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이 논문을 공학 석사학위신청 논문으로 제출함

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지금까지 원자력발전은 초기 건설비에 비하여 상대적으로 매우 낮은 운전비용으로 인해 주로 기저부하용 운전에만 이용되어 왔다. 그러나 전체 전력시스템 중 원자력이 차지하는 비중이 점점 더 커지면서 원자력발전소의 부하추종운전은 선택적이 아닌 필수적인 옵션이 되었다. 원자력발전의 비중이 높은 프랑스에서는 부하추종운전의 필요성을 매우 중요하게 인식하여, 이미 1970년대부터 기술을 개발하여 상용운전에 적용하고 있다. 한국의 경우, OPR1000과 APR1400 모델에 수동개념이라 볼 수 있는 부하추종운전 성능을 보유하고는 있으나 현재까지 실질적인 부하추종운전 능력을 갖추지는 못하였다.

현재 대부분의 기존 원전의 경우에는 출력 분포에 영향이 적은 냉각수 내 붕산농도를 변화시켜 반응도 제어를 달성하여 출력 운전을 수행하고 있다. 그러나 운전 유연성 확보를 위해서는 붕산의 사용을 가능한 억제하며, 제어봉을 효과적으로 사용할 필요가 있다. 제어봉을 사용할 경우, 반응도 제어는 냉각수 온도의 피드백을 통한 자동제어가 용이하지만, 출력 분포는 그 동적 특성이 매우 복잡하고 비선형적인 특성을 가지고 있어 사실상 기존의 아날로그에 근거한 보상기를 이용한 제어 방법으로는 원하는 성능을 달성하기가 매우 어렵다. 특히 제어봉을 이용하여 부하추종운전을 수행하는 경우, 제어봉의 움직임이 빈번하게 되어 지논-진동을 유발하게 되므로 이를 효과적으로 제압할 수 있는 제어기의 설계가 요구된다.

APR1400 원전의 경우 원자로 출력은 RRS(Reactor Regulating System)에 의해 자동 조절되지만 출력분포는 운전원이 수동으로 제어하여야 한다. 따라서 APR+에서는 이러한 출력과 출력분포를 동시에 자동제어하기 위해 새로운 개념의 원자로 제어기의 도입이 필요하다. 모델예측제어기법은 이러한 다중 입출력 제어가 가능하며 원자로와 같은 복잡하고 비선형적인 특성을 갖는 시스템에 적용할 수 있다. 이러한 모델예측제어의 특성으로 인하여 APR+의 노심출력과 축방향 출력분포를 적절히 제어할 수 있을 것으로 판단하여 도입하였다. 그리고 제어봉의 움직임의 최적화를 위하여 유전자 알고리즘을 적용하여 제어기의 성능을 향상시켰다. 개발된 제어기는 노심해석코드인 KISPAC-1D 코드를 이용하여 수치적으로 모델링된 1차원의 APR+ 원자로와 인터페이스를 통하여 일일부하추종운전에 대한 성능을 확인하였다.

수행된 시뮬레이션은 핵연료연소도에 따라 주기초부터 주기말 90%의 연소도까지 수행되었으며, 개발된 제어기는 APR+ 원전의 자동부하추종운전에 만족할만한 성능을 보여주었다. 이러한 결과를 통해 본 연구에서 개발되어진 부하추종운전 제어기가 국내 APR+ 원전뿐만 아니라 앞으로의 새로운 노형 개발 시 수준 높은 부하추종운전 기법을 확보하는데 초석이 될 수 있다.

I . Introduction

The necessity for the load-following operation of nuclear power plants have been evaluated differently according to the energy environment of the era and country-specific. Nowadays, many countries have been operating the nuclear power plants but the actual load-following operation has been carried out in some European countries. By contrast, most of the countries which have nuclear power plants including South Korea have used the NPPs for the base load operation due to the relatively low operating costs in comparison of the other power plants. However, the proportion of nuclear power is growing up more and more, thus, it is hard to control the electric grid by controlling the power of the only hydroelectric and fossil power plant. Therefore, the load following operation should be possible in nuclear power plants. Demand for the high-quality electric power from the precision industry is increasing, and the generating capacity of APR+ nuclear power plant is larger than current nuclear plants and others types of power plants. These are additional reasons for ensuring the capability of the load following operation. In addition, at the time of the export of nuclear power plants to developing countries such as Southeast Asia, Middle East, South America, when considering the electricity power grid of these importers, their total electric power capacity is small. Therefore, ensuring APR+ load-following operation technique can be advantages for exporting Korean nuclear power plants.

Currently, most of the existing nuclear power plants are operated by achieving the reactivity control using the adjustment of boron concentration in the coolant which is a relatively low impact on the power distribution. However, using the boric acid is difficult to respond quickly to demands for the power changes, and also it is restricted at the end of the fuel cycle because it is possible to generate a positive temperature coefficient. And it produces a lot of liquid waste. Therefore, it is necessary to use the control rod effectively with usage of the boric acid as little as possible. However, power distribution has very complex and nonlinear dynamic characteristics. Thus, it is difficult to achieve the desired performance by using existing analog control techniques based on lead and lag compensators. It relies on the manual control by experienced operators during operation, and these give the operators too much stress. Therefore, these are factors that limit the flexibility of nuclear power plant operation. Especially, in case of load-following operation using the control rods, control rod movements are frequent and this makes xenon-oscillation phenomenon. Therefore, it is required to design the controller which can effectively subdue these problems. Therefore, APR+ operation should be controlled automatically, and new advanced control techniques equipped with flexibility, reliability and ease of operation are required, rather than existing analog control methods. Furthermore, the APR+ nuclear power plant uses digital I&C system, so it is easy to apply advanced control methods that have the high-performance.

The reactor power and power distribution should be controlled simultaneously for the load-following operation. In case of the APR1400, reactor power is controlled automatically by the RRS (Reactor Regulating System), but axial power distribution is controlled manually by an operator. This thesis has introduced a new concept of MPC controller for the automatic load-following operation of APR+ nuclear power plant. This controller has a control method that can perform optimal control through predictive calculation. The MPC method can combine the optimal control, stochastic control and process control with time delay and multi-variable control. Another advantage of the MPC is that it can be applied to constraints and non-linear process that often exists in the industrial fields because MPC uses the finite control horizon. Due to these characteristics of MPC, it can be applied appropriately to the APR+ reactor control.

Ⅱ. Design of the Load-following Controller

A. Load-following Operation

The load-following operation means that the reactor power changes to match the turbine load variation. Normally, this operation technique is divided into the daily load-following operation and frequency control operation. The daily load-following operation requires the form of 14-2-6-2 (HR) 100-50-100 (%) output changes typically. On the other hand, frequency control operation has no specific forms and it requires fast and frequent output changes. Therefore, the control using boron concentration adjustment what takes long time to change the reactivity is difficult to play a large feature in the frequency control operation that requires fast and frequent changes. However it can be used for a daily load-following operation.

