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# Reconfigurable Control for Load-Following Operation of APR1400

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## 1. Introduction

If nuclear power plants are operated in a load-following mode, the control rods must move frequently, which induces axial xenon oscillations. The power distribution control gets important. Therefore, it is required that the thermal power follows the desired one and also, the axial shape index (ASI) stays in a desired band. A model predictive control (MPC) method is applied to design a reconfigurable controller for power level and axial power distribution controls in nuclear reactors according as ASI deviates from the specified ASI band. The model predictive control methodology [1-2] has received much attention as a powerful tool for the control of industrial process systems.

In this paper, a reconfigurable controller consisting of a normal controller and another standby controller is designed to control the load-following operation of APR1400 reactors. The normal controller and the standby controller use a model predictive control (MPC) method where the future power level and ASI (outputs) are predicted by using an optimal predictor and the difference between the desired outputs and the predicted outputs are minimized.

The results of numerical simulations to check the performance of the proposed controller show that the power level controlled by the proposed reconfigurable controller could track the target power level effectively, satisfying all control constraints. Also, the normal controller is automatically switched to the standby controller when the ASI deviates from a specified band.

## 2. Reconfigurable Control System Design

The reconfigurable controller consists of a normal controller and another standby controller. The normal controller which is a single input and single output (SISO) system controls reactor power level when ASI is inside a specified ASI band. The standby controller which is a multiple input and multiple output (MIMO) system controls both power level and ASI when ASI deviates from the specified ASI band. These two controllers use an MPC method.

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.

### *2.1 Normal Controller (SISO Controller)*

The normal controller controls only the nuclear power level by adjusting the regulating control rod bank position with the help of the boric acid concentration change. Therefore, the following cost function is presented for SISO control logic:

$$\begin{aligned} J=&\frac{1}{2}\sum_{j=1}^{N}\left(\hat{y}(t+j\mid t)-w(t+j)\right)^{T} Q\left(y(t+j\mid t)-w(t+j)\right)\\ &+\frac{1}{2}\sum_{j=1}^{M}\Delta u(t+j-1)^{T} R\Delta u(t+j-1), \end{aligned} \qquad (1)$$

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 $\hat{y}(t+j\mid t)$ 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 $\Delta u$ 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 $\Delta u$ 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 $M<N$.

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.

### *2.2 Standby Controller (MIMO Controller)*

The standby controller controls both the nuclear power level and the ASI by adjusting the regulating control rod bank and the part-strength control rod bank with the help of the boric acid concentration change. Therefore, the following cost function is presented for MIMO control logic:

$$\begin{aligned} J &= \frac{1}{2}\sum_{j=1}^{N}\left(\hat{\mathbf{y}}(t+j\mid t)-\mathbf{w}(t+j)\right)^{T}\mathbf{Q}\left(\mathbf{y}(t+j\mid t)-\mathbf{w}(t+j)\right) \\ &\quad +\frac{1}{2}\sum_{j=1}^{M}\Delta\mathbf{u}(t+j-1)^{T}\mathbf{R}\Delta\mathbf{u}(t+j-1), \end{aligned} \tag{2}$$

subject to constraints

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

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.

## 3. Application to APR1400

The proposed reconfigurable controller (refer to Fig. 1) was applied to the load-following operation of an advanced power reactor 1400 (APR1400) which was modeled numerically by MASTER code [3].

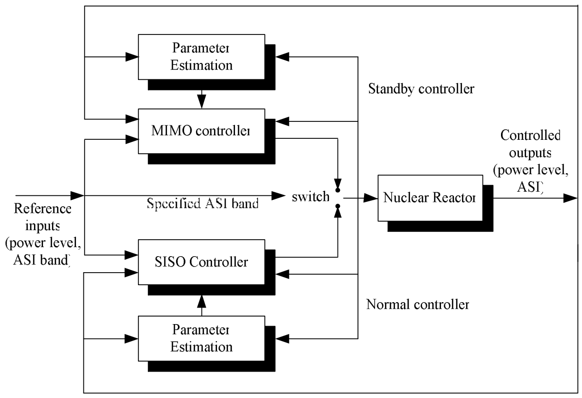

Fig. 1. Schematic diagram of the proposed reconfigurable controller.

Figure 2 shows the numerical simulation results for load-following operation. It is desired that the reactor power follows a daily load cycle of a typical 100-50-100%, 2-6-2-14hr pattern. Allowable ASI band was set to ±3% band from the ASI of 75% 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.

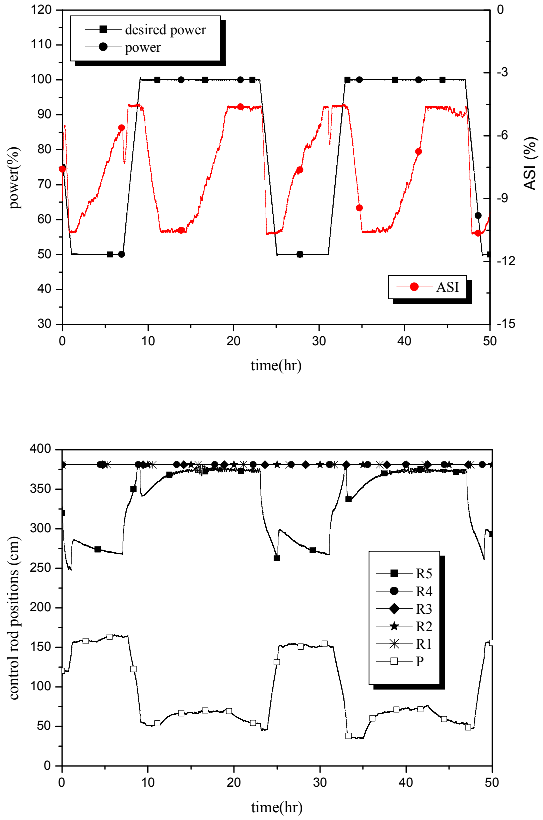

Fig. 2. Simulation results for load-following operation at burnup of 13 MWD/kgU.

## 4. Conclusion

In this work, we presented a reconfigurable controller to control the power level and maintain the ASI in a specified ASI band for load-following operation of APR1400. An MPC method is combined with a parameter estimator to additionally take into account the change of operating points and the time-varying characteristics. It was known from numerical simulations that the proposed reconfigurable controller controls the reactor power very well and also maintains the ASI in the specified ASI band.

## References

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