Proceedings of the Korean Nuclear Society Spring Meeting
Gyeongju, Korea, May 2003

The Power Maneuvering of PWRs with Axially Variable Strength Control Rods

Ung-Soo Kim and Poong-Hyun Seong

Department of Nuclear and Quantum Engineering
Korea Advanced Institute of Science and Technology
373-1, Guseong-Dong, Yuseong-Gu
Daejeon, Korea, 305-701

Abstract

In this research, axially variable strength control rods (AVSCRs) are suggested and developed to solve the problems related to the axial power distribution of reactor during the power maneuvering of PWRs. The control rods are classified into two types. The first type is 'multi-purpose control rod', and the other type is 'regulating control rod'. Two multi-purpose control rod banks (AVSCR1, AVSCR2) are newly developed and conventional-axially uniform strength-control rods are adopted as regulating control rod banks to minimize design change of PWRs. The newly developed AVSCRs are three sectioned control rods. And the worth shapes of these AVSCRs are optimized to obtain appropriate moving characteristics which are related to the variation of axial offset according to the motion of AVSCRs. Then the operation strategy for the power maneuvering is developed considering the moving characteristics of AVSCRs. This strategy consists of simple logics and no use of reactivity compensation by boron is considered. Finally, the AVSCRs are applied to the power maneuvering with a typical 100-50-100%, 2-6-2-14h pattern of daily load-follow for all burn-up state of core. From the application results, it is shown that the use of AVSCRs make it possible to regulate AO within the target band during the power maneuvering with only control rods and consequently the power maneuvering without reactivity compensation by boron concentration change is accomplished, and also the AVSCRs can cover the whole burn-up states of reactor core.

1. Introduction

The special considerations for core safety restrict the operation flexibility of nuclear power plants. Therefore, in the present operation of electricity grid in Korea, the load-follow operation of nuclear power plants has received relatively little attention and the most installed nuclear capacity is used as base-load generation and the change in electric power generation to follow load change is performed by other electric power sources such as fossil power plants. As the share of the nuclear capacity in total electric power generation increases, however, there is a growing needs for nuclear power plants to be able to follow load changes on a utility's power system, therefore the load follow capability of nuclear power plants becomes more important.

In a typical nuclear power plant, the reactor power change is caused by variation of reactivity and two primary mechanisms for reactivity changes are control rods and soluble boron. Cylindrical control rodlets of neutron absorbing material are assembled into clusters and manipulated as groups (banks) of clusters in a reactor. Soluble boron control involves the use of a neutron absorber in the form of boric acid, dissolved in the coolant to compensate for slow reactivity change. A moderator temperature control is auxiliary means. [1] During the power maneuvering of a nuclear power plant, the reactor core is in a transient state induced by transient effects of xenon. The reactivity variation that causes change in reactor power makes variation of xenon concentration and axial distribution, and a change in xenon axial distribution may cause xenon oscillation, which makes reactor be able to reach uncontrollable state or trip. Therefore, in order to prevent a xenon oscillation, maintaining the axial power distribution within some prescribed range is required during the power maneuvering. And this range is represented by a variable called axial offset (AO),

$$AO = \frac{P_T - P_B}{P_T + P_B}$$

where,

P_T : power in top half of the core

P_B : power in bottom half of the core

This is simply the normalized difference between the power in the top half of the core and the power in the bottom half of the core. And the AO target band is determined by selecting boundaries as typically $\pm$5% about a target AO value.

However, the reactivity change using the conventional mechanisms has difficulties in regulating axial power distribution within the prescribed range. In previous study, therefore, lower shifted worth control rods (LSWCRs) were devised as a kind of AVSCRs to mitigate variation of axial power distribution during the power maneuvering and the feasibility for the use of control rods that have axially varying worth shape is identified through this work. [2] However, the LSWCRs were developed in intuitive manner and the level of the result from suggesting these LSWCRs was showing feasibility for the use of AVSCRs. Hence, there exists some lack of reality and needs for progressing research.

In this research, the AVSCRs are newly developed to settle the utility of the control rods that have axially varying absorber and to solve the problems related with the axial power distribution of reactor during the power maneuvering of PWRs. The control rods are classified into two types such as 'multi-purpose control rod' and 'regulating control rod'. And two multi-purpose control rod banks are newly developed. The newly developed AVSCRs are three sectioned control rods. And the worth shapes of these AVSCRs are optimized to obtain appropriate moving characteristics which are related to the variation of axial offset according to the motion of AVSCRs. Then the operation strategy for the power maneuvering is developed considering the moving characteristics of AVSCRs. This strategy consists of simple logics and no use of reactivity compensation by boron is considered.