Generally, the performance of the load-following operation is discussed about the control problems of power level and power distribution. This is implemented by the appropriate combination of reactivity adjustment mechanisms which are control rods, boron concentration changes and average coolant temperature. The adjustment of boron concentration can be performed automatically or manually during load-following operation. However, performing the auto-adjustment using current operating conditions has several problems because of time-consuming in the boron concentration adjustment. In the actual load-following operation test, the adjustment of boron concentration is performed using predicted information by the simulated calculations. And the local output should not exceed the limit to prevent the nuclear fuel damages during the load-following operation. These considerations are represented by the ability to control the power level and power distribution simultaneously. In particular, if the Axial Shape Index (ASI) in a core cannot be controlled properly, xenon-oscillation phenomenon occurs and then the control of power distribution is becoming more difficult. Therefore, a reactor should be operated within the certain range of axial power distributions.

In order to change the power level, three factors such as the control rods, adjustment of boron acid and coolant temperature compensation effect can be used to control the core reactivity. In case of using the control rods, it shows fast response but the distortion on the power distribution is becoming bigger. In case of adjusting the boron concentration, the distortion of the power distribution is smaller than in adjusting control rods but radioactive waste is increased. And the way of coolant temperature compensation effect has an advantage that does not need an additional control because it uses inherent feedback effect in the nuclear reactor. However, it affects the safety analysis and the performance requirement satisfactions. Due to these characteristics, appropriate design fitted on the reactor types is required to perform the load-following operation. Major design direction in the load-following operation can be largely divided into two categories. First, it is the way of reducing the amount of reactivity compensations for the power changes. This is to decrease the requirements about control rods or boric acid adjustment by making temperature compensation that is responsible for some reactivity compensation using the average coolant temperature program. Second way is that the control rods are divided into the regulating control rods and part-strength control rod by optimizing the design of control rods. Power regulating control rods should be designed to minimize the changes of axial power distribution when adjusting the power level, and power distribution control rods should be designed to minimize the changes of power level when controlling the power distributions. Major countries which have nuclear power plants developed control techniques by considering the various characteristics of the nuclear power plants for the load-following operation in NPPs. Table 1 shows the status of load-following operation techniques of typical nuclear power plants. And in table 2, the reactor core control characteristics of each technique are compared in terms of the power defect compensation, average coolant temperature (Tavg) control, axial power distribution control and Xe control. In table 3, the performance of load-following techniques is compared in terms of the automatic adjustment of boron concentration, power return, daily load-following operation and frequency control operation.

Table 1. The status of load-following operation techniques of the typical NPPs

Status / Techniques	Design Phase	Operation Experience	Applied Plants	Features
(Formerly) ABB-CE	Detail	No	OPR1000 System80, System80+	- PSCEA (manual) - FSCEA (auto) - Boron (manual)
Mode-G	Detail	A lot	France PWR (900MWe, 1300MWe)	- G Bank (semi auto) - R bank (auto) - Boron (manual)
Mode-X	Detail	Demo	France N4 (15000MWe)	- X Bank (auto) - Boron (auto)
MSHIM	Conceptual	No	existing W/H types AP600	- MSHIM (auto) - Boron (manual)
KWU	Detail	A lot	Germany KONVOI	- D, L Bank (auto) - Boron (auto)

Table 2. The control characteristics of load-following techniques

Techniques	Power Defect Compensation	Tavg Control	Axial Power Distribution Control	Xe Control
MSHIM (AP600)	MSHIM (semi-auto)	MSHIM (auto) + AO Bank(auto)	AO Bank (auto or manual)	Boron + MSHIM (auto, manual)
Mode K	RROD (auto) + Boron(manual)	RROD (auto)	HROD (auto)	Boron (manual) + RROD (auto)
PSCEA	RRS(manual)+ PSCEA (manual) + Boron (manual)	RRS (auto)	PSCEA (manual)	Boron (manual)
Mode G	G Bank (auto)	R Bank (auto)	Boron when needed (manual)	Boron (manual)
Mode X	X Bank (auto)	X Bank (auto)	X Bank (auto)	Boron (auto) + X Bank (auto)
D/L	D Bank (auto) + Boron (auto)	D Bank (auto)	L Bank (auto)	Boron (auto) + D Bank (auto)

Table 3. The performance assessment of load-following techniques

Techniques	Automation	Degree of Adjusting Boron Concentration	Power Return Ability	Daily Load-following Operation	Frequency Control Operation
MSHIM (AP600)	normal	low	high	good	possible
Mode K	high	low	high	good	possible
PSCEA	low	low	high	possible	-
Mode G	normal	high	very high	good	good
Mode X	very high	low	high	good	good
D/L	very high	normal	high	good	good

The daily load-following operation is that power increase/decrease is repeated in a cycle of a day and usually 100-50-100%P (2-6-2-14hr) pattern is a simulating calculation target. It means that the power level decreases from 100% to 50% during two hours, and keeps 50% power level during six hours, and then the power level returns to 100%. Contingency operation can be divided into Grid Follow operation and rapid power fluctuating operation. And frequency control operation is divided into Local Frequency Control or Governor Free Operation that follows turbine speed adjustment and Remote Frequency Control that follow the electricity supply orders. Particularly, the capability to frequency control means that it can continue the frequency control operation during the daily load-following operation. This redundant operation is called Grid Follow operation specially. Actually, reactivity control means that it controls the power level and power distribution by inserting negative and positive reactivity through the means of control.

Here, there are three ways of control such as control rod, boric acid in the coolant and Moderator Temperature Coefficient (MTC). The control rod adjusts the reactivity in the core by varying the number of neutrons in the core inserting/withdrawing neutron-absorbing materials to the core. Adjusting boric acid is to control the reactivity by varying the quantity of boron dissolved in the coolant. MTC is to control the reactivity by using temperature feedback effects through changing the coolant temperature. Current nuclear power plants in South Korea have been using the control rods and boron to control the reactivity of reactor core. But European developed countries such as France which is using load-following techniques have controlled reactor core using not only control rods and boron but also MTC. In order to use MTC for controlling the core, the operation mode that controls the average coolant temperature should be changed.

As the operation mode controlling the average coolant temperature, there are Sliding Tavg Mode and Constant Tavg Mode. The Sliding Tavg Mode is applied to the reactor control program in the domestic nuclear power plants, and it have a characteristic that average coolant temperature rises at a constant rate depending on the secondary side power increase. If the reactor is operated by daily load-following operation, it is controlled by using part-strength control bank P and regulating control bank R5 in the beginning of fuel cycle, but bank P, R5, R4 and R3 should be inserted into the core as the fuel burnup continues. This is because the temperature feedback effect in the end of the fuel cycle is bigger than in the beginning of fuel cycle. The Constant Tavg Mode is a control scheme that makes the average coolant temperature constant, and this is a way to minimize the power defect. If the daily load-following operation is performed in this reactor core, reactor core can be sufficiently controlled only using P and R5 in the end of the fuel cycle by temperature feedback effect.

