Model Predictive Load-following Control for APR+ Reactors Through Discrete Control Rod Speed Optimization

Jae Hwan Kim, Ju Hyun Kim, Sun Ho Park, Kwae Hwan Yoo, Dae Seop Kim, Man Gyun Na*
Nuclear Engineering Dept., Chosun Univ., 309 Pilmun-daero, Dong-gu, Gwanggu
**Corresponding author: magyna@chosun.ac.kr*

1. Introduction

Until now, nuclear power has been only used for the base-load power operation. However, current nuclear power plants are recognized as the most reasonable energy source. As a result, the proportion of nuclear power has being grown increasingly. Therefore, load-following operation of a nuclear power plant should be an essential option. Most of the existing nuclear power plants perform reactor operation by varying the boron concentration in the coolant. But it is hard to respond quickly to demands for the power changes. In case of using the control rods, reactivity control is easy, but axial power distribution control is very hard because it has very complex and nonlinear dynamic characteristics. In this study, we have introduced a Model Predictive Control (MPC) method to control the average coolant temperature and Axial Shape Index (ASI) automatically at the same time, and we have improved the performance of controller by applying the Genetic Algorithm (GA) to optimize the control rod movement.

2. Methods and Results

In this section, some of the techniques that were used to design the controller for applying to the APR+ nuclear reactor and to optimize the control input by using GA are described. And the performance of this controller is tested by using the KISPAC-1D code.

2.1 Model Predictive Control Method

The MPC method has been developed in the fields of research and application because it can provide a general solution to the process control in the time-domain. Especially, MPC can combine a variety of control methods such as optimal control, stochastic control, time-delay process control, multivariable control and future reference control. And also, another advantage of the MPC is that can handle the various constraints arisen in the nonlinear control because it deals with the limited control horizon.

MPC means the control method to obtain the control signal that minimize a certain objective function by using a process model. Basically, MPC has the following features. 1) The control law is related with the predicted output of system. 2) Prediction for the output is determined by a process model. 3) The input at the present time is determined by optimizing the given objective function. 4) Control input is modified continuously at all sampling time. 5) The performance of MPC depends on the accuracy of the model. 6) It is easy to adjust directly several control variables likes the size of the control input and the system output. 7) MPC can handle the various constraints systematically according to the system model and the operating conditions. Therefore, it may have a better performance. 8) MPC is possible for the feed-forward design even if it has constraints, and can also be used in the design of Multi Input Multi Output (MIMO) system. The figure 1 shows the basic concept of MPC algorithm.

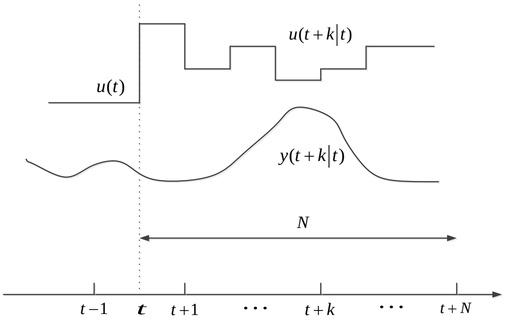


Fig. 1. The basic concept of Model Predictive Control algorithm.

A load following operation control is considered an MIMO control problem because the average coolant temperature and axial power distribution 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:

$$\begin{bmatrix} y_1(k) \\ y_2(k) \end{bmatrix} = \begin{bmatrix} G_{11}(q) & G_{12}(q) \\ G_{21}(q) & G_{22}(q) \end{bmatrix} \begin{bmatrix} u_1(k) \\ u_2(k) \end{bmatrix} \tag{1}$$

At the above matrix, $y_1(k)$ means the average coolant temperature and $y_2(k)$ means the power distribution (ASI). $u_1(k)$ and $u_2(k)$ mean the regulating control bank R5 and part-strength control bank P positions.