2. Development of Axially Variable Strength Control Rods

Since control rods tend to force power to the regions where no rod is inserted, a motion of control rods in the core involves variation of axial power distribution. Generally, in the viewpoint of the AO, a control rod insertion moves the AO to the negative direction and withdrawal moves the AO to the positive direction in the top half of the core. In the bottom half of the core, contrary phenomena occur.

On the other hand, the AO variation must be kept in the AO target band, as mentioned above, and this characteristic makes it difficult to maneuver reactor power using control rods and limits control rod motion. And for this reason, the reactivity change by boron used to be used as a complementary means to provide moving margin to control rods in the load follow operation of some nuclear power plants. There is another reason for using soluble boron of course. It is reactivity compensation for xenon build up. For instance, when a control rod is inserted to decrease power, the control rod should be withdrawn immediately to compensate xenon build up for maintaining the target power. However, the degree of control rod insertion is not large enough to produce the reactivity required to compensate xenon build up, therefore boron dilution is necessary.

In this work, AVSCRs are suggested to solve the problems related with the variation of axial power distribution during the power maneuvering and to accomplish the power maneuvering with only control rods and without the reactivity compensation by boron concentration change. AVSCRs are the control rods that have axially non-uniform strength differently from conventional control rods.

2.1 Axially Variable Strength Control Rods

The control rods are classified into two types in this work. The first type is 'multi-purpose control rod', and the other type is 'regulating control rod'. The multi-purpose control rods are used for dual purpose: The first is controlling the AO. The multi-purpose control rods regulate the AO not to violate the AO boundaries during the power maneuvering. The second is producing the required reactivity to compensate xenon build up, instead of a boron concentration change such as boration, and dilution. The regulating control rods perform the same role as conventional control rods, i.e., they are used to change reactivity of reactor.

Two multi-purpose control rod banks (AVSCR1, AVSCR2) are newly developed and conventional-axially uniform strength-control rods are adopted as regulating control rod banks to minimize design change of PWRs. Between two multi-purpose control rods, the first one is named ‘AVSCR1’ and the requirements of the AVSCR1 are defined as follows: The main purpose of the AVSCR1 is mitigating an AO distortion to the negative direction caused by the motion of the other control rods. In PWRs, since all of the control rods should be inserted from the top of the core, it is difficult to solve the problem of a negative AO distortion while a positive AO distortion can be mitigated relatively easy. Therefore, the AVSCR1 should have a tendency that strongly forces the AO to the positive direction while this rod is in the bottom half of the core and the AO should have larger value than the reference AO value while the AVSCR1 is at the initial position that is near to but upper than the bottom of the core. Also, the AVSCR1 moves mainly in the bottom half of the core during the power maneuvering. Then, the AVSCR1 is able to play a role to mitigate an AO distortion to the negative direction. It goes without saying that the AVSCR1 should cause the required reactivity compensation for xenon build up. The other multi-purpose control rod is named ‘AVSCR2’ and the requirements of this AVSCR2 are defined as follows: The main task of the AVSCR2 is controlling the AO to the positive and negative direction to keep the AO within the target AO band. And it should cause the required reactivity change to maintain a target reactor power instead of boron concentration change in such a case that the regulating rods are not available because of their reaching insertion or withdrawal limit. The AVSCR2 moves in the whole range of the core, differently from the AVSCR1, during the power maneuvering.

Before the development of AVSCRs, the moving characteristics that are related to the variation of the AO with the motion of control rods are investigated to provide AVSCRs with appropriate moving characteristics for the power maneuvering. Generally, the AO varies according to the motion of control rod as shown in Fig. 1. While a control rod is being withdrawn from the bottom of the core, the AO value decreases from its initial value before passing through the center of the core and have the minimum value at the center of the core. Then the AO value increases as the withdrawal of the control rod after passing through the center of the core.