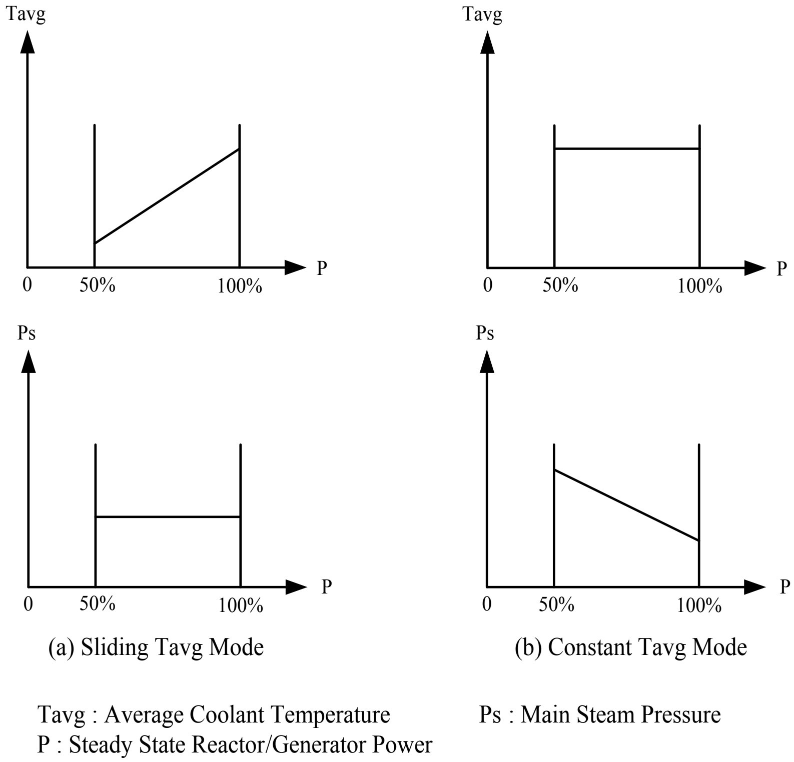


Fig. 1. Reactor control modes

In order to perform load-following operation of nuclear power plants, it requires a design of the control rod arrangement that can minimize the effect of power distribution, a controller that can control the power level and power distribution simultaneously, and a system that can support the adjustment of boron concentration. Also, in case of performing the long-term load-following operation because control rod movement is too frequent, the imbalance of fuel combustion in the core and the change of control rod worth are expected. Therefore, preparing the solutions for this problem and monitoring systems are required. For the load-following operation of APR+ reactors, the power level and power distribution should be controlled simultaneously. In the case of current APR1400 reactor, reactor power is controlled automatically by reactor regulating system (RRS) but the power distribution is controlled manually by an operator. In the APR+ plant, a MPC controller which has a new concept for the automatic load-following operation is being developed. This is a control method that can perform the optimal control through predicted calculations on the effect of the control action by a mathematical model. It is difficult to handle the reactivity changes in accordance with load-following operation using only control rods. To accommodate load-following using only control rods, initial inserted control rods should be allowed, and we have to use a significant amount of control rods, and also the distortion of power distribution should be small. However, if APR+ reactor is operated in full-power conditions that control rods are fully inserted at the beginning of load-following operation, it is difficult to accommodate due to the decrease of stop margin and the increase of peak power.

Therefore, it is hard to perform the load-following operation without boron concentration adjustment. APR+ reactor has adopted a way that adjusts boron concentration by an operator in load-following operation. If the boron concentration is adjusted by an operator, it is necessary to provide proper guidance to an operator. If the boron concentration change is not smooth and control rod is inserted more or less, then it will affect the power distribution. Therefore, the strategy of adjusting boron concentration is a required entry for the load-following operation. The on-line operator support system is made up for the strategy of adjusting boron concentration when operating load-following in APR+ plant. This system provides the strategy of adjusting proper boron concentration using the code containing MPC controller for the calculations of boron concentration in the core, systems and the load-following operation. That is, the operator support system that can provide the result of calculations of supplementary water for the boron concentration requirements is made up.

B. Model Predictive Control Method

The model predictive control (MPC) method aims to control the average coolant temperature and axial shape index (ASI) within an acceptable operating range automatically. It cannot afford all of changes of the core reactivity by using only control rods and adjusting the boron concentration is required. Therefore, the model predictive control technique means a comprehensive core control technique combined with the boron control scenarios. Basically, the logic of MPC was set to meet the following basic requirements.

- It should control the power distribution in the core and average coolant temperature properly during the daily load following operation.
- The control rod is controlled automatically.
- When the reactor is operating in full power steady state, the control rods hold the state of All Rod Out (ARO).
- Use mensurable variables as an input to the model predictive controller.
- Use the control rods as a way of reactivity control.
- The usage of boric acid complies with as fixed scenarios as possible.
- Minimize the moving distance of the control rods in the same boron concentration condition.
- Control the core power distribution by using only R5 and PSCEA control bank.

The model predictive control method is to solve an optimization problem for finite future time steps at present 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.

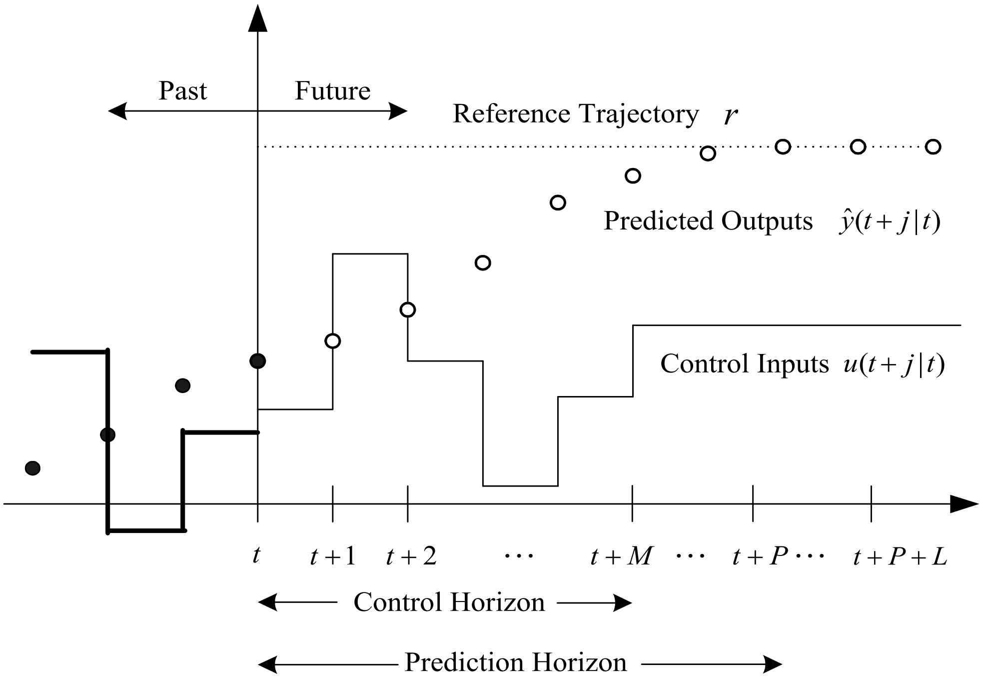


Fig. 2. The basic concept of MPC

Figure 2 shows the basic concept of MPC. That is, the future behavior of process output is predicted on the predictive horizon P and the number of M (M≤P) current and future control inputs under some assumed set of the current and future control inputs are calculated to minimize the quadratic objective function. Even though the number of M control input is calculated, only fist control input is implemented, new measured output value is obtained in the next time step, and the same calculation is repeated by moving one step forward.

