Evaluation of Extended Daily Load Following Operation Capability for APR+ with Model Predictive Controller

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1. Introduction

A Model Predictive Control (MPC) method [1] was applied to design an automatically load-following operation controller for controlling the reactor power and Axial Shape Index (ASI) control using regulating and part-strength Control Element Assembly (CEA) for an Advanced Nuclear Power Reactor Plus (APR+).

The reactor power follows a daily load cycle of 100-50-100%, 14-2-6-2 hour pattern which is typical daily load following operation.

The range of extended daily load following operation was decided to 100-20-100% power change conservatively more than the requirement of UK EPR that load follow can be activated between 25% and 100%.

In this paper, the extended daily load following operation followed 100-20-100%, 14-2-6-2 hour pattern which was evaluated for the APR+ with the model predictive controller with the adjustment of boron concentration change.

2. Methods and Results

2.1 Requirements

According to the European Utility Requirements (EUR) [2] and Advanced Light Water Reactor Utility Requirements Document (URD) of Electric Power Research Institute (EPRI) [3], the nuclear power plant must be capable of a minimum daily load following operation between 50% and 100% power with a rate of change of electric output of 3~5% power/minute during 90% of each fuel cycle throughout the entire design life of the plant with generation Ⅲ/Ⅲ+ reactors. Moreover, according to the United Kingdom European Pressurized Reactor (UK-EPR), the requirement of load follow is that can be activated between 25% and 100% [4].

a) EPRI URD requires as follows:

The ALWR plant shall be designed for a 24-hour load cycle with the following 100-50-100%, (10~18)-2-(2~10)-2hour.

b) EUR requires as follows:

The unit shall be capable of continuous operation between 50% and 100% of its rated power Pr during 90% of the whole fuel cycle.

c) UK-EPR requires as follows:

Load follow enables foreseeable developments in energy demand to be followed. It can be activated between 25% Pn and 100% Pn.

2.2 Definition for the load following operation

In case of pressurized water reactor, load following operation is controlled with adjustment of CEA position and boron concentration adequately.

The patterns of typical and extended load following operation for APR+ are as follows :

a) Typical : A 100-50-100% load cycle with power maintained initially at 100% power for 14 hours, followed by a power decrease from 100% to 50% in 2 hours, followed by 6 hours (typical value) at the reduced power level of 50% power. The load cycle is completed by increasing power to full rated power in 2 hours, and

b) Extended : A 100-20-100% load cycle with power maintained initially at 100% power for 12 hours, followed by a power decrease from 100% to 20% in 2 hours, followed by 6 hours at the reduced power level of 20% power. The load cycle is completed by increasing power to full rated power in 2 hours.

In the UK EPR, the load following operation can be activated between 25% and 100% power. The extended load following operation was decided to evaluate the capability of load follow between 20% and 100% power more conservative load follow range than the requirement of the UK EPR.

2.3 Model Predictive Control (MPC)

The MPC calculates an optimization problem for next time steps at present time and then to calculate the best control input as the present control input. At the next time step, new values of the calculated output can be obtained, the control horizon is shifted forward by one step, and the same calculations are conducted repeatedly. The objective of taking new measurements at each time step is to compensate for uncalculated disturbances and model inaccuracy, both of which cause the calculated output to be different from the one predicted by the model. At every time step, the MPC requires the solution of an optimization problem to calculate optimal control inputs over the fixed number of future time instants, known as the time horizon [5] refer to the Fig. 1.

The objective of MPC is to minimize the difference between reactor power and ASI and the desired output and the frequent variation of the CEA position. The power level and the ASI are controlled by regulating CEA groups and part-strength CEA together with the boron concentration.

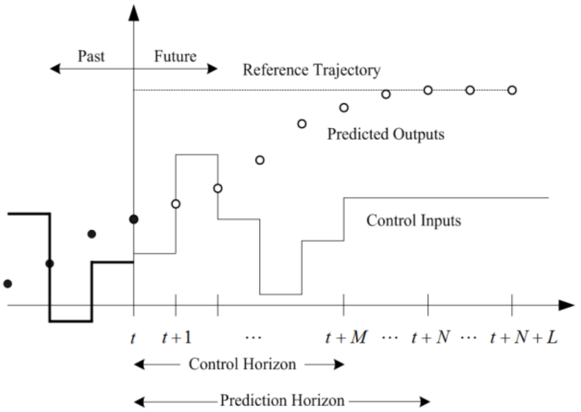

Fig. 1. The concept of Model Predictive Control.

Since KISPAC-1D code generates one-dimensional power distribution as well as T_{avg}, KISPAC-1D code was used as a reactor system for simulation of a daily load-following operation [6].

2.4 Calculation of boration/dilution capability

The volume of water in the Reactor Coolant System (RCS) is maintained by the Chemical Volume Control System (CVCS). Demineralized water from the Reactor Makeup Water Tank (RMWT) is used for dilution and the Boric Acid Storage Tank (BAST) is used for boration. Boron dilution capability is one of the limiting factors for load following operation. The following simple model is used for calculation of the RCS boron concentration change rate with respect to charging/letdown flowrate.

To calculate the change of boron concentration in RCS, the equation can be expressed as :

$$\frac{d(M \cdot C)}{dt} = C_{in} \cdot W - C \cdot W$$

where,

M = Total Mass of RCS,
C = Boron Concentration,
W = Charging/Letdown Flowrate, and
C_{in} = Charging Boron Concentration.

