Improvements of Core Protection System and Plant Availability

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1. Introduction

The digital Core Protection Calculator System (CPCS) is used basically to trip the reactor in case of low DNBR or high LPD. This is important because if the heat yield by the reactor is not properly removed the Specified Acceptance Fuel Design Limits (SAFDL) are violated and the fuel can be damaged. However, is the reactor trip the only possible option to avoid the fuel damage?

The reference [1] suggest the use of rapid power reduction to provide margin to SAFDL enough to avoid a reactor trip. The reactor power cutback system is designed to give that fast power reduction. It is considered a partial reactor trip using preselected regulating groups of control rods [1]. Therefore, the use of RPCS can permit the NPP remains operational during most of the anticipated operational occurrences (AOO) that CPCS is designed for.

Korean nuclear industry is developing a new algorithm of core protection system named Reactor Core Protection System (RCOPS). This system improves the operational margin and the plant availability [2]. The increasing of operational margin is achieved by reduction of uncertainties in the program CETOP, which is used to calculate the transport coefficient conservation equations. The increasing of plant availability is achieved by the addition of pre-trip alarms and the actuation of reactor power cutback system for 12-finger CEA drop [5].

At beginning of the digital core protection system development some issues were considered for the initial licensing process:

- The quality of the software development process.
- Software validation and verification.
- Hardware and software burn-in testing.
- Digital computer hardware environment qualification. [4]

There are two main goals for this work, (01) improved the issues considered above using the Matlab® Simulink, and (02) apply the values of DNBR and LPD as input in the reactor power cutback system to rapidly reduce the power and avoid unnecessary reactor trips.

2. Core Protection Calculator System on Matlab Simulink

Each of 24 Korean NPPs have different types of core protection systems [5]. The calculation of DNBR and LPD is more important for PWR reactors, which is the main type of reactors in Korea. The core protection systems used in Korean NPPs are presented in Table I [6][7][8][9].

TABLE I. Core Protection Systems in Korean Nuclear Power Plants

Type of Core Protection System	NPP models
Analogic OPΔT&OTΔT	WH-F and FRANCE CPI
Digital CPCS	OPR-1000
Digital Common-Q CPCS	OPR-1000 and APR1400
Regional Overpower Protection System (ROP)	CANDU-6

2.1. CPCS essentials

The digital Core Protection Calculator System (CPCS) is used in OPR-1000 and the Common Q CPCS is used in some OPR-1000 and in the APR1400 in Korea [5][6]. The CPCS system was first developed by C-E Combustion Company in the 1980's and since then it has been enhanced by the Korea Atomic Energy Research Institute (KAERI) and KEPCO E&C.

The CPCS consists of six interdependent modules that calculates the value of DNBR and LPD based on RCS temperatures and flow, CEA positions, and excore power detectors. The modules are Flow, Update, Power, Static, and Tripseq inside the CPS [10][11].

The Flow module calculates the mass flow rate using as input the reactor coolant pumps (RCP) speed, the reactor coolant system (RCS) pressure, RCS temperatures. The value of DNBR is updated by the number of RCPs running [11]. The CPCS flow module runs in cycles of 50 milliseconds [1].

The Static module is the most important module for minimum DNBR, hot channel quality, and thermal power calculation. It uses as input values from the modules Flow and Power, and from sensors adjusted by the Update module. The core is divided in 20 slices and in each one the equations for enthalpy transport coefficient are applied [11]. A hot channel assembly is modeled in four lumped channels that are used as reference model for minimum DNBR calculation [2]. This module runs in cycles of 2 seconds [1].

The UPDATE module runs in cycles of 100 milliseconds and uses values from the other modules as input. The module is responsible to update the values of DNBR and LPD based on the flow and power modules. The update is used to refresh the values of DNBR in cycles of 100 milliseconds instead of 2 seconds from static module [1] [11].