When considering the Multi Input Multi Output (MIMO) system controlling average coolant temperature and ASI simultaneously, the cost function can be expressed as the following quadratic function.

$$J = \frac{1}{2}\sum_{j=1}^{P}(\hat{\mathrm{y}}(t+j\,|\,t) - r(t+j))^{T}\mathrm{Q}(\hat{\mathrm{y}}(t+j\,|\,t) - r(t+j)) + \frac{1}{2}\sum_{j=1}^{M}\Delta\mathrm{u}(t+j-1)^{T}\mathrm{R}\Delta\mathrm{u}(t+j-1) \qquad (2.1)$$

Constraints are as follows.

$$\begin{cases} \hat{y}(t+P+i) = r(t+P+i),\ i = 1,\cdots,L \\ \Delta u(t+j-1) = 0,\ j > M\ \ (M < P) \\ y_{low} \le \tilde{y}(t+N+i) \le y_{high} \\ -\Delta u_{\lim} \le \Delta u \le \Delta u_{\lim} \\ u_{low} \le u \le u_{high} \end{cases} \tag{2.2}$$

$\hat{y}(t+j|t)$ is j-step-ahead optimal prediction value of a system output based on the data to the current time t. r means a series of output setpoint vector, Δu is control input changes between two neighboring time steps. Positive definite matrices Q and R are symmetric matrix weighting the certain components of $(\hat{y}-r)$ and Δu at some future time interval. The number of outputs is two. These are the average coolant temperature and the axial shape index. The number of inputs is also two. This is axial position (speed) of two kinds of the control bank (regulating control bank and part-strength control bank). P is usually called prediction horizon, and M is called control horizon. Prediction horizon means the limited time interval where the output follows the reference output.

Constraint $(\hat{y}(t+P+i) = r(t+P+i),\ i = 1,\cdots,L)$ means that the output should be equal to the reference output during L time steps after the prediction horizon P, and it ensure the stability of the controller.

Second constraint, $\Delta u(t+j-1) = 0,\ j > M\ \ (M < P)$ means that there is no change in the control input after M time steps from the current time. Additionally, three constraints are added by modifying the control algorithm of MPC methodology.

C. Optimization of the Controller Using a Genetic Algorithm

Since the control rod moves at a few of constant speeds in the actual nuclear power plant, the controller could be more practical and applicable by optimizing completely discrete five rod speed (rapid insertion, slow insertion, stop, slow withdrawal, rapid withdrawal) signals. Therefore, in order to get the fully discrete control inputs, a genetic algorithm (GA) was used. There is some negative opinion on the applicability of the genetic algorithm from some people who do not know exactly, but it provides superior capability to find solutions than conventional optimization algorithms. And also because the model predictive controller has been going through an optimization process every time step, even if it is less optimized in a time step, it can achieve optimization at the next step immediately. A genetic algorithm (GA) is one of the algorithms for solving optimization problems. As the representative methods of the optimization problem, there are a gradient method, a random search method and a enumerative method. Among these methods, the GA belongs to the random search method. The most important feature of the GA is that it is not limited to the objective function and constraints, and the scope of usage is very diverse. In addition, it does not need to differentiate the objective function, and it is easy to design general objective function considering constraints. The characteristics of GA as an optimization algorithm are as follows.

(a) It searches the solution space by coding a set of system variables.

(b) Searching a solution of GA is not a point search. It performs the concurrent search for many solutions in the population.

(c) It does not need additional information on a system such as the rate of change.

(d) It uses stochastic search method, not a deterministic search.

(e) It search not only the way to improving the objective function but also allows the search which makes objective function worsen, so it can reach the global optima without falling into the local optima.

The genetic algorithm is a optimization algorithm based on the concept of the survival of the fittest and natural selection. In the natural evolution, the organisms which have traits suitable for the environment have large probability of survival, and the organisms obtain the appropriate traits through the process of crossover and mutation. And the organisms which have inappropriate traits are left behind. Through these repeated process, finally most appropriate organisms are survived.

The GA is that these evolution laws apply to optimization problems. It gives the fitness for each object depending on the degree of violation of an objective function and constraints by distributing many objects to interpreting field. If the fitness of an object is large, it makes the probability that the object participates in the crossover and mutation processes at the next step higher. Therefore, the objects which have good fitness are produced more and more. And the fitness of the entire objects is going to good direction. The overall algorithm is as follows.

(a) Determine how to mapping the system variables to the individual which is expressed as the one string consisting of binary system.

(b) Produce initial population by generating randomly defined objects in step (a).

(c) Evaluate the fitness of each object by changing the string of each object to the decimal number.

(d) Make a mating pool by selecting and copying the object which has good fitness.

(e) Generate two strings at the mating pool by mating their genotypes after randomly selecting parents participating in the mating.

(f) Transform offspring genotypes with constant mutation probability.

(g) Make a population of a new generation by repeating steps (c)~(f) as many times as the population size.

(h) Repeat the above processes until a termination condition is satisfied.

A genetic algorithm is used for solving the optimization problem of multi objective function, and it has many advantages compared with traditional optimization methods. Unlike existing optimizing methods that move from one point to another, GA is a way to go up many peaks in parallel from numerous points. The configuration of an object or chromosome of GA consists of the following current and future control input.

$$s = \begin{bmatrix} u_1(t) & u_1(t+1) & \cdots & u_1(t+M-1) & u_2(t) & u_2(t+1) & \cdots & u_2(t+M-1) \end{bmatrix} \tag{2.3}$$

Here, u_1 is R5 control bank speed signals and u_2 is P control bank speed signals. These signals are marked in binary number to indicate five rod speed signals such as rapid insertion, slow insertion, stop, slow withdrawal and rapid withdrawal. In order to indicate five speeds to binary number, three bits are required. It is represented as 000 (rapid insertion), 001 (slow insertion), 010 (slow insertion), 011 (stop), 100 (stop), 101 (slow withdrawal), 110 (slow withdrawal), 111 (rapid withdrawal).

The following equation shows the fitness function that is used to optimize the objective function of the proposed MPC controller.

$$fitness = \exp\left(-\sum_{k=1}^{P} \hat{\mathbf{e}}(t+k|t)^T Q \hat{\mathbf{e}}(t+k|t) - \sum_{k=1}^{M} \Delta\mathbf{u}(t+k-1)^T R \Delta\mathbf{u}(t+k-1) - \sum_{k=1}^{M} \mathbf{n}_{dc}(t+k-1)^T H \mathbf{n}_{dc}(t+k-1) \right) \tag{2.4}$$

In the above equation, the first term is to make error as low as possible, and the second term has been intended to be small movement of the control rods. The third term is to prevent the change in direction of control rods between neighboring time steps. Figure 3 shows the flowchart of a basic genetic algorithm.

