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Application of RAST-K to Simulation of OPR1000 Daily Load Follow Operation

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1. Introduction

In Korea, the proportion of nuclear power generation is planned to increase to 29% by 2035. New large nuclear power plants such as OPR1000 and APR1400 are under construction to this end. But the impact of power grid breakaway due to a nuclear power plant accident will be a bigger issue. Thus a development of load follow operation is needed for the safety of power system and nuclear power plants. In this paper, two-step method has been chosen. Especially, a load follow module and a control logic (mode-K) are implemented in a nodal code, RAST-K.

2. Methods and Results

In this section some of the process and methods used for the load follow simulation module and logic are described.

2.1 XS Generation and Design Equilibrium Core

The first step is producing two-group constants of each PLUS7 type fuel assembly using lattice code KARMA was developed by KAERI for the use in the second step. These two-group constants are converted to RAST-K table-set form by KATORA code.

Using these Plus7 type fuel assembly model, design the equilibrium core model OPR1000 which is the most-operated model in Korea by multi-cycle depletion calculation.

Same works done by HELIOS/MASTER code. The difference of length of EOC is about 0.5 MWD/MTU.

2.2 Daily Load Follow Calculation Strategy

The simulation of daily load follow operation has been performed in accordance with the time scenario 3-6-3-12(hour) and the power change to 100-50-100(%). The reactor power is controlled with regulating bank R5 and R4, part strength bank and soluble boron. Since it takes some time to work of boron concentration, boron concentrations step are predetermined for each time step [1]. With this boron scenario, certain combination of each positions of R5, R4 and part strength bank is determined to maintain the critical state. After that, the design limits such as power dependent insertion limit (PDIL), inlet temperature (Tin), power peaking factor (Fq), axial offset (AO) are checked.

2.3 Mode K

2.3.1 Definition of Mode K

Mode K is CEA control logic during load follow operation [2]. RRS generate CEA driving demand signal and CEDMCS drive selected CEAs by determined direction and speed.

Table I: Definition of Mode K

Purpose	1. [Core Power Control]: Maintain TM_{avg} (average moderator temp.) to be in reference band. 2. [Power Distribution Control]: Maintain *ASI* (Axial Shape Index) to be in reference band.
Tool	1. CEA (PS, R5, R4) 2. Boron Concentration (if CEA can't be drove)
Composition	1. Mode K RRS 1.1 Input: ΔTM_{avg} ($\equiv TM_{avg} - TM_{avg,ref}$), ΔASI ($\equiv ASI - ASI_{target}$) 1.2 Output: CEA driving demand signal (driving CEA, direction, speed) 2. CEDMCS 2.1 Input: CEA driving demand signal 2.2 Output: CEA driving

2.3.2 Set $TM_{avg,ref}$ and ASI_{target}

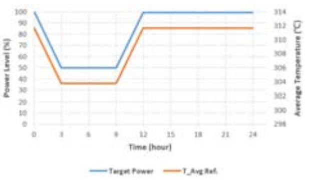


Fig. 1. TMavg,ref according to core power.

Since TM_{avg} has a nearly linear relationship with core power, $TM_{avg,ref}$ follow core power scenario.

2.3.3 Temperature-ASI control plane

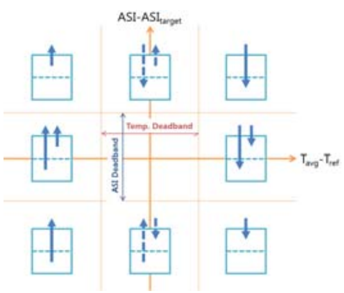


Fig. 2. Temperature-ASI control plane

Fig. 2 shows the change trend of TM_{avg} and *ASI* according to CEA driving. Dot line means axial half line of core. Short arrow means CEA in the upper core region and long arrow means CEA in bottom core region. Center square area (dead band) is reference band region. The other 8 area shows that how should CEA be drove in each case. This plane is basic principle of Mode K RRS logic.

2.3.4 Mode K RRS

Mode K RRS is same with existing RRS except one thing. Although ΔTM_{avg} is in the reference band, if ΔASI is in outside of reference band, CEA should be drove to recover *ASI*. Thus stage flag need to be input of determine (direction, speed) module.

