Transactions of the Korean Nuclear Society Autumn Meeting
Gyeongju, Korea, October 26-27, 2017

Development of Model Predictive Control (MPC) Validation Tool for APR+

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1. Introduction

One of the challenging design goals of advanced power reactor plus (APR+) is to have daily load following capability and frequency control design features. It is well-known that highly sophisticated control algorithms are required to accomplish successful load following operations because of non-linear characteristics of core dynamics. By this reason, a new type of control algorithms has been developed for the automatic control of thermal power and axial shape index (ASI) with state-of-the-art technology known as model predictive control (MPC) method [1,2]. Because it is a newly introduced system for the nuclear power plant, its performances against comprehensive test cases have to be analyzed. For this purpose, a validation tool for the MPC was developed with the window based nuclear plant analyzer (Win-NPA). Also a test matrix was derived to cover all postulated operational modes that the MPC is expected to experience. In this paper, the features of the dynamic performance validation tool, test method and test results are presented.

2. Design Characteristics of MPC

2.1 System Configuration

The MPC of APR+ provides automatic controls for part strength control element assembly (PSCEA) and control group CEAs. Fig.1 shows the signal interfaces between the power regulation distribution system (PRDS), the reactor regulating system (RRS) and the digital rod control system (DRCS) of APR+. The MPC is included in the PRDS and requires additional input signals from the information processing system (IPS) including fuel burn-up, position signals of control group and part strength CEAs, etc.

2.2 Characteristics of MPC Algorithm

The digital control systems in the nuclear plants are based on the programmable logic controller (PLC) or the distributed control system (DCS) which use conventional control algorithms such as dynamic filters, PID functions, flip-flop, binary logic gates, and so on. The control algorithms are typically implemented by connecting those functions with dedicated engineering tools. However, the MPC consist of sophisticated mathematical algorithms developed based on the C++ language which cannot be implemented by the standard engineering methodology.

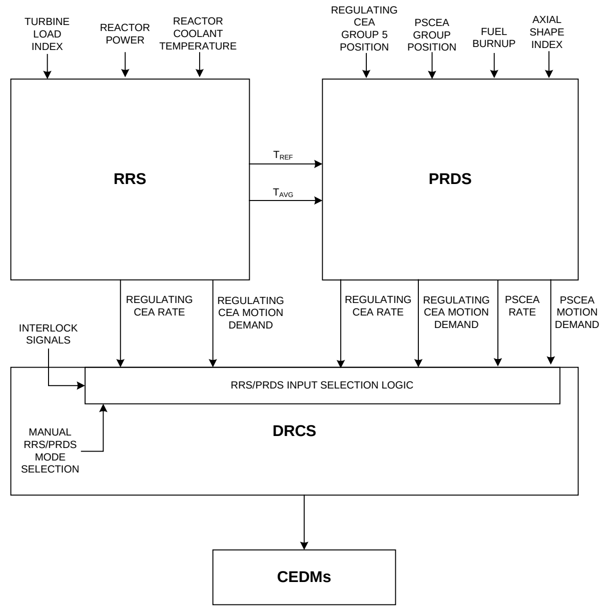

Fig. 1. The configuration of MPC in APR+

2.3 Feasibility of MPC Implementation

According to the technical survey of commercial controllers, some of the state-of-the-art controllers are found to provide development tools to realize customized user functions by using C++ language. If this kind of controller is selected for the MPC implementation, the engineering activities of the MPC can be performed based on the same C++ source code which enables to maintain the consistency from the functional design to the final validation test phases. Therefore it is concluded that the control algorithm of the MPC can be migrated from the system development environment of engineering simulator to the commercial controller without major modification.

3. Development of Validation Tool

3.1 Engineering Simulator

Fig. 2 shows the Win-NPA which has been widely used for best-estimate performance analyses [3,4]. The Win-NPA is an interactive, high fidelity, real-time engineering simulator for nuclear power plants. The Win-NPA consists of the process model simulating plant behavior, the graphical user interface (GUI), and the simulation executive for an enhanced user interface. It can cover a wide range of nuclear power plant operations during normal, abnormal, as well as accident conditions.