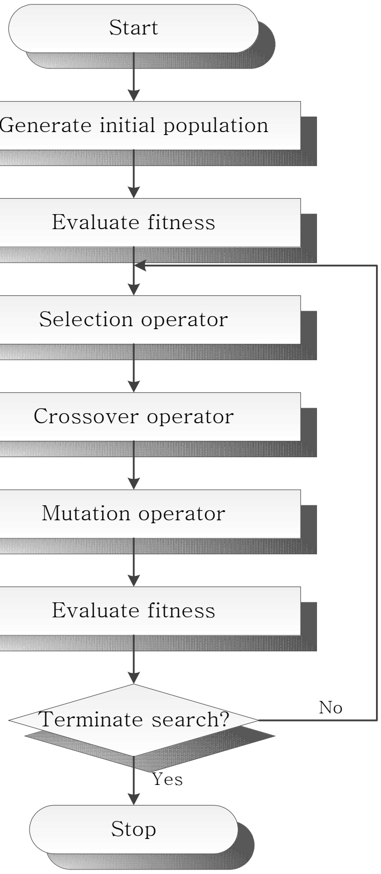


Fig. 3. The flowchart of a basic genetic algorithm

Ⅲ. Application to APR+ Reactors

A. Interface with the KISPAC-1D code

To perform the numerical simulations of the daily load-following operation, the MPC controller is interfaced with KISPAC-1D code that is a NSSS performance analysis code. The numerical simulations of the daily load-following operation are carried out at the conditions of the beginning of fuel cycle, 8000MWD/t, and 16000MWD/t fuel burnup. The existing KISPAC-1D code and MPC controller was coded by FORTRAN language and it was not optimized systematically. So, in order to consider the constraints of the MPC controller systematically, a new MPC algorithm is needed, and it was interfaced with KISPAC-1D code to perform the comprehensive simulations.

For this purpose, a controller was coded using MATLAB. Therefore interfacing with KISPAC-1D code is required. The existing KISPAC-1D code based on the FORTRAN language environment needs to be interfaced with a MPC controller coded by the MATLAB program. For this interface process, the MATLAB files are integrated with KISPAC-1D code that is converted to the library files using latest FORTAN compiler. For the conjunction with them, first the KISPAC-1D code is converted to a library file by using the Visual FORTRAN compiler. And the gateway routine is used to integrate a library file with MATLAB. To compile FORTRAN library files and Gateway Routine on the MATLAB, the FORTRAN compiler is set up by typing "mex -setup" by using mex tool supporting the interface with other programs. When you compile the KISPAC-1D files and the Gateway Routine file typing the keyword in the MATLAB command window, it is converted to the shared library executable at the MATLAB program environment (KISPAC-1D_CONT.mexw64). KISPAC-1D_CONT.mexw64 file which is a form of the shared library that is generated on the MATLAB program environment is used by being called in the MPC controller (written in MATLAB) every calculation step, and the interface variables in the KISPAC-1D code are used by being declared as the global variables.

B. Simulation Conditions

The model predictive control method requires to solve the optimization problems in online to calculate the optimal control input about certain future time steps. The load following operation should control the average coolant temperature and axial power distribution simultaneously. Accordingly, it is considered as a multi-input multi-output (MIMO) system. To explain MIMO transfer function briefly, it is assumed that there is the transfer function matrix of the following type.

$$\begin{bmatrix} G_{1,1} & G_{1,2} & \cdots & G_{1,n_u} \\ G_{2,1} & G_{2,2} & \cdots & G_{2,n_u} \\ \vdots & \vdots & \ddots & \vdots \\ G_{n_y,1} & G_{n_y,2} & \cdots & G_{n_y,n_u} \end{bmatrix} \tag{3.1}$$

Where $G_{i,j}$ is the transfer function of the i^{th} output in terms of the j^{th} input.

In this thesis, the controller was designed as two-input and two-output system for the load following operation. This system can be represented by the following equation.

$$\begin{bmatrix} y_1(k) \\ y_2(k) \end{bmatrix} = \begin{bmatrix} G_{11}(q) & G_{12}(q) \\ G_{21}(q) & G_{22}(q) \end{bmatrix} \begin{bmatrix} u_1(k) \\ u_2(k) \end{bmatrix} \tag{3.2}$$

In above equation, $G_{11}(q)$ is expressed by a discrete transfer function, and it can be expressed by the following equation.

$$G(q) = \frac{b_0 + b_1 q^{-1} + \cdots + b_n q^{-n}}{a_0 + a_1 q^{-1} + \cdots + a_n q^{-n}} q^{-d} \quad (3.3)$$

Where d is equal to zero or greater. It indicates the real delay by sampling time. The above MIMO system is expressed as a discrete function.

$$\begin{aligned} y_1(k) &= \theta_{d_1}(q) y_1(k) + \theta_{n_{11}}(q) u_1(k) + \theta_{n_{12}}(q) u_2(k) \\ y_2(k) &= \theta_{d_2}(q) y_2(k) + \theta_{n_{21}}(q) u_1(k) + \theta_{n_{22}}(q) u_2(k) \end{aligned} \quad (3.4)$$

The requirements related on the daily load following operation of an APR+ reactor are as follows:

- Operation should be possible at the operation patterns of 100%-below 50%-100% power on a 24-hour cycle.
- In power increase or decrease, the rate of change should be 25%/hr or more, the time of partial power level is 4 to 10 hours. In other words, the form of (10-16)-2-(4-10)-2 operation should be possible.
- It should be possible from the beginning of fuel cycle to the end of fuel cycle (about 90% fuel burned up).

The control input for the plant satisfies the constraints on the regulating and part-strength control rod position and the optimized control input signals were used as their control rod speed. And part-strength control bank P1 and P2 move only at the upper part of core as the same speed. As shown in figure 4, the constraints are imposed on the control rod position to meet the long-term and short-term steady-state insertion limit of the regulating control banks. The control banks speed use five types of signals. The control bank of R5 and P1&P2 speed is 1.27cm/sec (rapid insertion), 0.127cm/sec (slow insertion), 0 (stop), 0.127cm/sec (slow withdrawal), and 1.27cm/sec (rapid withdrawal).

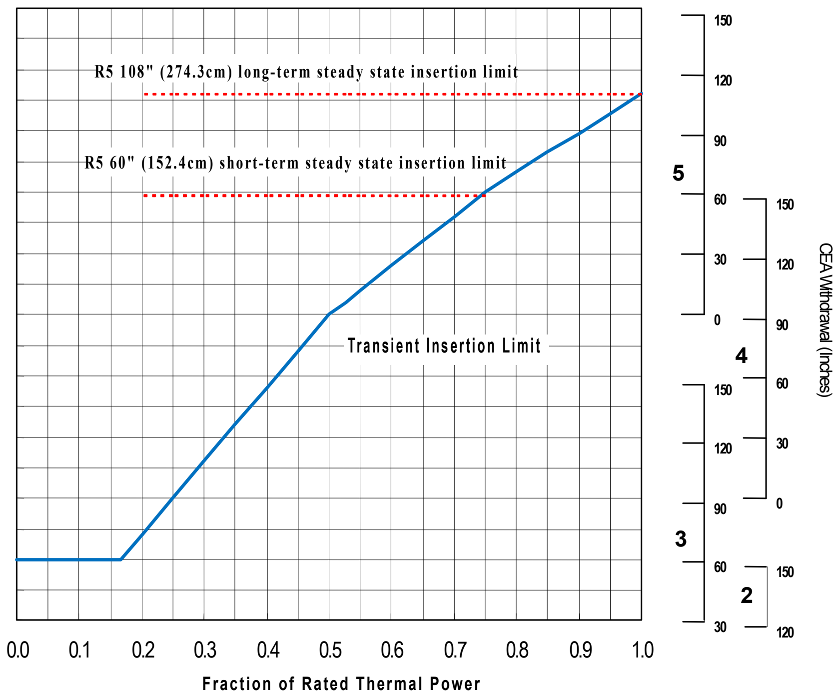


Fig. 4. The long-term and short-term steady-state insertion limit of control banks

To perform numerical simulations of the MPC controller using a genetic algorithm, the following initial conditions were used.

