is a setpoint sequence for the output vector and Δu is a control input change (R5 control rod position change) between two neighboring time steps. Q and R weight particular components of $(\hat{y} - w)$ and Δu at certain future time intervals, respectively. N is the prediction horizon and M is the control horizon. The prediction horizon represents the limit of the instants in which it is desired for the output to follow the reference sequence. Equation (2) can be solved by using the Lagrange multiplier technique.[3]

2.3 Constraints

There are two constraints. The first constraint, $\hat{y}(t+N+i) = w(t+N+i),\ i = 1,\cdots,L$, which makes the output follow the reference input beyond the prediction horizon, guarantees the stability of the controller. The second constraint, $\Delta u(t+j-1) = 0$ for $j > M$, means that there is no variation in the control signals after a certain interval $M < N$.[4]

2.4 Control Input and Output variables

The number of outputs is two and the outputs consist of the power level and the ASI. The number of inputs is also two and the inputs are the axial positions of two types (regulating control banks and part-strength control banks) of control rod banks.

2.5 Parameter Estimation

The reactor core dynamics changes according to reactor power, a variety of control rod positions, and so on. In order to reflect these various conditions and non-linear characteristics, it is required to estimate the reactor core dynamics every time step. Therefore, the parameter estimation algorithm is used to identify the system dynamics every time step. This identified system model is used to solve the control problem.[4]

3. Application to APR1000 reactor

The numerical simulation was performed to the daily load follow operation of APR1000 which was performed by KISPAC-1D code [5]. Following figures are show results for daily load-following operation at 12,000 MWD/T. It was applied for simulation that a daily load cycle of a typical 100-50-100%, 2-6-2-14hr pattern. Allowable ASI band was set to ±5% band from the ASI of 100% power equilibrium xenon state. It is shown that the reactor power follows well the desired reactor power and also the ASI remains within the specified ASI band.

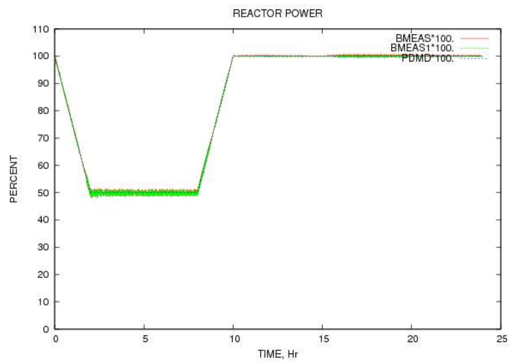

Fig. 1. Reactor Power (%)

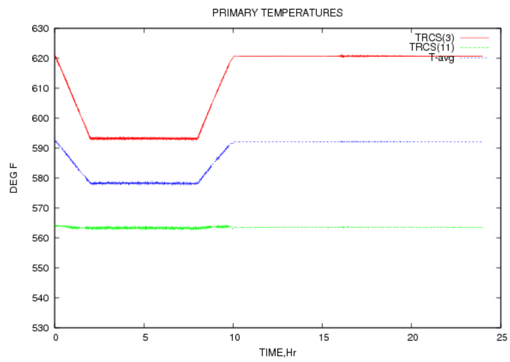

Fig. 2 Primary Temperature (Deg. F)

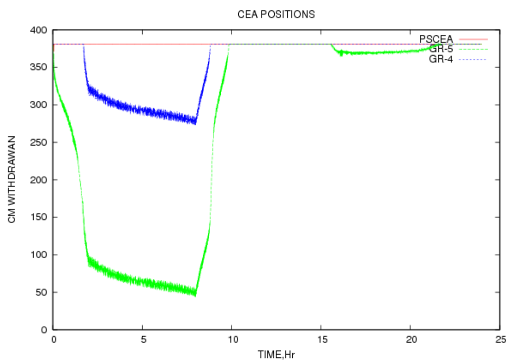

Fig. 3. CEA Positions (cm)

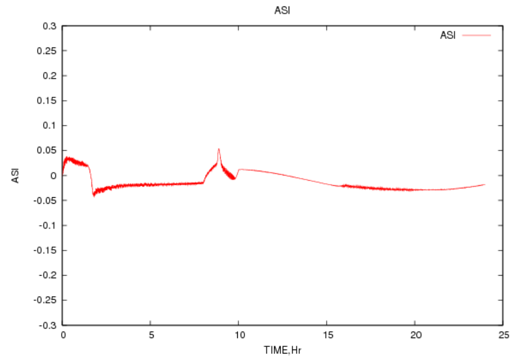

Fig. 4. Axial Shape Index

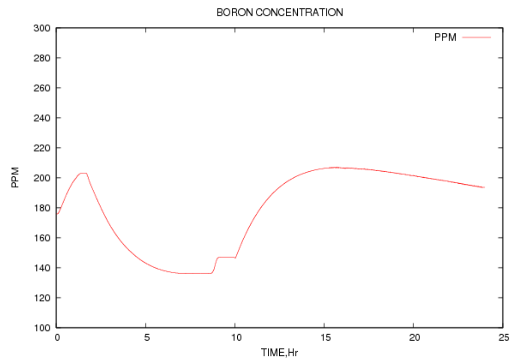

Fig. 5. Boron Concentration (ppm).

4. Conclusion

MPC controller is designed to control the power level and maintain the ASI in a specified ASI band for daily load-following operation of APR1000. As a result of this work, Model Predictive Control works well in a condition of properly given boric acid scenario from boron control logic of KISPAC-1D. It is shown that daily load follow operation could be maneuvered at near EOC of APR1000.

Reference

[1] C. E. Garcia, D. M. Prett, and M. Morari, “Model Predictive Control: Theory and Practice – A Survey,” *Automatica*, Vol. 25, No. 3, pp. 335-348, 1989.

[2] M.G. Na, D.W. Jung, S.H. Shin, J.W. Jang, K.B. Lee, and Y.J. Lee, “A Model Predictive Controller for Load-Following Operation of PWR Reactors,” *IEEE Trans. Nucl. Sci.*, Vol. 52, No. 4, pp. 1009-1020, Aug. 2005.

[3]“Development of MPC Program for Load Following Operation of APR1400”, TM.S02.P2009.0100, KEPRI,2009.

[4] Y. S. Choi, et al., “Numerical Simulation of Load-Following Operation for APR1400,” Trans. of KNS Spring Meeting, May 2009.

[5] “Development of the KISPAC-1D Code For the Performance Analysis of the Korea Next Generation Reactor”,KOPEC/NED/TR/99-008, June 1999.