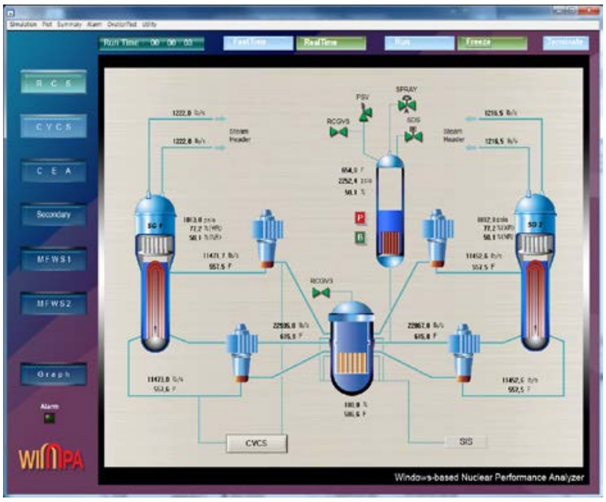

Fig. 2. Main display page of Win-NPA [3]

3.2 Integration of MPC and Win-NPA

The developed source code of the MPC was integrated into the Win-NPA by connecting the I/O signals listed in Table I. Since, the Win-NPA is written in Fortran and the MPC is written in C++ language, the signal interfaces were realized through Fortran/C++ mixed language development.

Table I: Interface Signals of MPC

Signal Type	Systems	Signals
Inputs	RRS	RCS average temperature
		RCS reference temperature
	IPS	COLSS ASI
		Core Burn-up
		CEA Position of Group 5
		CEA Position of PSCEA
		Pos. Deviation of Group 5
		Pos. Deviation of PSCEA
Outputs	DRCS	Insertion of Regulating CEAs
		Withdrawal of Regulating CEAs
		Low rate insertion of Reg. CEAs
		Low rate withdrawal of Reg. CEAs
		Insertion of PSCEAs
		Withdrawal of PSCEAs
		Low rate insertion of PSCEAs
		Low rate withdrawal of PSCEAs

3.3 Execution Intervals and Backup System

The execution time scheduling of the RRS, which is the legacy control system for the MPC, is once per 100msec. It is not necessary to execute the MPC algorithm within such a small period of time. The optimum time step to execute MPC was decided to be once per every 10 sec. If any detection of input or functional failure, the DRCS will use the control outputs from the RRS instead of the MPC for CEA controls.

4. Tests and Results

4.1 Test Matrix

To perform a comprehensive dynamic test for the newly adopted MPC, a test matrix was prepared as shown on Table II. Because the daily load following operation highly depends on the core burn-up conditions, test cases were prepared for the beginning, middle and end of cycle (BOC, MOC, and EOC) conditions with the daily load following profiles as in the turbine power. Other test cases with various initial positions of CEAs and boric acid control logics were added to verify the robustness of MPC functions.

The test cases other than daily load following operation were added to verify whether the performance of the MPC for these cases is acceptable.

Table II: Validation Test Matrix

Operational modes	Core burn-up	Changes of test conditions	Acceptance criteria
Daily load following	BOC MOC EOC	- Reference case - Various initial positions of CEAs - Various boric acid control logics	Adequate T-avg and ASI control
Frequency Control	BOC EOC	- Reference case - Various initial positions of CEAs	Stable CEA control
±5%/min ramp	BOC EOC	- Reference case	Adequate control of CEAs
±10% step	BOC EOC	- Reference case	
Loss of a feed pump	BOC	- Reference case	
Loss of load	BOC	- Reference case	
Opening of turbine bypass valve	BOC	- Reference case	

4.2 Test Results

Fig. 3 shows one of test results for the daily load following case (2-8-2 hours at BOC). The result shows that the deviation between T-avg and T-ref is within 2 ^{o}F and ASI is maintained within $\pm$2%.

