Load-following Control of APR+ Nuclear Reactors

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Keywords: Load-following Operation, Model Predictive Control, APR+ Reactor, Thermal Power Level, Axial Shape Index (ASI), KISPAC-1D Code.

Abstract: The load-following operation of APR+ reactor is needed to control the power effectively using the control rods and to restrain the reactivity control from using the boric acid for flexibility of plant operation. The xenon has a very high absorption cross-section and makes the impact on the reactor delayed by the iodine precursor. The power maneuvering using automatically load-following operation has advantage in terms of safety and economic operation of the reactor. Therefore, an advanced control method that meets the conditions such as automatic control, flexibility, safety, and convenience is necessary to load-following operation of APR+ reactor. In this paper, the MPC method is applied to design APR+ reactor's automatic load-following controller for the integrated average coolant temperature and ASI control. The KISPAC-1D code, which models the APR+ nuclear power plants, is interfaced to the proposed controller to verify the tracking performance of the average coolant temperature and ASI. It is known that the proposed controller exhibits very fast tracking responses.

1 INTRODUCTION

The performance of load following operation on a nuclear power plant has been assessed differently depending on the need for age and regional energy environment. Now that nuclear power has emerged as the most realistic alternative when fossil-fuel prices increasing and global warming problem has become a serious globally, nuclear power plant construction plans have been announced in many countries, and in case of Korea, also plan to increase the share of nuclear power. So, it is difficult to maintain the electric power demand by controlling the power of only hydro and fossil power plants that have the relatively low impact on an overall power system. APR+ is a nuclear reactor which has the power more than 1500MWe under development in Korea. Dynamics of a nuclear power plant depends on the reactivity changes according to the operating conditions and fuel combustion. Thus, the reactor power must be controlled well to maintain the integrity of the nuclear power plant and to maximize the thermal efficiency. Most of the existing nuclear power plants change operating power by controlling boron concentration in the coolant. However, the use of boric acid is difficult to respond quickly to demand for power changes, and it is limited for usage at the end of a nuclear fuel cycle due to the concern of a positive temperature coefficient. In case of using the control rods, reactivity control can be easier through the feedback of coolant for automatic control, but power distribution control is very complex due to nonlinear dynamic characteristics.

In this study, model predictive control (MPC) technique is applied to design the automatic load following controller for controlling the average coolant temperature and axial shape index (ASI) of APR+ reactors. The model predictive controller can accomplish better tracking performance because it considers not only the trace command of current time but also future time. MPC technique has been applied to many industrial process systems, and its performance was also proven. The objectives of the proposed MPC are to minimize the difference between the estimated output (average coolant temperature and ASI) and the desired output and the frequent variation of the control rod position. And KISPAC-1D code is interfaced to the proposed controller to verify its performance for controlling average coolant temperature and ASI.

Kim J., Na M., Yu K. and Kim H..
Load-following Control of APR+ Nuclear Reactors.
DOI: 10.5220/0004006604460451
In *Proceedings of the 9th International Conference on Informatics in Control, Automation and Robotics* (ICINCO-2012), pages 446-451
ISBN: 978-989-8565-21-1

2 LOAD-FOLLOWING OPERATION

Load following operation of a nuclear power plant means the operation mode that reactor power follows the load variation of the turbine. Daily load following operation, frequency control operation, and contingency power change operation belong to the category of the load following operations. Daily load following operation means that reactor power is retained for a period of time as a constant rate of change by up to 50%, and then return to 100% power as a constant speed. However, the frequency control operation of nuclear power plants causes the frequent movement of control rods because of the volatility of an ever-changing power system.

Therefore, the purpose of controller development was set up to design the controller capable of daily load following operation. Reactor power fluctuation can be achieved by regulating the parameters that cause the change of core reactivity. Core reactivity is affected by changes of the boron concentration, fuel and coolant temperature, xenon and samarium concentration in the core.

Xenon and samarium concentrations are excluded from the direct target which can be controlled because it cannot be measured directly during reactor operation, and fuel consumption rate and fuel temperature are already determined in the time of fuel loading. Control rod movement can be used as a control factor for immediate reactor power changes because it impacts on the reactor within a few seconds, and the change of boron concentration in the coolant should be used essentially to control the surplus reactivity since it is affected to the reactor within few minutes. Coolant temperature can be used as a control factor which reduces the use of control rods and boron.

3 DESIGN OF MODEL PREDICTIVE CONTROLLER

The average coolant temperature and reactor power distribution should be controlled at the same time for load following operation. The MPC controller is introduced for the automatically load following operation of an APR+ reactor. It uses a control method that can perform optimal control with the predictive calculations. Through this study, an MPC controller will be designed so that it can control the average coolant temperature and power distribution at the same time.

