Load-Following Control of PWR Reactors Using a Model Predictive Control Method

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1. Introduction

The nuclear plant characteristics vary with operating power levels, and ageing effects in plant performance and changes in nuclear core reactivity with fuel burnup generally degrade system performance. Also, if load-following operation is desired, daily load cycles can change plant performance significantly. In this work the model predictive controller combined with a parameter estimator is used to take into account the change of operating points and the time-varying characteristics.

2. Model Predictive Control Method

The model predictive control method solves an optimization problem for finite future time steps at current time and to implement the first optimal control input as the current control input. At the next time step, new values of the measured output are obtained, 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 inaccuracy, both of which cause the measured system output to be different from the one predicted by the model. The associated performance index is the following quadratic function:

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

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

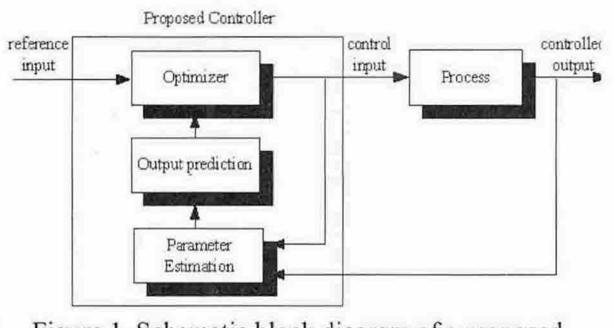


Figure 1. Schematic block diagram of a proposed controller.

The prediction horizon represents the limit of the instants in which it is desired for the output to follow the reference sequence. The first constraint, $\hat{\mathbf{y}}(t+N+i) = \mathbf{w}(t+N+i), i=1,\cdots,L$, which makes the output follow the reference input over some range, guarantees the stability of the controller. The second constraint, $\Delta\mathbf{u}(t+j-1)=0$ for $j>M$, means that there is no variation in the control signals after a certain interval $M<N$. To obtain control inputs, the predicted outputs first have to be calculated as a function of past values of inputs and outputs and of future control signals. The one-step-ahead optimal prediction of $\hat{\mathbf{y}}(t+1\,|\,t)$ is derived as follows:

$$\hat{\mathbf{y}}(t+1\,|\,t) = -\hat{\mathbf{A}}_1\mathbf{y}(t) - \hat{\mathbf{A}}_2\mathbf{y}(t-1) - \cdots - \hat{\mathbf{A}}_{nA}\mathbf{y}(t-nA+1) + \hat{\mathbf{B}}_0\Delta\mathbf{u}(t) + \hat{\mathbf{B}}_1\Delta\mathbf{u}(t-1) + \cdots + \hat{\mathbf{B}}_{nB}\Delta\mathbf{u}(t-nB).$$

It can be rewritten as

$$\hat{y}_i(t+1) = \hat{\boldsymbol{\theta}}_i^{\,T}(t)\cdot\boldsymbol{\varphi}(t),$$

The parameter vector $\hat{\boldsymbol{\theta}}_i(t)$ that denotes the i-th row of the matrix $\hat{\boldsymbol{\theta}}$ is estimated as follow:

$$\hat{\boldsymbol{\theta}}_i(t) = \hat{\boldsymbol{\theta}}_i(t-1) + \mathbf{F}_i(t)\boldsymbol{\varphi}(t-1)\left[y_i(t) - \hat{\boldsymbol{\theta}}_i^{\,T}(t-1)\cdot\boldsymbol{\varphi}(t-1)\right]$$

$$\mathbf{F}_i(t) = \mathbf{F}_i(t-1) - \frac{\mathbf{F}_i(t-1)\boldsymbol{\varphi}(t-1)\boldsymbol{\varphi}^T(t-1)\mathbf{F}_i(t-1)}{1+\boldsymbol{\varphi}^T(t-1)\mathbf{F}_i(t-1)\boldsymbol{\varphi}(t-1)}$$

where the covariance matrix $\mathbf{F}_i(0) > 0$.