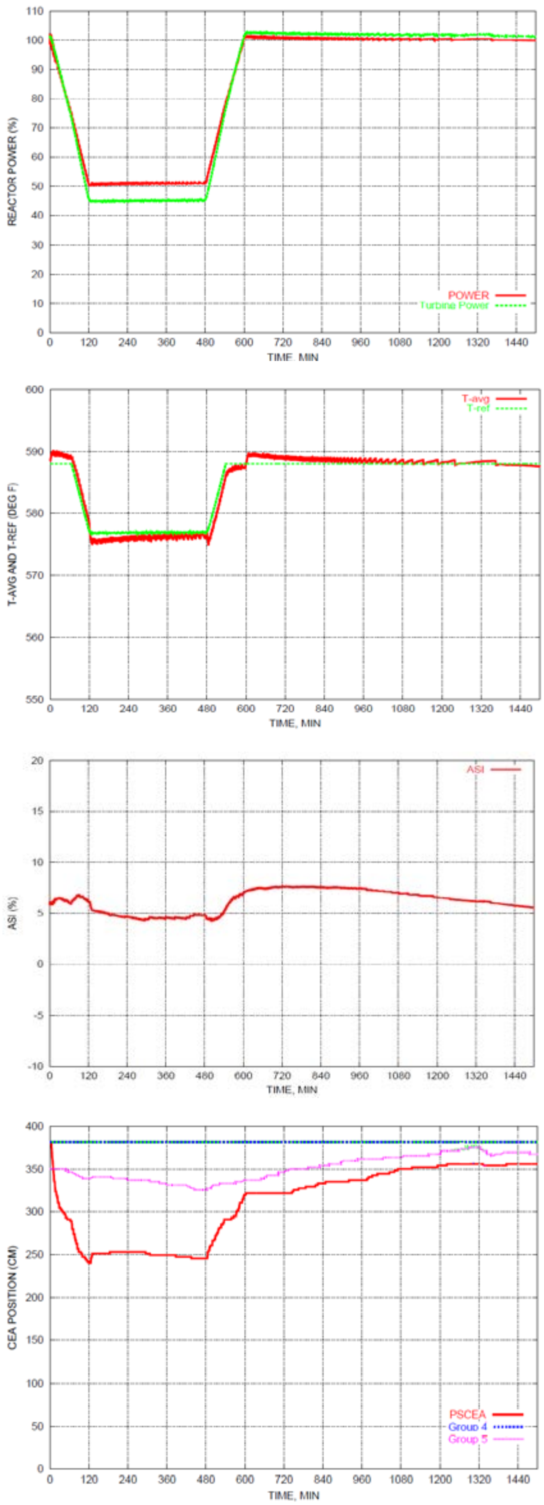

Fig. 3. Daily load following (2-8-2 hours) test result of MPC at BOC

When the temperature deviation between T-avg and T-ref exists, the PSCEA shows more dynamical movement as compared to the regulating CEA because the PSCEA controls ASI as well as reactor power. The control of CEAs is stable and the MPC control function is acceptable for this test case.

The test results of all other test cases for daily load following operations are similar and meet acceptance criteria with minor differences. Also, it was evaluated that the dependency on the fuel burn-up is not too high to affect the stability of MPC control functions.

The results for the all test cases per the test matrix of Table II have been evaluated to be acceptable and, therefore, the newly designed MPC is considered to be applicable to the APR+ plant.

5. Conclusions

The validation tool of the MPC for APR+ has been developed by using Win-NPA and applied to the well-defined test cases. The performance of the MPC was evaluated to be acceptable for all test cases and, therefore, it was concluded that the newly introduced load following controller MPC can be applied to the APR+ plant.

In addition to that, by the development of the validation tool for the MPC, a consistent working environment become available from the design stage of control logic to the last stage of equipment validation test, because the same set of C++ code can be applied throughout the whole engineering processes. It is expected that if any design change is required such as optimization of control algorithm or functional changes in the future, it can be easily performed with high efficiency.

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