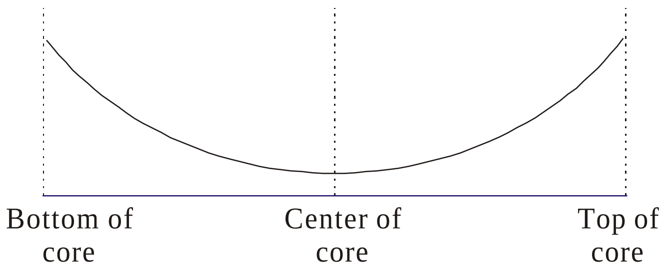


Fig. 1 Variation of AO according to motion of control rod

Based on this nature, in this work, the moving characteristics of AVSCRs are defined as follows: The moving characteristics are determined based on two indexes. The first index is the AO value when the AVSCR1 is at initial position, which may be lower part of the bottom half of the core, under the condition that the AVSCR2 is at the bottom of the core and regulating rods are fully withdrawn. Also this index has a direct relation with the initial position of the AVSCR2 that is determined as the position of the AVSCR2 which puts the AO value beneath the upper AO boundary when the AVSCR1 is at its initial position, as shown in Fig. 2. The reason for determining the initial position of AVSCR2 like this is that the AO transient starts with decreasing the AO value in the power maneuvering. If the first index moves to the positive direction, the initial position of AVSCR2 is moved toward center of the core. In other words, as the first index becomes larger, the initial position of the AVSCR2 is determined higher to depress the AO toward the upper AO boundary. The second index is the minimum AO value while the AVSCR2 is being withdrawn from its initial position. As shown in Fig. 2, this minimum AO value appears when the AVSCR2 is near to the center of the core.

And based on this definition of the moving characteristics of AVSCRs, the appropriate moving characteristics for the power maneuvering are determined as follows: Since the main requirement of the AVSCR1 is mitigating an AO distortion to the negative direction, as mentioned before, the first index becomes a measure of the capacity of the AVSCR1. Therefore, this index should be sufficiently greater than the value of the upper AO boundary and it is thought to be sufficient that this index is greater as the degree of the gap between the upper and lower AO boundary. Also, considering it is desirable that the AO variation with the motion of AVSCR2 is kept within some range, it is appropriate that the second index (minimum AO value) is located at the position higher than lower AO boundary as one-third of the gap between the two AO boundaries as shown in fig. 2.

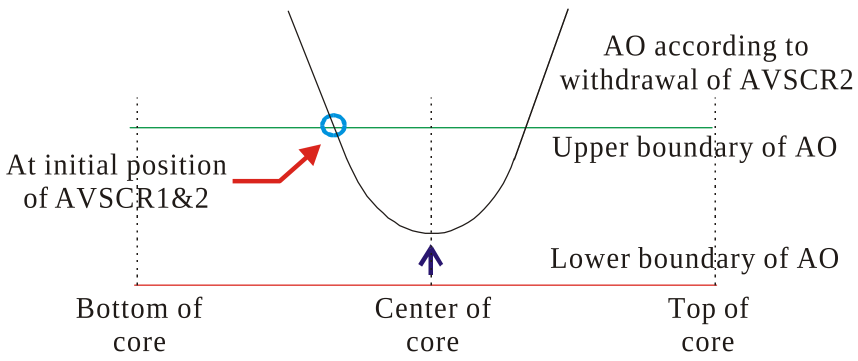


Fig. 2 Desirable moving characteristics of AVSCRs

The newly developed AVSCRs, in this work, are axially three sectioned control rods. As shown in Fig. 3, this control rod is divided into three sections that have different strength each other. The word 'strength' means the capability of neutron absorption and variable strength can be implemented by varying the concentration of neutron absorbing materials. The variables x_1, x_2, and x_3 in Fig.3 indicate the values of strength at each section of the AVSCR, and this set of thee variable reflects a worth shape of the AVSCR.

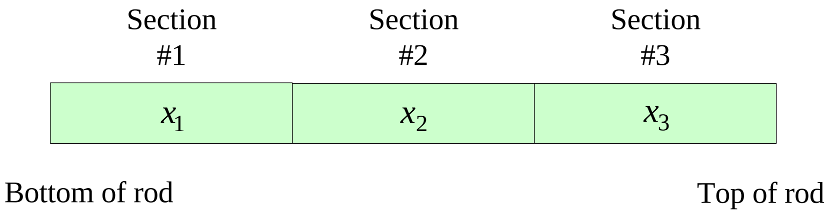


Fig. 3 Three-sectioned AVSCR

2.2 Optimization of Axially Variable Strength Control Rods

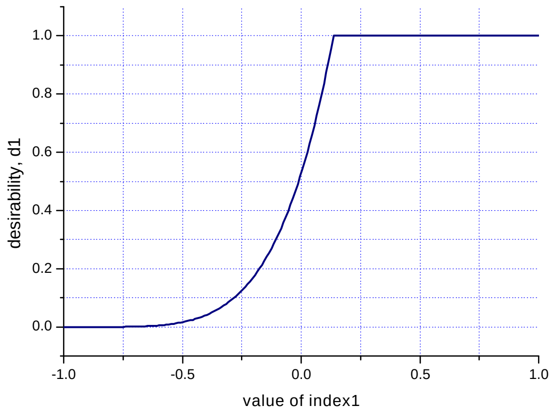
The optimization of the worth shape of the AVSCRs is performed to find optimal worth shape that provides the AVSCRs with optimal performance for the power maneuvering of PWRs. The optimization objective is to obtain the predetermined appropriate moving characteristics. The moving characteristics are determined by two indexes and, as mentioned above, the appropriate moving characteristics are determined as follows: The first index is greater than the upper AO boundary as the degree of the gap between the upper and lower AO boundary. And the second index is located at the position higher than lower AO boundary as one-third of the gap between the two AO boundaries.