2.3.5 Decision logic of CEA direction and speed

Driving direction and speed are determined by ΔTM_{avg}'s magnitude and sign. The different thing with existing RRS is that although ΔTM_{avg} is small, if ΔASI is big, CEA driving demand signal is generated.

2.3.6 Selection logic of CEA to drive.

'Stage' is indicator how big is ΔASI in the Mode K [3]. It is classified ORS (Overlap Restoring Stage), FOS (Fixed Overlap Stage) + and FOS-, ARS (ASI Restoring Stage) + and ARS-. According to ΔASI, only one stage flag turned 'on' and the others turned 'off'.

Table II: Control priority of each stage flag

Stage Flag	Control Priority
ARS+/-	TM_{avg} > *ASI* > prevent overlap worseness
FOS+/-	TM_{avg} > prevent overlap worseness > *ASI*
ORS	TM_{avg} > overlap recover > *ASI*

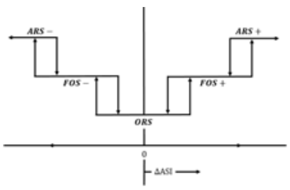


Fig. 3. Stage flag change set points

Selection logic of CEA to drive can be established using temp.-ASI plane and stage flag's control priority. Based on these two things, design selection logic for each 12-detail stage flag as shown in the Table III.

'ARSpTi' means that ARSp → ARS+ stage, T → due to large ΔTM_{avg} and i → insertion. 'Axial Shape' shows axial power shape.

'Direction (ΔASI)' shows CEA driving direction for *ASI* control in the top and bottom core region. 'Direction (ΔTM_{avg})' shows CEA driving direction for TM_{avg} control in the core region. Since always TM_{avg} control priority is higher than *ASI* control priority, actual CEA driving direction is follow 'Direction (ΔTM_{avg})'. 'ASI Effect' shows *ASI* effect after CEA driving with that direction.

Amount of ASI change is larger when driving CEA which in near the core top or bottom region. And there is order of insertion/withdrawal. Insertion order is PS, R5, R4 and withdrawal order is reverse. It means R5 can't insert deeper than PS and PS can't withdraw higher than R5.

'Optimal Drive' means that if 'Precede' case, preceding CEA is prior to following CEA in the selection. It is based on upper explanation about amount of ASI change.

'Drive Priority' means CEA selection priority based on 'ASI Effect' and 'Optimal Drive'. Dot in the upper region means that if there is no CEA to drive in bottom core region, CEA driving is impossible. So only CEA in the bottom core region can be selected. Dot in the bottom region means opposite.

'Multi Drive' means possibility of multiple CEA driving. It can occur when that multiple CEA driving good for *ASI* recovering.

Table III: Selection logic of CEA to drive for 12-detail stage flag

Detail Stage Flag	Axial Shape	Direction (ΔASI)	Direction (ΔTM_{avg})	ASI Effect	Optimal Drive	Drive Priority	Multi Drive
① ARSpTi		↑	↧	Worse	Precede	Precede	X
		↓		Recover	Precede		O
② ARSpAi		↑	↧	Worse	Precede	·	·
		↓		Recover	Precede	Precede	O
③ ARSpTw		↑	↥	Recover	Follow	Follow	O
		↓		Worse	Follow		X
④ ARSpAw		↑	↥	Recover	Follow	Follow	O
		↓		Worse	Follow	·	·
⑤ FOSpi		↑	↧	Worse	Precede	Precede	O
		↓		Recover	Precede		
⑥ FOSpw		↑	↥	Recover	Follow	Follow	O
		↓		Worse	Follow		
⑦ ORSi	·	·	↧	·	·	Overlap Recover	O
⑧ ORSw	·	·	↥	·	·	Overlap Recover	O
⑨ FOSmi		↓	↧	Recover	Follow	Follow	O
		↑		Worse	Follow		
⑩ FOSmw		↓	↥	Worse	Precede	Precede	O
		↑		Recover	Precede		
⑪ ARSmTi		↓	↧	Recover	Follow	Follow	O
		↑		Worse	Follow		X
⑫ ARSmAi		↓	↧	Recover	Follow	Follow	O
		↑		Worse	Follow	·	·
⑬ ARSmTw		↓	↥	Worse	Precede	Precede	X
		↑		Recover	Precede		O
⑭ ARSmAw		↓	↥	Worse	Precede	·	·
		↑		Recover	Precede	Precede	O

2.3.7 Design detail stage flag algorithm.

Based on Table III, design 12-detail stage flag algorithm.