- Initial reactor power : 100%
- Regulating control bank R5 position : 370cm
- Other regulating control bank position : 381cm
- Part-strength control bank P position : 370cm
- Sampling period (T) : 4sec
- Prediction horizon (P) : 5
- Control horizon (M) : 3
- Control input weighting factor μ_{wt0} = [0.001, 1.0, 1]
- The number of the maximum optimization run : maxRun = 40

- Crossover probability : Pc = 1
- Mutation probability : Pm = 0.05
- Population size : size_pop = 20

In this thesis, the proposed MPC controller using a genetic algorithm was designed to control the average coolant temperature and axial power distribution and adjust the boron concentration automatically according to the output changes by using control logic. And it is confirmed that the proposed controller satisfies the conditions of daily load following operation and show satisfactory performance by performing the simulations during 72 hours that is three days as the rate of power change 50%/120min.

C. Simulation Results for the Daily Load-following Operation

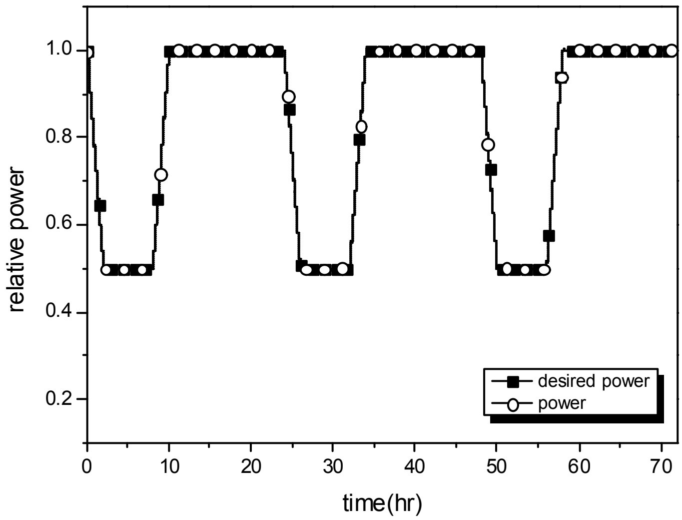
Figure 5~7 indicate the reactor power, average coolant temperature, axial power distribution (ASI), control bank positions and boron concentration and the control bank speed obtained by performing simulations at the beginning of fuel cycle (0MWD/t fuel burnup), the middle of fuel cycle (8000MWD/t fuel burnup) and the end of fuel cycle (16000MWD/t fuel burnup).

Figure 5 shows the results of a numerical simulation for the daily load following operation at the beginning of fuel cycle. Figure 5(a) shows how the reactor power level follows the desired power well. From the graph, the reactor power is controlled exactly for the daily load-following operation. The average coolant temperature and ASI follows the programmed target values fairly well as shown in figure 5(b). The reason why initial response characteristic is slightly inadequate due to incomplete initial parameter prediction. There are little differences with target values in some periods, but it was tracked well mostly to the target values.

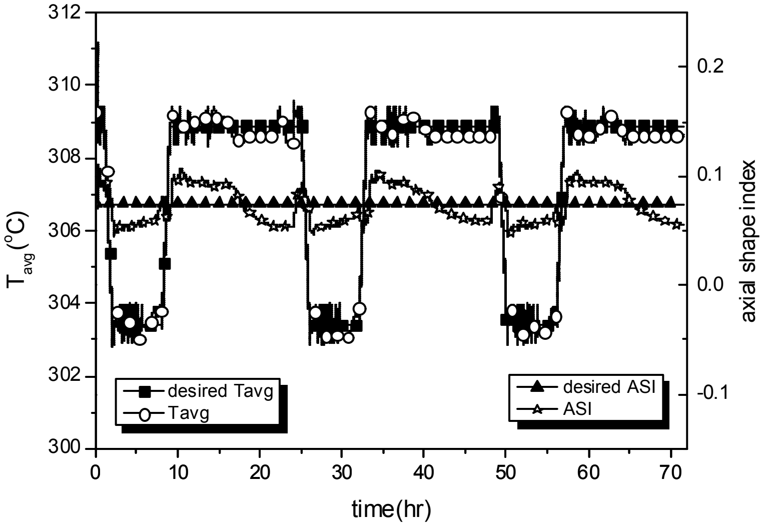
It is not easy to control the average coolant temperature and axial power distribution exactly at the same time with regulating control bank and part-strength control bank, because the characteristics of these two kinds of control banks are not different specially. Figure 5(c) shows the position of regulating control banks and part-strength control bank. The regulating control bank R5 is moving when the reactor power level decreases to 50%.

Figure 5(d) shows the control rod speed of the banks R5 and P. As mentioned previously, the rod speed signals consist of five signals (rapid insertion, slow insertion, stop, slow withdrawal, rapid withdrawal), and rapid rod moving speed is 1.27cm/sec, and slow rod moving speed is 0.127cm/sec. Additionally, the performance of the proposed controller can be checked through this graph. If the control rod is inserted/withdrawn frequently between neighboring steps or rapid insertion/withdrawal of control rods happens repeatedly, it can be judged that the performance of a controller is not good. However, as shown in this figure, the proposed controller shows the good performance.

In this thesis, boron concentration in the coolant was adjusted automatically by using a boron acid adjustment logic. Therefore, it does not require so much change of reactivity by regulating control banks. The regulating control bank R5 and the part-strength control bank P move to control the average coolant temperature and axial power distribution. A control rod consumption problem can be solved by relocating control rods periodically.