3. APPLICATION TO Load-Following Operation of PWR Reactors

The proposed load-following controller was applied to the Yonggwang unit 3 nuclear power plant (YGN 3) modeled by the three-dimensional MASTER code. The MASTER code is written in Fortran and the proposed control algorithm in MATLAB. Visual C++ is in charge of the variable transfer between the MASTER code and the proposed control algorithm. The power level is mainly controlled by the 5 regulating control banks, R5, R4, R3, R2, and R1, and the axial shape index is mainly controlled by the 2 part-strength control banks, P1 and P2. However, the regulating control rod movement affects the axial shape index as well as the power level. Also, the part-strength rod movement affects the power level as well as the axial shape index. Actually, these inputs and outputs are closely coupled with one another. In this work, it is assumed that the bottom half part of the part-strength control banks (P1 and P2 control banks) contains grey absorber material (refer to Fig. 2) and the top half part does not in order to effectively be in charge of the axial shape index control, but actually YGN 3 has part-strength control rods which contain grey absorber material in full space of the bottom and top half parts.

Figure 3 shows its simulation results. It is desired that the reactor power follows a daily load cycle of a typical 100-50-100%, 2-6-2-14hr pattern. It is shown that the power level well follows the desired power level. Also, it is shown that the ASI tracks the desired ASI very well.

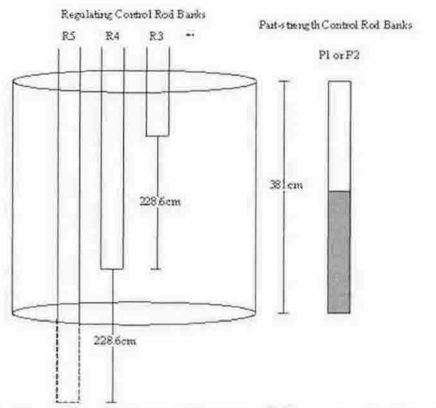
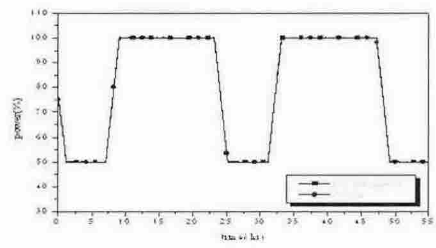
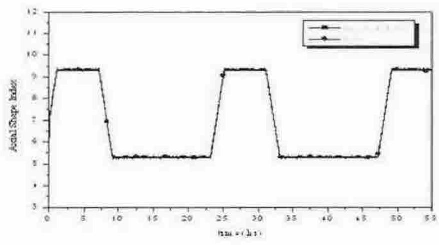


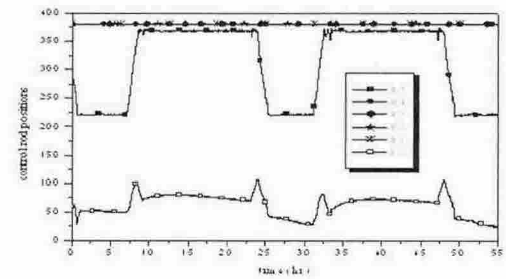
Figure 2. Overlapped positions of the regulating control rod banks and the part-strength control rod banks of which only the bottom half is filled with the neutron absorber material.



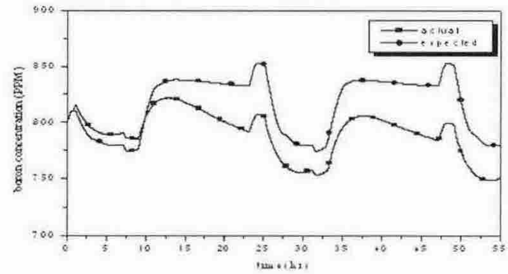
(a) reactor power



(b) axial shape index



(c) control rod bank positions



(d) boron concentration

Figure 3. Numerical simulation results

4. CONCLUSIONS

In this work, a model predictive control algorithm to systematically control the power level and the axial power distribution for load-following operation has been presented. The model predictive controller is combined with a parameter estimator to additionally take into account the change of operating points and the time-varying characteristics. The proposed controller was applied to verify the load-following operation of KSNPs which are simulated numerically by MASTER. The power level and the axial shape index are controlled simultaneously and systematically by the regulating control rod banks and the part-strength control rod banks. It was known that the power level well follows the desired power level, and also ASI follows the desired ASI well.

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