In the Mode K overlap between CEA can be changed. Reference overlap between PS and R5 is 45 inch and reference overlap between R5 and R4 is 90 inch. Also R5 and R4 can't insert deeper than PDIL5 and PDIL4.

2.4 Daily Load Follow Calculation Algorithm

In the calculation, divide 24 hours by the 5 minute intervals, i.e. assume that core state of each interval is quasi equilibrium state and solve steady state problem. During the calculation, core power has to be changed like Fig.1 and using Mode K algorithm, maintain ΔTM_{avg} and ΔASI to be in reference band.

2.4.1 Algorithm I

Algorithm I is same with conventional method had done by other people. For each time interval, magnitude of time interval, core power, boron concentration, inlet moderator temperature and CEA positions are given. Based on these input, calculate eigenvalue problem and deliver *k-eff* and *ASI* calculated to Mode K RRS. At this time, instead of $TM_{avg,ref}$, reference *k-eff* (= 1) is used to find steady state solution. Mode K RRS generate CEA driving demand signal until Δ*k-eff* and Δ*ASI* are in reference band.

2.4.2 Algorithm II

Algorithm I fixed core power as an input. But in actual plant, control core power based on TM_{avg}. Thus core power should be output variable not input. Also, core power must be controlled based on TM_{avg} in transient calculation for load follow. Because in transient calculation, core power does not input variable. So Mode K RRS should generate CEA driving demand signal based on present TM_{avg} value.

For example, let assume that present core power is 80% and TM_{avg} is 308 K, but target power is 82% in present time interval as shown Fig 1. Then CEA withdrawal demand signal must be generated to rise core power. But in actual situation, we don't know present core power, we know inlet/outlet moderator temperature. Going back to the beginning, we don't know present core power is 80% or 84%. But we know core power has a nearly linear relationship with TM_{avg}. So we know approximately TM_{avg} value when core power is 82%. This value is one of the $TM_{avg,\ ref}$ in the Fig 1. So Mode K RRS can judge know whether insert or withdrawal CEA by comparing present TM_{avg} and $TM_{avg,\ ref}$. Since it assume quasi equilibrium state, power search iteration is needed like critical boron concentration search. It is shown in the Fig. 5.

But in the load follow calculation assuming quasi equilibrium state, this algorithm II will show similar calculation result with algorithm I. Magnitude of time interval, boron concentration and inlet moderator temperature are same in the two algorithm. Then the thing effect core reactivity are core power (strictly fuel/moderator temp.) and CEA position. And two algorithm solve quasi equilibrium state problem. Therefore total core reactivity is zero and it means if core power between two algorithms are similar, CEA position calculated are similar too. Difference comes from the error of linear relationship between core power and TM_{avg} (i.e. $TM_{avg,\ ref}$ error) and different history of core state like Xe-135 or burn-up distribution due to $TM_{avg,\ ref}$ error in the beginning of time interval.