3.1 Basic Principle of MPC

MPC method can calculate control input of the constant horizon by solving the optimization problems about finite future time steps in the current time, and actually implement solely the first optimal input as a control input. As shown in the Figure 1, new output is measured at the next time step, and control horizon moves one step forward, and these calculations are repeated.

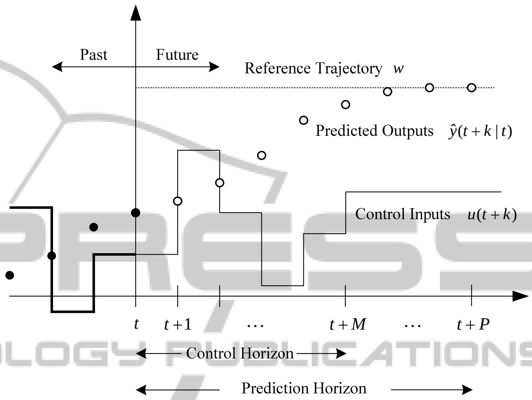


Figure 1: Concept of the Model Predictive Control.

The purpose of using a new measured value at each time step is to compensate the model inaccuracy or unmeasured disturbance. The basic elements of MPC contain a specific model (prediction model) for predicting the process output of a point in the future, an objective functions and its optimization.

Using this prediction model, outputs for the prediction horizon P , $[\hat{\mathbf{y}}(t+k\,|\,t),\ k=1,2,\cdots,P]$ are predicted, and these outputs depend on the past input, output and future input (control signal), $[\mathbf{u}(t+k|t),\ k=1,2,\cdots,M]$.

A series of optimal control signal is calculated by optimizing a given objective function to let the output follow the target output as fast as possible. In case the objective function is quadratic form, and the model is linear, and constraint does not exist, the control input can be derived analytically. However the actual control input in most of the processor is obtained numerically. At this time, the optimal control input is obtained in a range which satisfies the constraints by including the constraint which will be applied to the system to the algorithm. Among the optimized control signals, the first input $\mathbf{u}(t/t)$ is sent only to the process input. And the remaining control input signals are meaningless because $\mathbf{y}(t+1)$ was already known in the next sampling period. So, control input is calculated newly by repeating the previous procedure for every sampling period. Performance indicator can be written to obtain a fast response and to prevent excessive control effort as follows:

$$J = \frac{1}{2}\sum_{k=1}^{P}(\hat{\mathbf{y}}(t+k\,|\,t) - \mathbf{w}(t+k))^T \mathrm{Q}(\hat{\mathbf{y}}(t+k\,|\,t) - \mathbf{w}(t+k)) + \frac{1}{2}\sum_{k=1}^{M}\Delta\mathbf{u}(t+k-1)^T \mathrm{R}\Delta\mathbf{u}(t+k-1) \tag{1}$$

the constraints are:

$$\begin{cases} \hat{\mathbf{y}}(t+P+i) = \mathbf{w}(t+P+i), \; i = 1,\cdots,L \\ \Delta\mathbf{u}(t+k-1) = 0, \;\; k > M \;\; (M < P) \end{cases} \tag{2}$$

where $\hat{\mathbf{y}}(t+k|t)$ is k-step-ahead optimal prediction of the system based on data until the current time t. And $\mathbf{w}$ indicates a series of output set point vector, and $\Delta\mathbf{u}$ is the control input change between two neighboring time steps. Positive definite matrices Q and R are symmetric matrices that it gives each weight to the particular component of $(\hat{\mathbf{y}} - \mathbf{w})$ and $\Delta\mathbf{u}$ in some future time horizon.

The number of output has two, and they consist of average coolant temperature and ASI. And the number of input has also two. These indicate the axial position of two types of control banks (regulating control bank, part-strength control bank).

Usually, P is called a prediction horizon, and M is called a control horizon. Prediction horizon means limited time intervals to follow the output on the demand output. It has two constraints. The constraint, $\hat{\mathbf{y}}(t+P+i) = \mathbf{w}(t+P+i), \; i = 1,\cdots,L$, which makes the output follow the reference input over some range and guarantees the stability of the controller. $\Delta\mathbf{u}(t+k-1) = 0, \;\; k > M$ means that there is no variation in the control signals after a certain interval $(M < P)$, which is the control horizon concept.