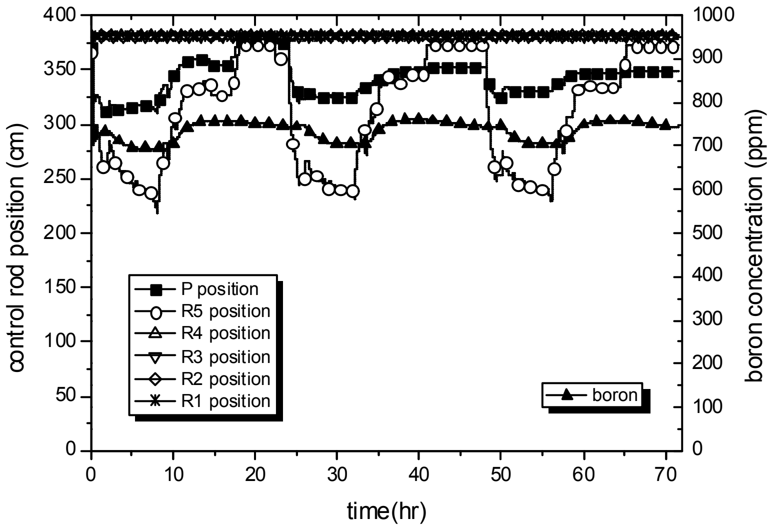


(a) reactor power

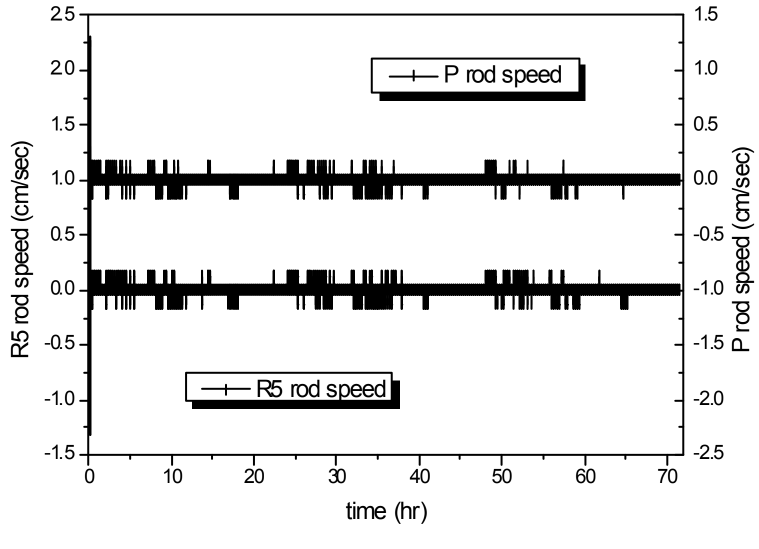


(b) Tavg and ASI

Fig. 5. The simulation results for a daily load following operation (0MWD/t)



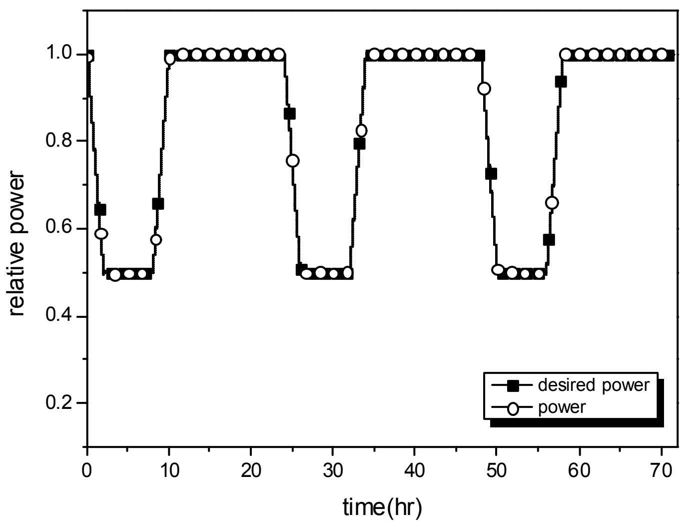
(c) control rod position and boron concentration



(d) control rod speed

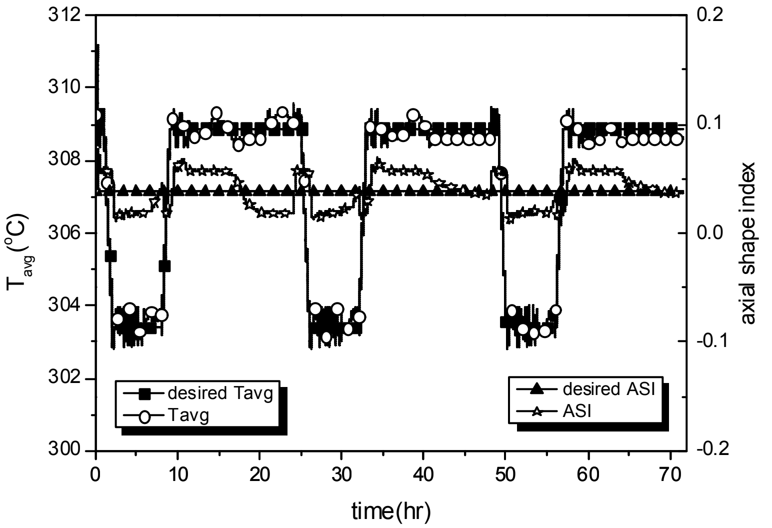
Fig. 5. The simulation results for a daily load following operation (0MWD/t) (continued)

Figure 6 shows the simulation results of a daily load-following operation at 8000MWD/t fuel burnup that is the middle of fuel cycle (MOC). According as the fuel is burning up, the target ASI value (equilibrium ASI at the fuel burnup) was set lower than the beginning of fuel cycle (BOC) at the figure 6(b). And also, as shown in figure 6(c), boron concentration is decreased. Likewise, in this condition, the average coolant temperature and axial shape index (ASI) follow target values, and also the reactor power level follows the desired power level exactly.

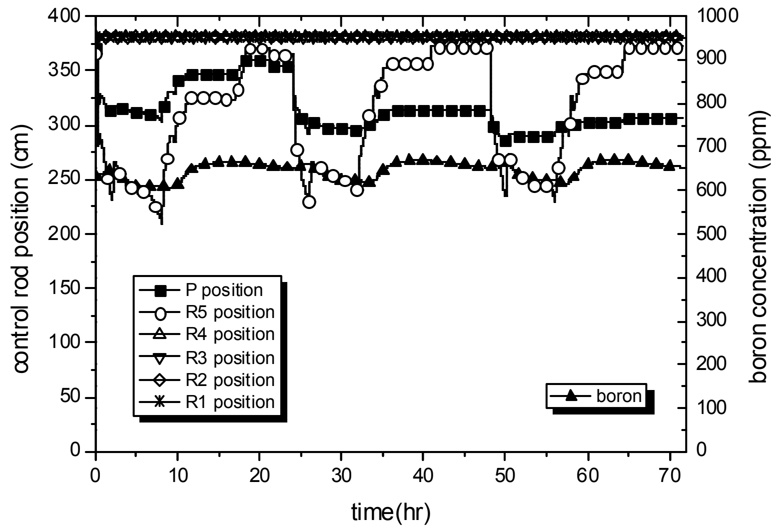


(a) reactor power

Fig. 6. The simulation results for a daily load following operation (8000MWD/t)