The Power module is responsible for core average axial power distribution computation. It uses as input the normalized core coolant mass flow and the normalized average cold leg specific volume from Flow module, and the excore neutron flux detectors adjusted in the Update module. The maximum peaking factor, the power normalization factor corrected by shape annealing, the CEA shadowing factor and the average of the hot pin distribution are outputs of Power module [11].

2.2. CPCS in Matlab Simulink

The CPCS modeled in Matlab Simulink using the functional requirements available in the reference [11] and the Shin Kori units 3 and 4 as references. The algorithm used to develop the model is described in [11] and all the plant design details were provided by KEPCO E&C using the CPCS developed for Shin Kori units 3 and 4.

The model is divided in 4 main modules as mentioned above. Each module was built on Matlab Simulink using the same equations and iterations. The main difference between the Matlab code and the KAERI test facility is running condition. Matlab can run a dynamic transient and the calculations executed during all the transient rather than a static input values as KAERI facility provides.

In order to validate the system, the Matlab modules were compared with the validation files from KAERI. However, the inputs and outputs from validation files are being applicable for a static running, what means that results can be different because of initial condition considered in the model. Therefore, the system was compared with the transient run in Barakah simulator and the maximum deviation in DNBR and LPD calculation were 12.657% and 6.716% respectively.

The figure 1 is showing the normal power reduction transient of DNBR and figure 2 is showing the transient of LPD in Matlab and Barakah simulator. The power was reduced from 100% to 75% by load demand reduction.

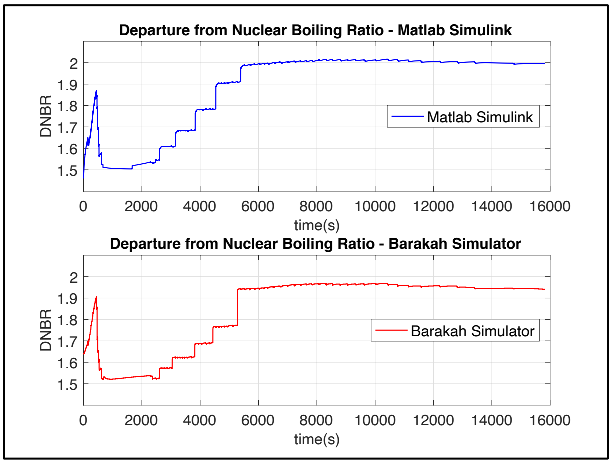

Fig. 1. DNBR comparative results.

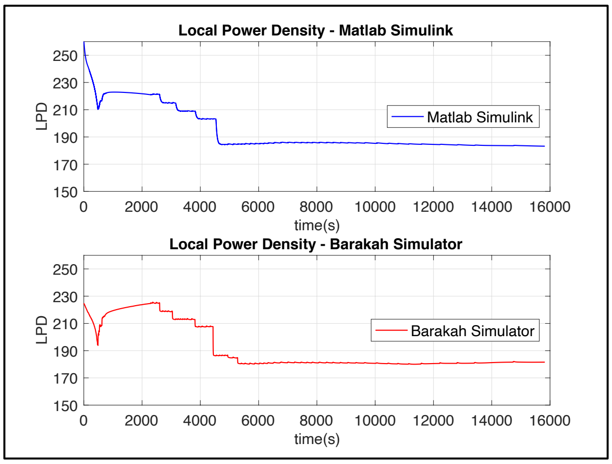

Fig. 2. LPD comparative results.

3. Reactor Power Cutback System on Matlab Simulink

The reactor power cutback system is a non-safety system designed to accommodate certain types of imbalances by providing a step reduction in reactor power [5]. The purpose of the system is to initiate a rapid reduction of NSSS power a rate greater than provided by reactor regulating system when large plant imbalances occur, such as large turbine load rejection, turbine trip or loss of two main feedwater pumps [3].

3.1. RPCS essentials

There are 04 inputs on RPCS, (01) loss of two out-of-three operating feedwater pumps, (02) steam bypass control system signal for large load rejection, (03) turbine runback, and (04) CEA bank selection. The CEA back selection is used to indicate which of the regulating groups has to drop by RPC event, regulating group 5 or regulating groups 4 and 5 or regulating groups 4, 5, and spare [3]. The RPCS has capability to drop up to three banks simultaneously.