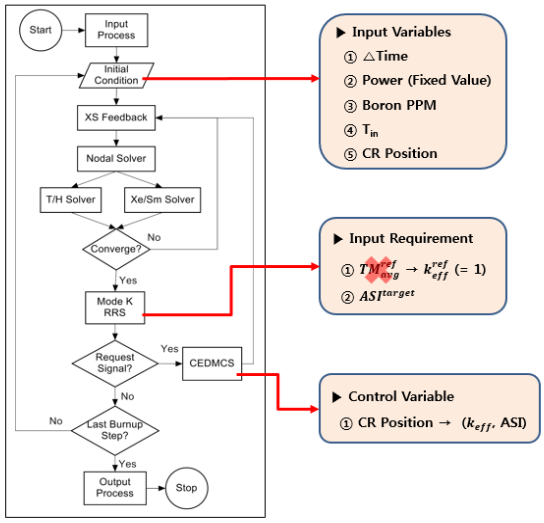


Fig. 4. Load follow calculation algorithm I

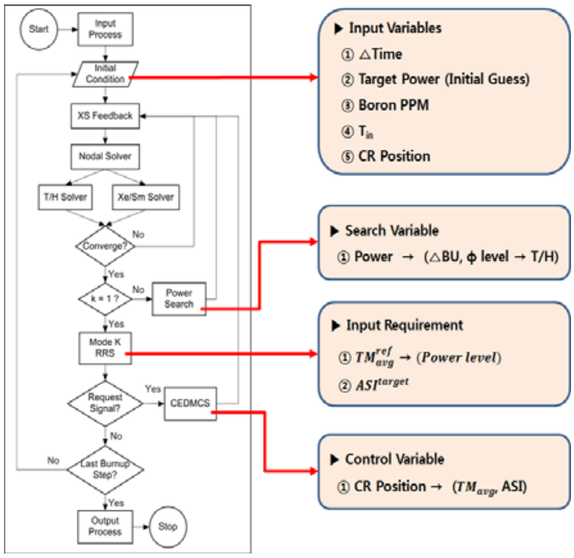
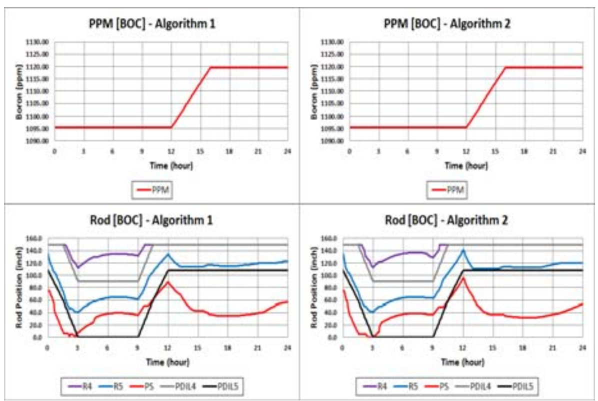


Fig. 5. Load follow calculation algorithm II

2.4.2 Calculation Result

Load follow calculation result is shown in the Fig. 6. Two algorithm results are similar and the design limits such as power dependent insertion limit (PDIL), inlet temperature (Tin), power peaking factor (Fq), axial offset (AO) are not exceed limit criterion.



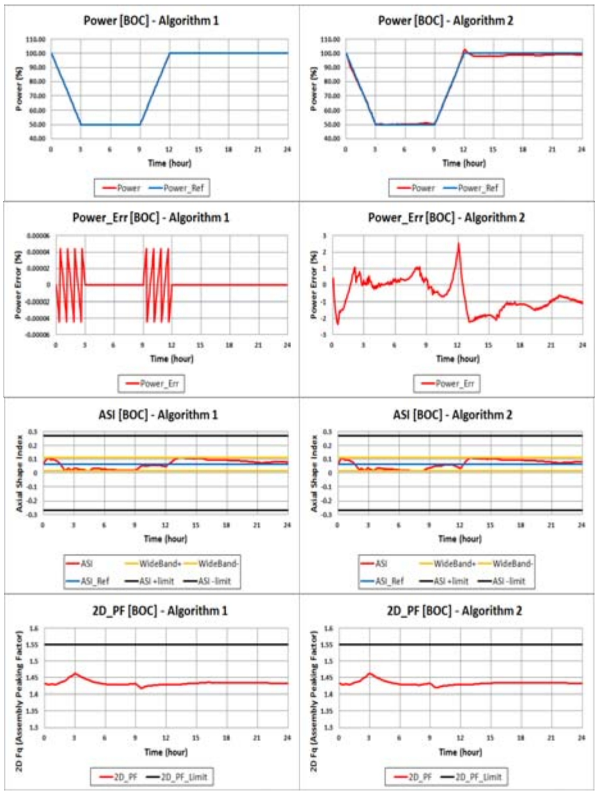


Fig. 6. Load follow calculation result of algorithm I and II

3. Conclusions

A computer code system for the simulation of load follow operation of OPR1000 has been developed using a nodal transient code RAST-K. An equilibrium reactor core has been designed using the code system and the mode-K logic and its updated version have been applied to the daily load follow operation simulation such that all the design limits are satisfied during the simulation.

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REFERENCES

[1] "Development of the KISPAC-1D Code for the Application to the Performance Analysis of the Korea Next Generation Reactor", KOPEC/NED/TR/99-008, Code Development Report, p. 4, 1999.
[2] J. H. Jang, S. Y. Oh, "The Mode K Technique for Enhanced Load Following Operation Capability in PWRs", KAERI/TR-1218/99, p. 8-46, 1999.
[3] YongHee Kim, KuneHo Cha, "Reactor Control Method for Load Follow Operation of KNGR", KEPRI, 1999.