In this case, the objective functions for the optimization are relationships between these two indexes and axial worth shape of the AVSCRs. However, there exist no analytic objective functions for this case because both two indexes are the responses that can only be evaluated by computer simulations using a reactor simulation code. Therefore the simulation optimization methodology is used. And the response surface methodology (RSM) is adopted as the simulation optimization algorithm for the optimization of the worth shape of the AVSCRs. The RSM is a procedure for fitting a series of regression models to the output variable of a simulation model by evaluating it at several input variable values and optimizing the resulting regression function. [3] The process starts with a first order regression function and the steepest ascent/descent method. After reaching the vicinity, higher degree regression functions are employed.

Because there are more than one objective functions, this work becomes multiple objective optimization problem. For solving this problem, the use of desirability function in which the researcher’ s own priorities and desires on the response value are built into the optimization procedure is considered. [4] And following desirability functions are used: For index1, the desirability function is given as Fig. 4(a) so that the value may be greater than the upper AO boundary (= 0.0365 in this work) as the degree of the gap between the upper and lower AO boundary. The desirability function for index2 is given as Fig. 4(b) in order to force the value toward the position higher than lower AO boundary as one-third of the gap between the two AO boundaries. And a single composite response D is calculated as:

$$D = \sqrt{d_1 \cdot d_2}$$

A value of D close to 1.0 implies that both two indexes are in a desirable range simultaneously. Then the optimization that maximizes the value of D is performed in following conditions: The optimizations of both AVSCR1 and AVSCR2 are performed simultaneously. The design variables x_1, x_2, and x_3 are the values of strength at each section of the AVSCR1 and x_4, x_5, and x_6 are those of the AVSCR2. The initial value of $\mathbf{x} = (x_1, x_2, x_3, x_4, x_5, x_6)$ is set as (3.0, 3.0, 3.0, 3.0, 3.0, 3.0) where the number 3.0 means the three times of the strength of normal control rod. For experiments, the ONED94 code is used for an application plant. The ONED94 code is a one-dimensional reactor core simulation code. [5]



$$d_1 = \left(\frac{\hat{y}_1 - (-1.0)}{AO_{upper} + (AO_{upper} - AO_{lower}) - (-1.0)} \right)^5, \quad \text{for index1}$$

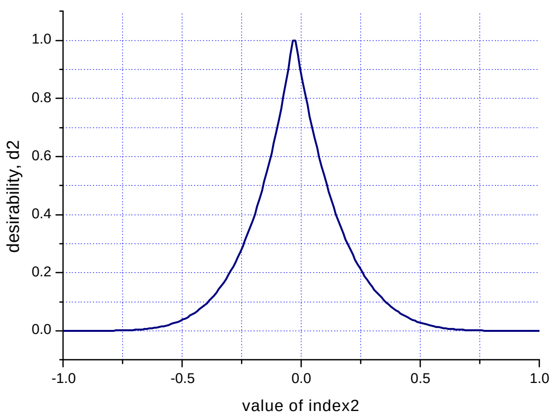
where,

$\hat{y}_1$: the value of index1

AO_{upper} : the value of the upper AO boundary $(= 0.0365)$

AO_{lower} : the value of the lower AO boundary $(= -0.0635)$

Fig. 4(a) Desirability function for index1



$$d_2 = \begin{cases} \left(\dfrac{\hat{y}_2 - (-1.0)}{AO_{lower} + \frac{1}{3}(AO_{upper} - AO_{lower}) - (-1.0)} \right)^5 & \text{if } \hat{y}_2 < AO_{lower} + \frac{1}{3}(AO_{upper} - AO_{lower}) \\ \left(\dfrac{\hat{y}_2 - (1.0)}{AO_{lower} + \frac{1}{3}(AO_{upper} - AO_{lower}) - (1.0)} \right)^5 & \text{if } \hat{y}_2 \geq AO_{lower} + \frac{1}{3}(AO_{upper} - AO_{lower}) \end{cases}, \quad \text{for index2}$$

where,

$\hat{y}_2$: the value of index2

AO_{upper} : the value of the upper AO boundary (= 0.0365)