3.2 Future Output Prediction

In the case of dynamic systems, future output behavior can vary depending on the input of past, present and future. Thus, past inputs should be remembered in some forms for the prediction. Dynamic states can be defined as a memory about the past inputs that is necessary to predict the future output behavior. States can be defined in many other ways in the same system.

In case of a finite impulse response (FIR) system, it is sufficient to keep P past inputs alone:

$$x(k) = [\upsilon(k-1), \upsilon(k-2), \cdots \upsilon(k-P)]^T \tag{3}$$

The future output behavior can be definitely predicted by selecting $x(k)$. The ultimate goal of the memory is to predict the future output, so the past can be tracked more easily in terms of its effect on the future than the past itself. In linear systems, the effect on the past and (hypothesized) future inputs can be calculated separately and added through the principle of separation. $Y^0(k)$ is defined as future output deviation due to past input deviation:

$$Y^0(k) = [y^0(k/k), y^0(k+1/k), \cdots, y^0(\infty/k)]^T \tag{4}$$

where

$y^0(i/k) \triangleq y(i)$ assuming $\upsilon(k+j) = 0$ for $j \geq 0$

Even if $Y^0(k)$ is infinite dimensional, for an FIR system, it needs to keep only P terms:

$$Y^0(k) = [y^0(k/k), y^0(k+1/k), \cdots, y^0(P/k)]^T \tag{5}$$

This vector can be chosen as the states because it describes the effects of the past input deviation on the future output deviation. Future output can be written as:

$$\begin{bmatrix} y(k+1) \\ y(k+2) \\ \vdots \\ \vdots \\ y(k+P) \end{bmatrix} = \underbrace{\begin{bmatrix} y^0(k+1/k) \\ y^0(k+2/k) \\ \vdots \\ \vdots \\ y^0(k+P/k) \end{bmatrix}}_{\text{Effect of Past Inputs From } Y^0(k)} + \underbrace{\begin{bmatrix} H_1 \\ H_2 \\ \vdots \\ \vdots \\ H_P \end{bmatrix} \upsilon(k) + \begin{bmatrix} 0 \\ H_1 \\ \vdots \\ \vdots \\ H_{P-1} \end{bmatrix} \upsilon(k+1) + \cdots + \begin{bmatrix} 0 \\ 0 \\ \vdots \\ \vdots \\ H_1 \end{bmatrix} \upsilon(k+P-1)}_{\text{Effect of Hypothesized Future Inputs}} \tag{6}$$

This equation shows that the definition of the states can be very convenient for the predictive control. For computer implementation, the memory should be updated in a recursive manner from one time step to next. $Y^0(k)$ can be updated recursively as follows:

$$Y^0(k) \rightarrow \Omega^0 Y^0(k) + Hv(k) = Y^0(k+1)$$

$$\begin{bmatrix} y^0(k/k) \\ y^0(k+1/k) \\ \vdots \\ \vdots \\ y^0(k+P-2/k) \\ y^0(k+P-1/k) \end{bmatrix} \rightarrow \begin{bmatrix} y^0(k+1/k) \\ y^0(k+2/k) \\ \vdots \\ \vdots \\ y^0(k+P-1/k) \\ y^0(k+P/k) \end{bmatrix} + \begin{bmatrix} H_1 \\ H_2 \\ \vdots \\ \vdots \\ H_{P-1} \\ H_P \end{bmatrix} \upsilon(k) = \begin{bmatrix} y^0(k+1/k+1) \\ y^0(k+2/k+1) \\ \vdots \\ \vdots \\ y^0(k+P-1/k+1) \\ y^0(k+P/k+1) \end{bmatrix} \tag{7}$$

The above equation can be expressed as follows:

$$Y^0(k+1) = \underbrace{\begin{bmatrix} 0 & 1 & 0 & \cdots & 0 \\ 0 & 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & 1 \\ 0 & 0 & 0 & \cdots & 0 \end{bmatrix}}_{\Omega^0} Y^0(k) + \begin{bmatrix} H_1 \\ H_2 \\ \vdots \\ H_{P-1} \\ H_P \end{bmatrix} \upsilon(k) \tag{8}$$

The multiplication by Ω^0 in Eq. (8) represents the shift operation which can be implemented efficiently on the computer.

