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Numerical Simulation of Load-Following Operation for APR1400 using KISPAC-1D

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1. Introduction

A model predictive control (MPC) method is applied to APR1400 reactor power controller for power level and axial power distribution controls. The model predictive control methodology has received much attention as a powerful tool for the control of industrial process systems. [1-4]

In this paper, daily load follow operations are numerically simulated by KISPAC-1D [5]. In this simulation, boric acid concentrations scenario are fixed from KOPEC generating data sets.

2. Methodology

The basic concept of the MPC is to solve an optimization problem for a finite future at current time and once a future input trajectory has been chosen, only the first element of that trajectory is applied as the input to the plant. At the next time step, new values of the system output are measured, the control horizon is shifted forward by one step, and the same calculations are repeated. The purpose of taking new measurements at each time step is to compensate for unmeasured disturbances and model inaccuracies, both of which cause the measured system output to be different from the one predicted by the model.

In order to achieve fast responses and prevent excessive effort, a performance index for deriving an optimal input is represented by following quadratic function:

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

subject to constraints

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

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. 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]

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. Equation (1) can be solved by using the Lagrange multiplier technique.[3]

$$A(q^{-1})\,y(t) = B(q^{-1})\Delta u(t-1) + C(q^{-1})\xi(t) \quad (2)$$

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, and q^{-1} is backward shift operator, $A(q^{-1})$ is monic matrix, $B(q^{-1})$ is n x m polynomial .

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.

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 nonlinear 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 APR1400 reactor

The numerical simulation was performed to the daily load-following operation of APR1400 which was performed numerically by KISPAC-1D code [5].

Figure 1 and 2 show the numerical simulation results for daily load-following operation for 0.5GWD/T and 12,000GWD/T, respectively. 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 inside the specified ASI band.

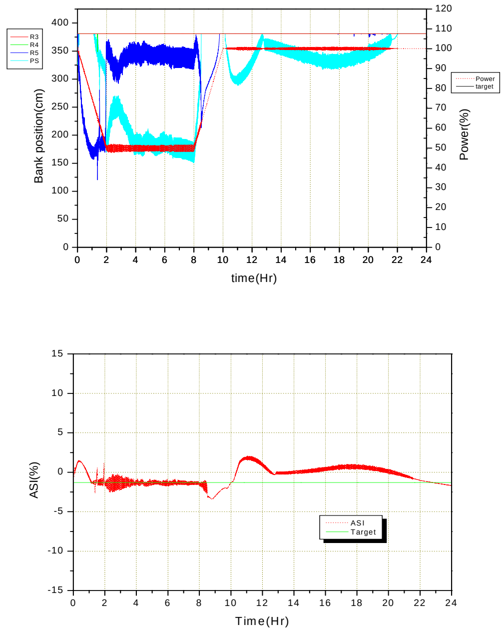

Fig. 1. Simulation results at 0.5GWD/T.

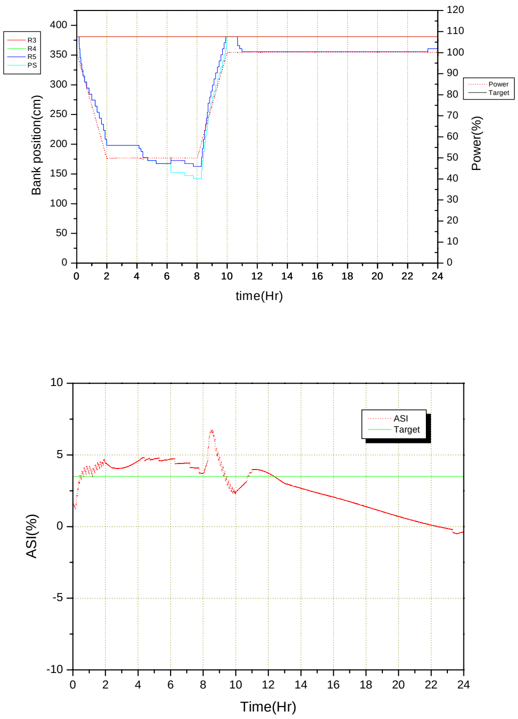

Fig. 2. Simulation results at 12.0GWD/T.

4. Conclusion

In this work, we presented a MPC controller to control the power level and maintain the ASI in a specified ASI band for daily load-following operation of APR1400.

It is found that KISPAC-1D code is a useful system design tool which has one dimensional core geometry model in core, and can handle thermal dynamic analysis of Balance of Plant(BOP). It has many functions of NSSS (Nuclear Steam Supply System), such as Reactor Regulating System, Chemical Volume Control System, Control Element Drive Mechanism, Steam Bypass System and so on.

From a result of this work, Model Predictive Control works well in a condition of properly given boric acid scenario each burn-up steps with KISPAC-1D.

It also be shown that daily load-following operation for APR1400 could be maneuvered by annul cycle length core with reasonable control rod movement.

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