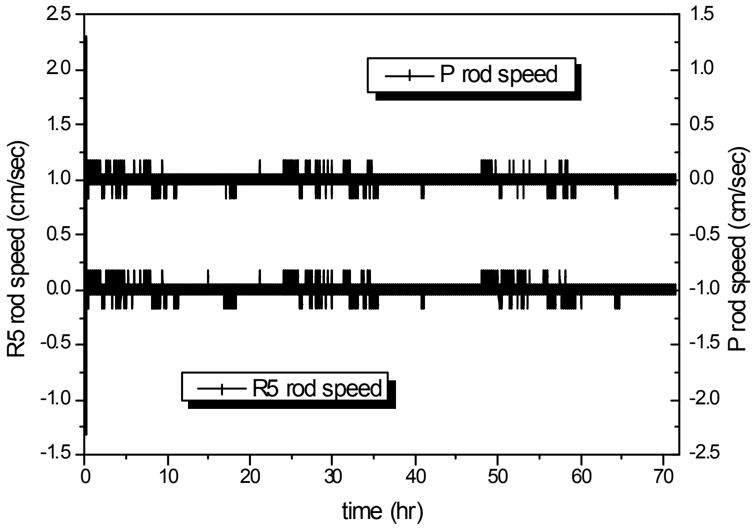


(b) Tavg and ASI



(c) control rod position and boron concentration

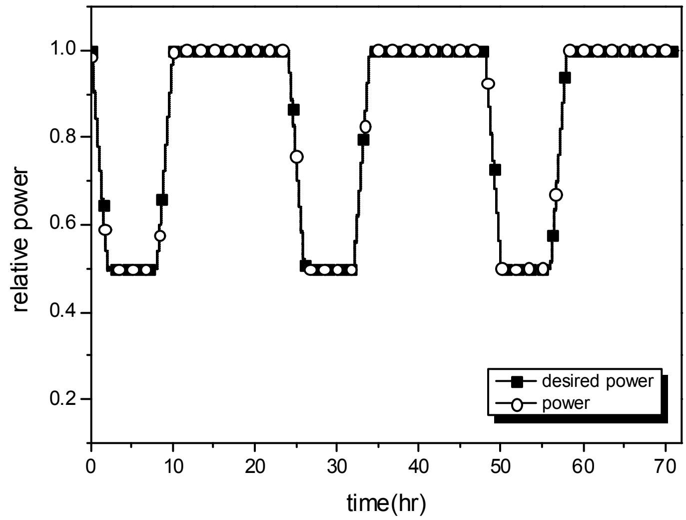
Fig. 6. The simulation results for a daily load following operation (8000MWD/t) (continued)



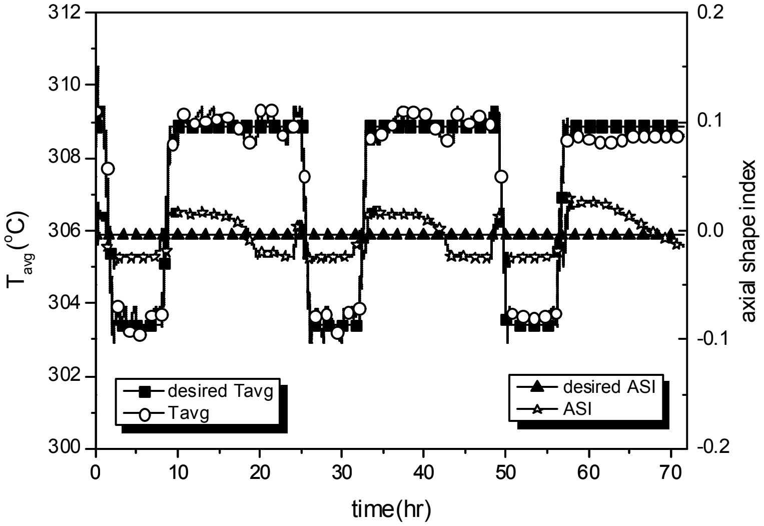
(d) control rod speed

Fig. 6. The simulation results for a daily load following operation (8000MWD/t) (continued)

Next, figure 7 shows the simulation results of a daily load-following operation at 16000MWD/t fuel burnup, that is almost the end of the fuel cycle (EOC). In this fuel burnup, the boron concentration is significantly decreased as shown in figure 7(c). The regulating control banks R5 and even R4 were inserted into the core for controlling reactor power. Likewise, in this condition, the average coolant temperature and axial power distribution follow the target values. And also the reactor power level follows the desired power level exactly.

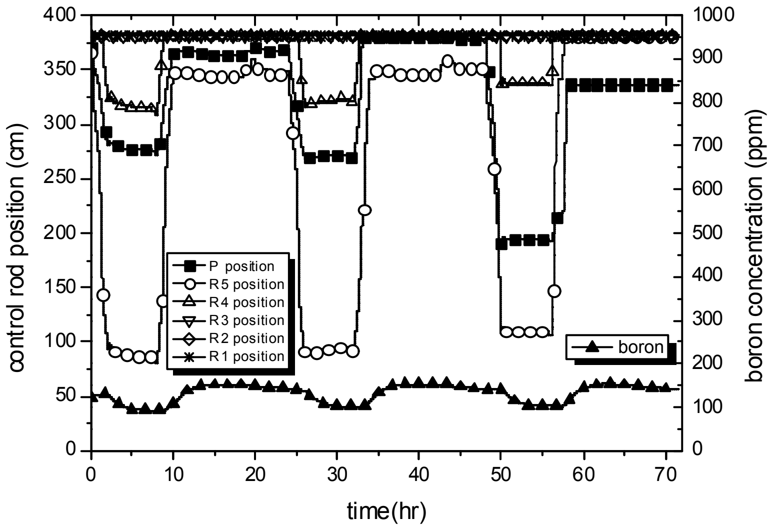


(a) reactor power

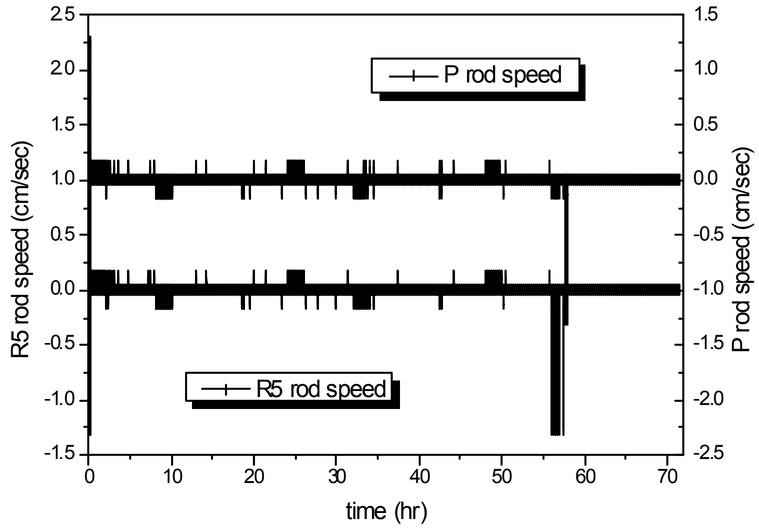


(b) Tavg and ASI

Fig. 7. The simulation results for a daily load following operation (16000MWD/t)



(c) control rod position and boron concentration



(d) control rod speed

Fig. 7. The simulation results for a daily load following operation (16000MWD/t) (continued)

Ⅳ. Conclusions

In this thesis, a model predictive control (MPC) methodology was applied to designing a load-following controller for the APR+ reactor, and some of the constraints were added to apply for the APR+ reactor based on the MPC basic constraints. As a result of this thesis, a new MPC controller that can control the reactor power level and axial power distribution systematically has been developed for the load following operation. Furthermore, unlike the existing control rod moving mechanisms, a fully discrete control rod moving mechanism was used, and a genetic algorithm was used for optimizing the movement of control rods.

The proposed controller was applied to ensure the possibility of the load following operation of an APR+ reactor which was simulated numerically by KISPAC-1D code. The performance of the controller was tested by performing numerical simulation from the beginning of the fuel cycle (BOC) to the end of fuel cycle (EOC). Through this thesis, the reactor power level follows the desired power level well and the average coolant temperature and ASI tracking performance is good. It was hard to control the reactor power level 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 part-strength control bank. From the results of numerical simulations, in order to check the performance of the proposed controller at the ramp increase or decrease of a desired load and its step increase or decrease, the proposed controller adjusts the control rod position so that the reactor power level and ASI track its set point change very well according to the plant load.

Finally, this thesis presented a new method of controlling the nuclear power plants, and the substantial I&C portions of the nuclear power plant have being digitized. So, I think that this thesis can provide a useful method that applies to the load-following operation of nuclear power plants.

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