3.3 Added Constraint Conditions

In this paper, some constraints have been added, so the control algorithm of MPC methodology has been modified. The control system outputs are a coolant average temperature (average coolant temperature) and ASI. The control inputs are the two types of control rod positions (considering long-term, short-term steady-state insertion limits).

$$\begin{cases} \mathbf{y}_{\min} \le \mathbf{y}(t) \le \mathbf{y}_{\max}, \\ \mathbf{u}_{\min} \le \mathbf{u}(t) \le \mathbf{u}_{\max}, \\ -d\mathbf{u}_{\max} \le \Delta\mathbf{u}(t) \le d\mathbf{u}_{\max}. \end{cases} \tag{9}$$

The limited range of average coolant temperature is $290^o C \le y_1 \le 315^o C$, and the limited range of ASI is $-0.27 \le y_2 \le 0.27$. Control inputs are control rods position and speed (R5 position, P1&P2 positions). Considering the short-term and long-term steady-state insertion limits, the R5 control rod position is limited within $152.4cm \le u_1 \le 381cm$. The P1&P2 control rod position limit is $190.5cm \le u_2 \le 381cm$.

Five types of a signal (high-speed insertion, low-speed insertion, stop, low-speed withdrawal, high-speed withdrawal) are used as the control rod speed that is adjusted by the rod speed program. The control rod speed of R5 and P1&P2 is 1.27 cm/sec for high-speed insertion or withdrawal and 0.127 cm/sec for low-speed insertion or withdrawal, and 0 for stop. In this study, P1&P2 is moving together.

4 APPLICATION TO NUCLEAR REACTOR POWER CONTROL

Load following operation control is considered an MIMO (Multiple Input and Multiple Output) control problem because the average coolant temperature and ASI (Axial Shape Index) should be controlled simultaneously. Load following operation is a two-input and two-output system using the regulating control bank and part-strength control bank as input and the average coolant temperature and power distribution as output.

This system can be expressed as follows:

$$\begin{bmatrix} y_1(k) \\ y_2(k) \end{bmatrix} = \begin{bmatrix} G_{11}(q) & G_{12}(q) \\ G_{21}(q) & G_{22}(q) \end{bmatrix} \begin{bmatrix} u_1(k) \\ u_2(k) \end{bmatrix} \tag{10}$$

From the above matrix, $G_{11}(q)$ can be represented by a discrete-time transfer function as follows:

$$G(q) = \frac{b_0 + b_1 q^{-1} + \cdots + b_n q^{-n}}{a_0 + a_1 q^{-1} + \cdots + a_n q^{-n}} q^{-d} \tag{11}$$

where d is an integer (≥ 0) and represents the sampling periods of pure delay.

Eq. (10) can be represented by a discrete function as follows:

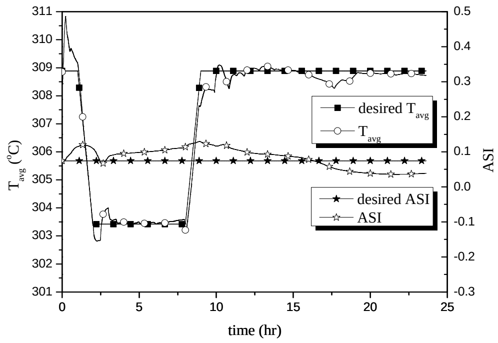
$$\begin{aligned} y_1(k) &= \theta_{d_1}(q) y_1(k) + \theta_{n_{11}}(q) u_1(k) + \theta_{n_{12}}(q) u_2(k) \\ y_2(k) &= \theta_{d_2}(q) y_2(k) + \theta_{n_{21}}(q) u_1(k) + \theta_{n_{22}}(q) u_2(k) \end{aligned} \tag{12}$$

$y_1(k)$ means the average coolant temperature and $y_2(k)$ means the power distribution (ASI). Adjusted parameters in the numerical simulation are the prediction horizon P , the control horizon M , and the input weighting factors μ_1 and μ_2 of regulating control bank R5 and part-strength control bank P, respectively. To consider the constraints of MPC controller systematically, a new MPC algorithm is needed, and the control algorithm is required to be interfaced with KISPAC-1D code that models the reactor core dynamics and thermo-hydraulic parts.

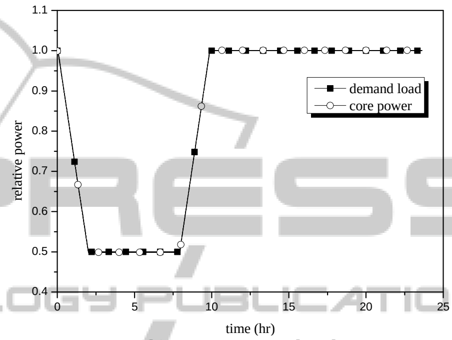
The control algorithm was coded using MATLAB. KISPAC-1D coded with the FORTRAN language is needed to be interfaced with the MPC controller programmed with MATLAB. Therefore, KISPAC-1D code was converted into a library file using the latest FORTRAN compiler to be integrated with the control algorithm. To evaluate the load following operation capability of the APR+ reactor using the MPC method, we performed various simulations using the KISPAC-1D code. The purpose of simulation is to evaluate how well the average coolant temperature and power distribution of the reactor are controlled for a daily-load following operation.