The actuation of reactor power cutback system can reduce the power to between 30% and 75% of rated power. It operates dropping the CEA groups only when the power is greater than 75%. [3]

3.2. RPCS in Matlab Simulink

The RPCS is developed in Matlab Simulink. The system is a logical circuit that uses inputs of feedwater pumps, steam bypass control system and turbine runback.

This system was modified by adding inputs from CPCS. The values of DNBR, LPD, and their gradients were added to RPCS using the same approach of the current system. The figure 3 is showing the inputs and part of the logic of the current RPCS and the figure 4 is showing the modified RPCS with the inputs added.

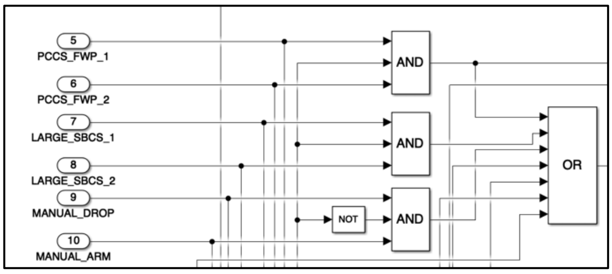

Fig. 3. Current RPCS inputs and partial logic circuit.

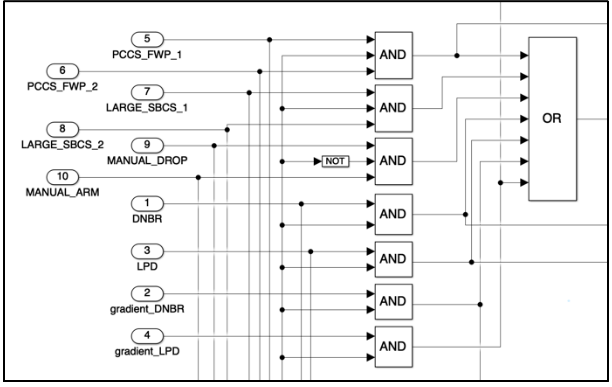

Fig. 4. Modified RPCS with DNBR and LPD inputs added.

4. Reactor Trips of the Core Protection Calculator System in Republic of Korea

The Korea Institute of Nuclear Safety publishes all events at Korean NPPs [12]. Using the data available on the website is possible to verify which events are directly or indirectly related to the core protection system.

Observing the data, the core protection system has actuated mainly because of reactor coolant pump trips, CEA signal positions and misalignment, human errors (addressable constants and operational mistakes), device and instrument failures, CEA dropping. [12]

Thus, the results and events analyzed showed that the core protection systems have done what they are designed to do. However, spurious signals and unnecessary reactor trips could be avoided. The average time NPPs took to get normal operation after the reactor trips was 10 hours and 41 minutes, with the maximum time of 23 hours and 50 minutes in the event Hanul-6-2018-05.

5. Results

The modified RPCS uses DNBR and LPD as input. For demonstrative analysis the DNBR setpoint limit is set 1.6 and DNBR absolute gradient setpoint is set to 0.3. Using a normal transient of power reduction on mode 1 from 100% to 75% power, the actuation of the system is showed in figure 5. The RPCS is active when the setpoints are reached. Therefore, instead of scram the reactor the power is drastically reduced by RPCS actuation. The same approach can be used for LPD.

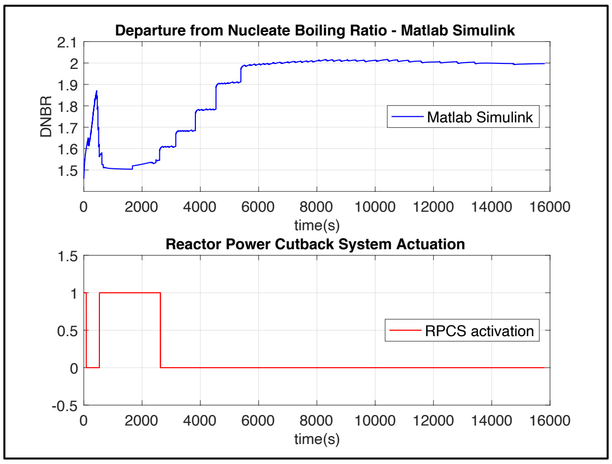

Fig. 5. RPCS actuation during a normal transient.