AO_{lower} : the value of the lower AO boundary (= –0.0635)

Fig. 4(b) Desirability function for index2

The optimization results are shown in Fig. 5. Fig. 5(a) shows the variation of $\mathbf{x} = (x_1, x_2, x_3, x_4, x_5, x_6)$ as the optimization is progressed. From the result, it is shown that the shape of the AVSCR1 is optimized to (6.996, 1.6357, 1.2498) and the shape of the AVSCR2 is optimized to (3.3943, 2.3253, 0.3886) in 621 search steps. Fig. 5(b) indicates the variation of D-value. The initial D-value is 0.18671 and it is not desirable. However, as the optimization is progressed, the D-value approaches 1.0 and becomes 0.99991. This implies that both two responses (index1 and index2) are in a desirable range simultaneously. This is shown in Fig. 5(c). The index1 has increased from –0.0166 to 0.3034 and it is sufficiently greater than the upper AO boundary. The index2 has increased from –0.4272 and got the value of –0.0302 and it is a desirable value.

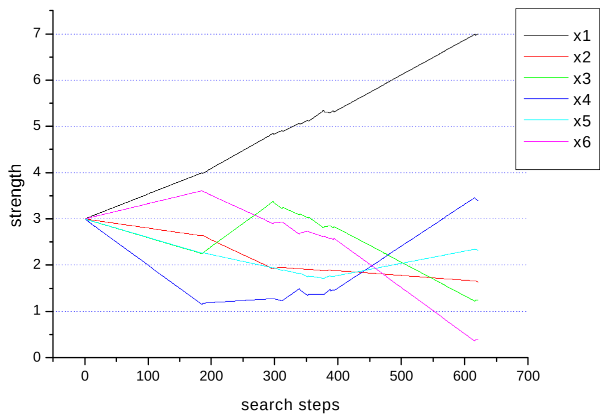


Fig. 5(a) Variation of $\mathbf{x} = (x_1, x_2, x_3, x_4, x_5, x_6)$

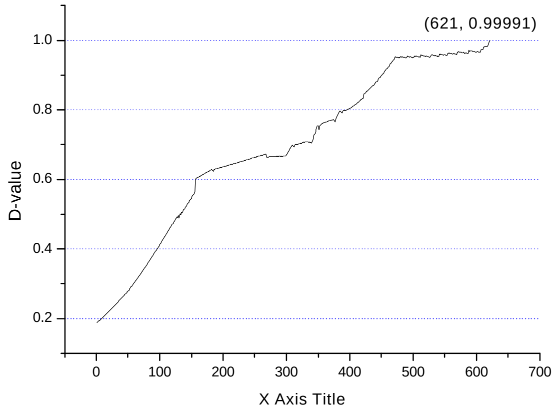


Fig. 5(b) Variation of D-value

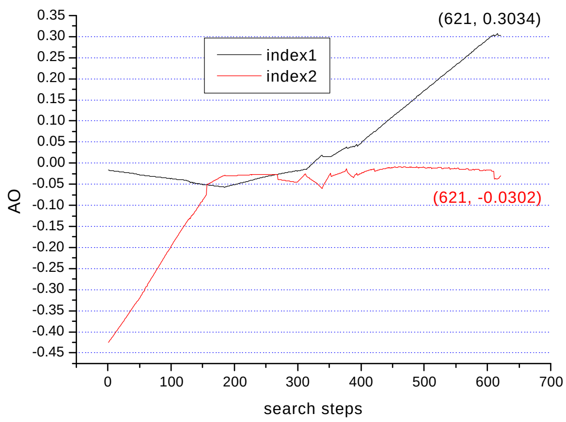


Fig. 5(c) Variation of AO violation and initial AO

Consequently, the developed AVSCRs have obtained the appropriate moving characteristics, as determined before, through optimization. And the resultant moving characteristics are shown in Fig. 6.