Daily-load following operation has a load cycle of typical 100-50-100%, and power increasing /decreasing speed is 25%/hr. We performed simulations such as the following load change: 100-50-100% power operation during a period of 24 hours. And the following initial conditions were used in the numerical simulation. The initial reactor power is 100%, regulating control bank (R5) position is 370cm, other regulating control bank position is 381cm, part-strength control bank (P) position is 370cm, sampling period (T) is 4sec, bank maximum speed is 1.27T cm/time step, prediction horizon (P) is 5, control horizon (M) is 2, first input weighting factor (μ_1) is 10, and second input weighting factor (μ_2) is 30.

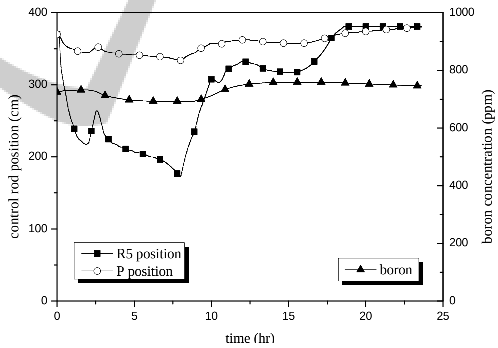
Figure 2 shows the results of numerical simulation for daily-load following operation at the beginning of a reactor fuel cycle. As shown in this Figure 2(a), average coolant temperature are different slightly from the desired temperature in the power changed interval, but it follows desired average coolant temperature in other sectors according to target power level, and the tracking performance of ASI shows that calculated ASI doesn't follows desired ASI perfectly. As shown in the Figure 2(b), the calculated power level follows the desired power level well. Figure 2(c) shows the position of the regulating control bank and the part-strength control bank and also shows the concentration of boric acid. The rate of change of the concentration of boric acid does not exceed the boric acid capacity of the CVCS. Figures 2(d) and (e) show that the parameters of $\theta_1(q)$ and $\theta_2(q)$ is predicted repeatedly every time step, and show that dynamic characteristic of the reactor changes depending on the power level and the positions of the control rod banks.



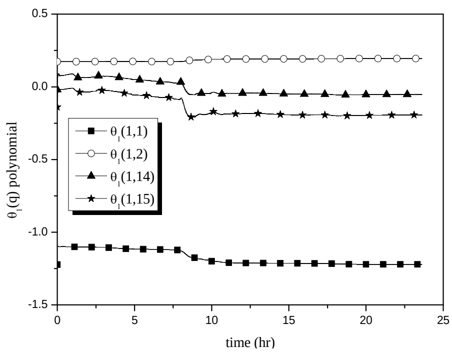
(a) average coolant temperature and ASI



(b) reactor power level

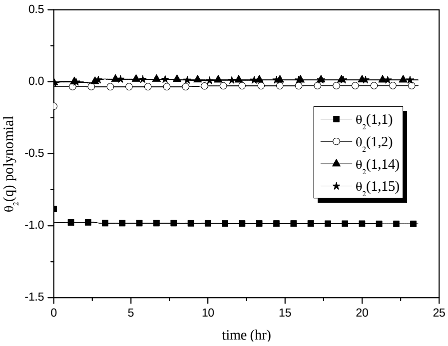


(c) control rod bank position and boron concentration



(d) $\theta_1(q)$ polynomial

Figure 2: Simulation Results for Daily-Load Following Operation.



(e) $\theta_2(q)$ polynomial

Figure 2: Simulation Results for Daily-Load Following Operation (Cont.).

5 CONCLUSIONS

In this study, we developed a new MPC algorithm that can control the average coolant temperature and axial power distribution systematically for load following operation. The proposed controller was applied to ensure the possibility of the load following operation of APR+ reactor simulated numerically by KISPAC-1D code. And a controller design model used for designing the model predictive controller is estimated every time step by applying a parameter estimation algorithm to reflect the time-varying condition. We examined the performance of the controller by performing numerical simulation at the beginning of the fuel cycle. Through this study, we could see that the average coolant temperature follows the desired average coolant temperature well, but ASI tracking performance is not good. It was hard to control the average coolant temperature and ASI precisely at the same time using two similar types of the control rods because the dynamic characteristics of a regulating control rod bank R5 is not much different from that of the PSCEA. Through further study, we will improve the performance of a model predictive controller.

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