The RPCS system is actuated when the setpoint is reached. The figure 5 is showing the actuation of the RPCS when the value of DNBR is lower than 1.6. The best setpoint value can be investigated by using thermal hydraulics analysis and easily applied in the system.

6. Conclusion

The core protection calculator system is applied in the Matlab Simulink using the same algorithm from the functional design requirements of the current CPCS. The response of CPCS built in Matlab is dynamic, what means that a transient can be applied to the system. The validation of the modules was by comparison with the current system in KAERI facilities. All the validation files are considering single input and static calculation.

The modified RPCS is a logic circuit that has more inputs than the current system. Using a normal transient of power reduction in Barakah simulator was possible to implement the RPCS actuation by DNBR and LPD values from the CPCS, what can contribute to increase the plant availability by unnecessary reactor trips avoidance.

Acknowledgement

This work was supported by the 2020 Research fund of the KEPCO International Nuclear Graduate School (KINGS), Republic of Korea.

REFERENCES

[1] Peter L. Lung, Core Protection Calculator System: past, present, and future, 18th International Conference of Nuclear Engineering, No. 29001, 2010.

[2] Wang Kee In, Young Ho Park, Chang-Ho Kim, Seung-Yeob Baeg, Tae-Young Yoon, "Assessment of Advanced Reactor Core Protection System for Pressurized Water Reactor", 19th International Conference on Nuclear Engineering, May 16-19, 2011, Chiba, Japan.

[3] Korea Hydro & Nuclear Power Co. LTD, Human Resource Development Institute, Control & Protection Systems. Manual Book.

[4] John H. Bickel. Risk Implications of Digital Core Protection System Operating Experience. Reliability Engineering and System Safety 93. December 2006.

[5] Wang Kee In, Young-Ho Park, Seung-Yeob Baeg, "Development and Assessment of Advanced Reactor Core Protection System*", Journal of Power and Energy Systems,* Vol 06, nº 02, 2012.

[6] Bon Seung Koo, Jin Young Cho, Jae Seung Song, Keung Koo Kim, "Core Protection Method with 4-Channel CEA Signals for Application of OPR-1000 Plants", *Transactions of the Korean Nuclear Society Spring Meeting*, Gyeong-ju, Korea, May 2008.

[7] Chang Joon Jeong, Hangbok Choi, "Regional Overpower Protection System Analysis for a CANDU-6 Reactor with the DUPIC fuel", *Proceedings of the Korean Nuclear Society Autumn Meeting*, Yongpyong, Korea, 2003.

[8] IAEA, "Countries Nuclear Power Profiles: Republic of Korea", Updated 2019, Available at: https://cnpp.iaea.org/countryprofiles/KoreaRepublicof/KoreaRepublicof.htm.

[9] Wang Kee In, Yeon Jong Yoo, Dae Hyung Hwang, Sung Qunn Zee, "Thermal Margin Budgets in the Analog/Digital Core Protection and Monitoring Systems" *Proceedings of the Korean Nuclear Society Spring Meeting*, Kori, Korea, May 2000.

[10] KOREA HYDRO NUCLEAR POWER (KHNP), *Nuclear Power Education Institute*, "APR1400 Protection System", training material, pp. 119-120.

[11] KOREA ELECTRIC POWER CORPORATION AND NUCLEAR POWER Co., Ltd, "Functional Design Requirements for a Core Protection Calculator System for APR1400", August 2014.

[12] KINS, Korea Institute of Nuclear Safety, "Operational Performance Information System for Nuclear Power Plant", Available.