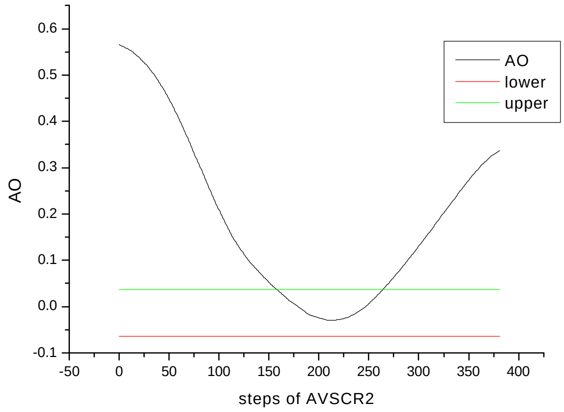


Fig. 6 Resultant moving characteristics of AVSCRs from optimization

3. Development of An Operation Strategy with AVSCRs for the Power Maneuvering

The operation strategy with AVSCRs for the power maneuvering is established based one the moving characteristics of AVSCRs as shown in Fig. 6. Firstly, the time interval is divided into following two stages as shown in Fig. 7: The first is the stage named ‘transient interval’. In this stage, the objectives of the operation strategy are controlling power and regulating the AO in target band using all rods actively. The second stage is ‘recovering interval’ and the operation strategy is aimed to recover the status of reactor core in order to prepare next transient for the power maneuvering. Especially, the AVSCRs are forced toward their initial position as near as possible in this stage.

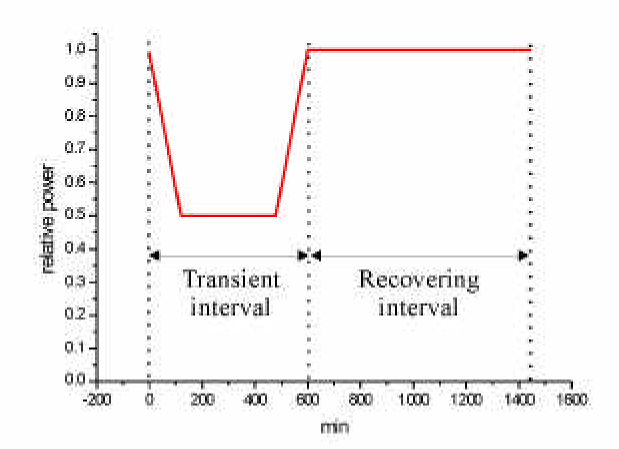


Fig. 7 Division of time interval for establishing operation strategy

Another important consideration in developing the operation strategy is no reactivity compensation by boron concentration changes. This makes it possible to automate power maneuvering and consequently relieves operator’s burden for operating CVCS to change boron concentration because CVCS is operated manually. Also it has some other advantages such as reducing liquid waste, decreasing corrosion of components in nuclear power plants, and so on.

Then the operation strategies corresponding to the objectives of each time interval are established as follows: For operation, six reactor states are defined and Table I shows these states.

Power AO	Increase is required	Decrease is required
Increase is required. ($AO < AO_{lower}$)	I	III
AO is in target AO band.	V	VI
Decrease is required. ($AO > AO_{upper}$)	II	IV

Table I. Six reactor states

Each state is defined according to the required actions from the viewpoint of power and the AO respectively. For example, when a power increase is required and an AO decrease is required, the core is in the state numbered II and other states are defined in the same manner. The developed operation strategy for the power maneuvering is shown in table II. It is for the motion of each rod such as AVSCR1, AVSCR2, and regulating rods and there are rules for total 12 conditions according as which the time stage is and which state the reactor core is in.

State	At transient interval	At recovering interval
I	**If steps of AVSCR2 < half of core** Move AVSCR1 to the lower direction and stop AVSCR2. Stop regulating rods.	**If steps of AVSCR2 < half of core** Move AVSCR1 to the lower direction and stop AVSCR2. Stop regulating rods.
	Otherwise Move AVSCR1 to the lower direction and move AVSCR2 to the upper direction. Stop regulating rods.	**Otherwise** Move AVSCR1 to the lower direction and move AVSCR2 to the upper direction. Stop regulating rods.
II	**If steps of AVSCR2 < half of core** Move AVSCR1 to the upper direction and move AVSCR2 to the upper direction. Stop regulating rods.	**If steps of AVSCR2 < half of core** Move AVSCR1 to the upper direction and move AVSCR2 to the upper direction. Stop regulating rods.