The analysis is performed with APR+ design data. The normal and maximum charging and letdown flowrate are 80 gpm and 140 gpm respectively. The value of C_{in} of 4,000 ppm is used for boration conservatively and 0 ppm for dilution. The dilution capability is very low as shown in the Fig. 2.

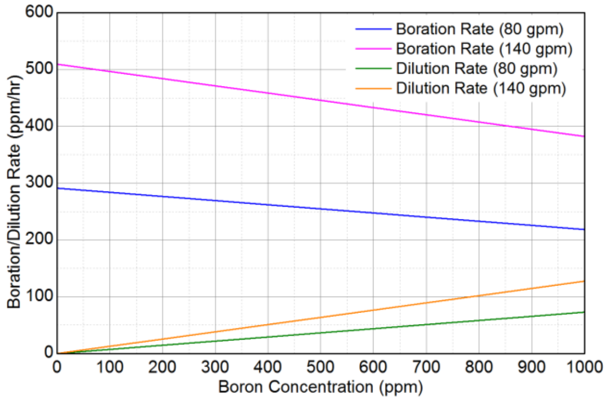

Fig. 2. The maximum boron concentration change rate.

2.5 Evaluation of extended load following operation range

The extended load following, 100-20-100%, 14-2-6-2 hour, capabilities of APR+ is evaluated with the MPC and boron concentration adjustment.

The required boron concentration change rate is not highly dependent on burnup and maximum dilution rate of 40 ppm/hr is needed for extended load following operation as shown in Fig. 3. Dilution rate of 40 ppm/hr can be met with more than 300 ppm in RCS boron concentration from the Fig. 2. This value corresponds to 80% of EOC, approximately 14,000 MWD/MTU, in APR+.

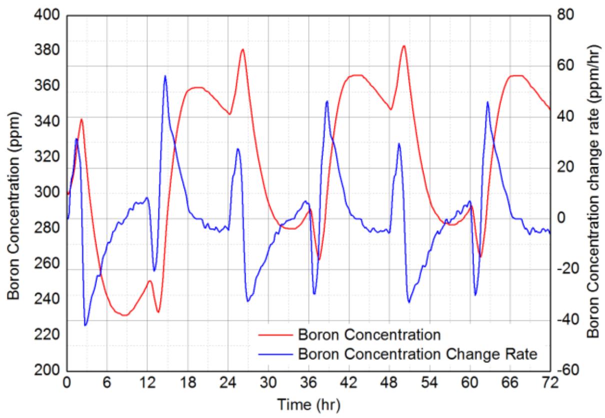

Fig. 3. Results of boration/dilution capability at 80% of EOC.

CEA Position was traveled to control reactor power and ASI together with the boron concentration as shown in the Fig. 3 and Fig. 4 during load following operation.

Empirically, ASI can be controlled using by CEA if ASI is within Equilibrium Shape Index (ESI) ±5%. Even though ASI control was more challenging in the extended load following operation, ASI was controlled within approximately ±5% with the MPC as shown in the Fig. 5 at 80% EOC.

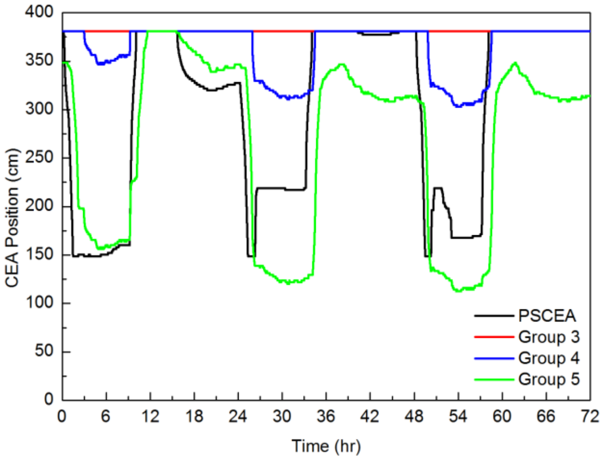

Fig. 4. Results of CEA Position at 80% of EOC.

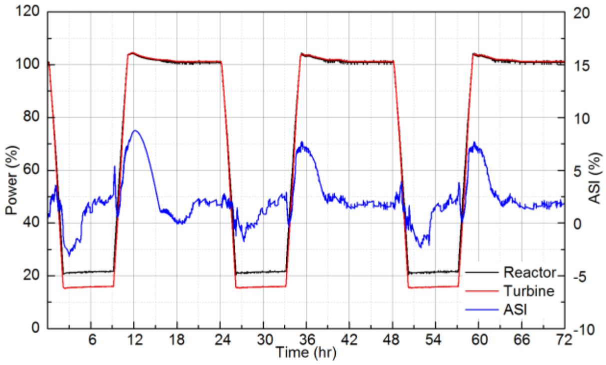

Fig. 5. Results of 100-20-100%, 14-2-6-2 hour case at 80% of EOC.

3. Conclusions

In this paper, the capability of extended daily load following operation, 100-20-100%, 14-2-6-2 hour pattern, was evaluated for APR+ using the MPC with boron concentration change. Dilution rate is one of the limiting factors at EOC because the dilution rate is decreasing as the boron concentration is decreasing. Dilution rate of 40 ppm/hr is required for extended load following operating and this valve approximately corresponds to 80% EOC. The reactor power and ASI can be controlled using the MPC within limit until 80% EOC. In conclusion, the extended load following operation as 100-20-100%, 14-2-6-2 hour pattern is possible to operate to 80% of EOC.

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