2.2 Optimization of Control Rod Movement

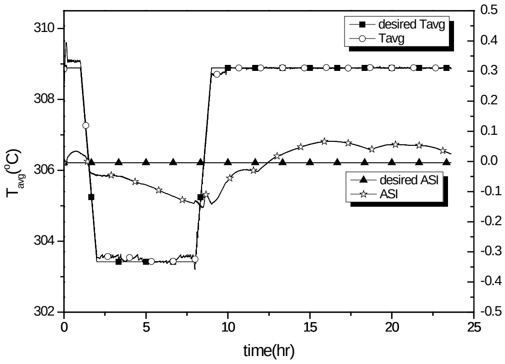
The role of control rods is important to perform the automatic load-following operation. In this study, control rod bank can be driven by the forms of five movements such as rapid withdrawal, slow withdrawal, stop, slow insertion and rapid insertion. This control rod movement is not a continuous but discrete. Therefore, we used a GA to optimize the movement of control rod. The most important feature of the GA is that this algorithm is unaffected by the objective function and constraints. Also, the scope of usage is very diverse. As the GA is that the law of evolution is applied to the optimization problem, it assigns fitness to each object depending on the degree of violation and objective function by distributing a number of objects to the interpreting area. The higher fitness of an object makes high the probability to participate in the process of cross and mutation at the next steps. Then, the objects which have good fitness are reproduced in the next step and improve the fitness of the entire objects.

2.3 Application to APR+ Nuclear Reactor

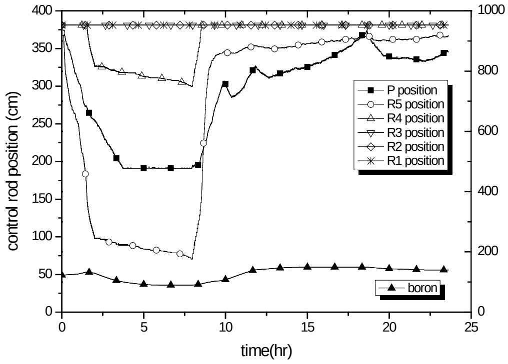
A proposed controller is connected with KISPAC-1D code in order to perform the simulations of the automatic load-following operation. The KISPAC-1D code that was developed by using FORTRAN language needs the interface with a MPC controller which was coded by MATLAB. For this purpose, KISPAC-1D code has been integrated with MATLAB files after being converted to the library files by using the latest FORTRAN compiler. The requirements related on daily load-following operation of the APR+ nuclear reactor are as follows. First, the load-following operation pattern can be possible for 100% - under 50% - 100% power operation on a 24 hour cycle. Second, the rate of power change should be above 25%/hr when the reactor power increase or decrease, and the load-following operation should be possible for (10~16)-2-(4~10)-2 periodic time pattern. Third, daily load-following operation should be possible from the beginning of fuel cycle to the 90% burnup of the fuel cycle. And the following initial conditions are used at every numerical simulation. Initial reactor power: 100%; regulating control bank R5 position: 370cm; regulating control bank R4~R1 positions: 381cm; part-strength control bank P position: 370cm; sampling period (T): 4sec.; high control rod speed: 1.27T cm/time-step (T=period); low control rod speed: 0.127T cm/time-step. The figure 2(a) shows the results of numerical simulation about the daily load-following operation at the 16000MWD fuel burn-up. As you can see, the calculated average coolant temperature and ASI follow target values quite well. And figure 2(b) shows the positions of regulating control bank and part-strength control bank and boron concentration during the daily load-following operation.

3. Conclusions

Through this study, we have introduced a MPC controller for APR+ reactors which can control the average coolant temperature and the axial shape index systematically, and evaluated the performance of proposed controller by connecting with KISPAC-1D code. The controller was designed through the fully discrete control rod speed optimization by a genetic algorithm. We have examined the performance of proposed controller by performing numerical simulations from the beginning of fuel cycle to the 90% burnup of fuel cycle. Through these various test, we can see that developed controller can be applied successfully to the APR+ nuclear reactor.



(a) average coolant temperature and ASI



(b) control rod bank positions and boron concentration

Fig. 2. The result of numerical simulation at 16000MWD fuel burnup.

REFERENCES

[1] E. F. Camacho, C. Bordons, Model Predictive Control, Springer-Verlag, London, 1999.

[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., No. 52, p. 1009-1020, Aug, 2005

[3] M. G. Na, A Model Predictive Controller for the Water Level of Nuclear Steam Generators, Nucl. Eng. Tech., Vol.33, p.102-110, Feb, 2001

[4] Y. J. Lee, J. I. Choi, Robust Controller Design for the Nuclear Reactor Power Control System, Nucl. Eng. Tech., Vol.29, p.280-290, Aug, 1997