	Otherwise Move AVSCR1 to the upper direction and stop AVSCR2. Stop regulating rods.	**Otherwise** Move AVSCR1 to the upper direction and stop AVSCR2. Stop regulating rods.
III	**If steps of AVSCR2 < half of core** Stop AVSCR1 and move AVSCR2 to the lower direction. Stop regulating rods.	**If steps of AVSCR2 < half of core** Stop AVSCR1 and move AVSCR2 to the lower direction. Stop regulating rods.
	Otherwise Stop AVSCR1 and move AVSCR2 to the upper direction. Move regulating rods to the lower direction.	**Otherwise** Move AVSCR1 to the lower direction and move AVSCR2 to the upper direction. Move regulating rods to the lower direction.
IV	**If steps of AVSCR2 < half of core** Stop AVSCR1 and move AVSCR2 to the upper direction. Move regulating rods to the lower direction.	**If steps of AVSCR2 < half of core** Stop AVSCR1 and move AVSCR2 to the upper direction. Move regulating rods to the lower direction.
	Otherwise Stop AVSCR1 and move AVSCR2 to the lower direction. Stop regulating rods.	**Otherwise** Stop AVSCR1 and move AVSCR2 to the lower direction. Stop regulating rods.
V	**If all regulating rods are fully withdrawn** Stop AVSCR1 and move AVSCR2 to the upper direction. Stop regulating rods.	**If all regulating rods are fully withdrawn** Move AVSCR1 to the initial position and move AVSCR2 to the upper direction. Stop regulating rods.
	Otherwise Stop both AVSCR1 and AVSCR2. Move regulating rods to the upper direction.	**Otherwise** Move both AVSCR1 and AVSCR2 to the initial position. Move regulating rods to the upper direction.
VI	**If all regulating rods are fully inserted** Stop AVSCR1 and move AVSCR2 to the lower direction. Stop regulating rods.	**If all regulating rods are fully inserted** Move AVSCR1 to the initial position and move AVSCR2 to the lower direction. Stop regulating rods.
	Otherwise Stop both AVSCR1 and AVSCR2. Move regulating rods to the lower direction.	**Otherwise** Move both AVSCR1 and AVSCR2 to the initial position. Move regulating rods to the lower direction.

Table II. Operation strategy with AVSCRs for the power maneuvering

4. Application Results

Applications of the developed AVSCRs to the power maneuvering are performed. A typical 100-50-100%, 2-6-2-14h pattern of daily load-follow power maneuvering is adopted based on the demand pattern in Korea. The power varies from 100 to 50% in 2h, holds at

50% for 6h, then rise to 100% in 2h. The target plant for application is APR-1400 6^{th} cycle and the applications are performed under all burn-up states of the reactor core such as begin of cycle (BOC), middle of cycle (MOC), and end of cycle (EOC). And five-day load follow power maneuvering is considered.

In Fig. 8(a), the application results at BOC are represented. The upper part of the left figure shows the variation of the AO value. As shown in this figure, the AO is regulated well within the target AO boundaries. The lower part of this figure indicates reactor power and the reactor power follows the target well as shown in this figure. The upper graphs of the right figure show the motions of control rods. The black line represents the AVSCR1 and the red one indicates the AVSCR2 and others shows the motions of regulating rods. The lower part of this figure shows the boron concentration according to time. As shown, the boron concentration does not vary during the power maneuvering. And it means that no reactivity compensation by boron is used. The application results at MOC are shown in Fig. 8(b). The results can be analyzed in the same manner. As shown in this figure, the AO is regulated very well like the result at BOC. Also the power follows the target well too. It goes without saying that there is no reactivity compensation by boron. Finally, Fig. 8(c) represents the results at EOC. Like other burn-up states, the AO and reactor power are controlled well by the AVSCRs at EOC also. From these results, it can be known that the power maneuvering with only control rods is possible simultaneously regulating the AO within the target band, due to use of AVSCRs.

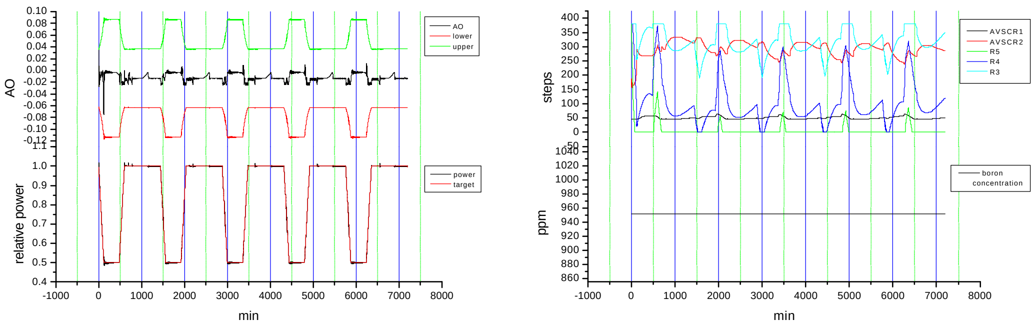


Fig. 8(a) Application results at BOC

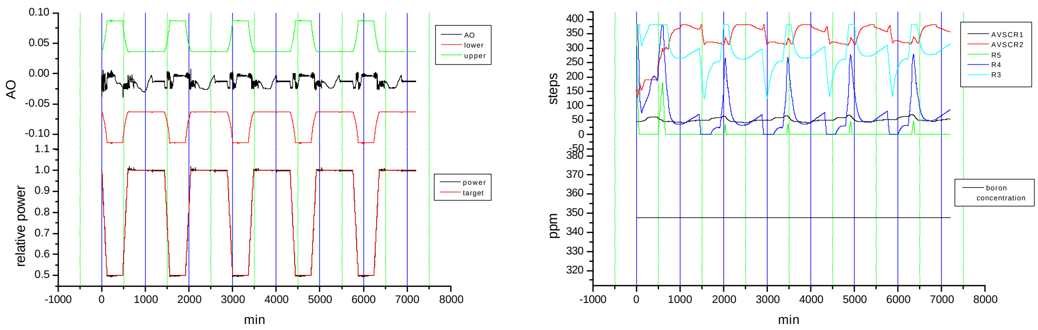


Fig. 8(b) Application results at MOC

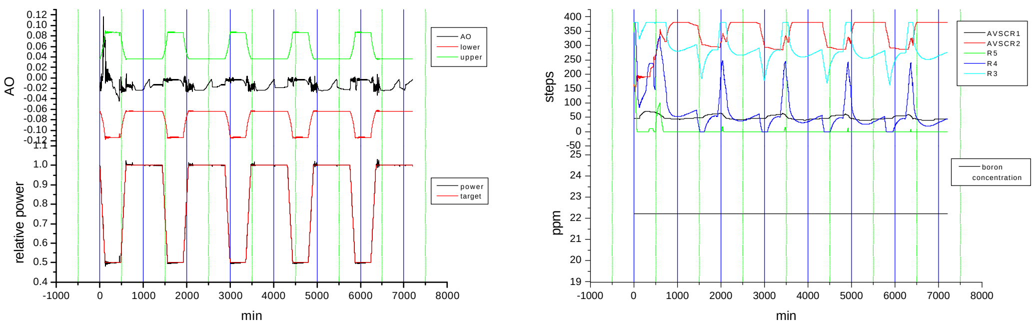


Fig. 8(c) Application results at EOC

5. Summary and Conclusions

In this work, AVSCRs are developed to cope with difficulties related to the variation of axial power distribution during the power maneuvering and to accomplish the power maneuvering with only control rods and without the reactivity compensation by boron concentration change. Control rods are classified into two types. The first type is 'multi-purpose control rod', and the other type is 'regulating control rod'. Two multi-purpose control rod banks (AVSCR1, AVSCR2) are newly developed and conventional-axially uniform strength-control rods are adopted as regulating control rod banks to minimize design change of PWRs. The multi-purpose control rods are used for dual purpose: The one is controlling the AO and the other is producing the required reactivity to compensate xenon build up, instead of a boron concentration change. The regulating control rods perform the same role as existing control rods. Between two multi-purpose control rods, the first one is named ‘AVSCR1’ and the main purpose of the AVSCR1 is mitigating an AO distortion to the negative direction caused by the motion of the other control rods. And it also causes the required reactivity compensation for xenon build up. The other one is named ‘AVSCR2’ and the main task of the AVSCR2 is controlling the AO to the positive and negative direction to keep the AO within the target AO band. And it should cause the required reactivity change to maintain a target reactor power instead of boron concentration change in such a case that the regulating rods are not available because of their reaching insertion or withdrawal limit.

The newly suggested AVSCRs are developed as three-sectioned control rods and the worth shapes of these rods are optimized to obtain appropriate moving characteristics that are related to the variation of axial offset according to their motion. The moving characteristics are determined by two indexes in this work and through optimization, both two indexes have got appropriate values. Then the operation strategy for the power maneuvering is developed considering the moving characteristics of AVSCRs. This strategy consists of simple logics and no use of reactivity compensation by boron is considered. Finally, some applications of AVSCRs to the power maneuvering are performed with a typical 100-50-100%, 2-6-2-14h pattern of daily load-follow for all burn-up state of core. From the application results, it is shown that the use of AVSCRs make it possible to regulate AO within the target band during the power maneuvering with only control rods and consequently the power maneuvering without reactivity compensation by boron concentration change is accomplished, and also the AVSCRs can cover the whole burn-up states of reactor core such as BOC, MOC, and EOC

Through this work, the performance of the AVSCRs is validated and the power maneuvering without reactivity compensation by change of boron concentration is accomplished. And, for implementation to real plant, the safety analyses remain as future works considering several constraints such as regulation guides, shutdown margin, and etc.

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