Journal of KOSSE. (2020. 12) Vol. 16, No. 2 pp. 47-58
DOI: https://doi.org/10.14248/JKOSSE.2020.16.2.047
www.kosse.or.kr

ISSN (print) : 1738-480X
ISSN (online) : 2288-3592

Concept Development of Core Protection Calculator with Trip Avoidance Function using Systems Engineering

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Abstract : Most of the reactor trips in Korean NPPs related to core protection systems were caused not because of proximity of boiling crisis and, consequently, a damage in the core, but due to particular miscalculations or component failures related to the core protection system. The most common core protection system applied in Korean NPPs is the Core Protection Calculator System (CPCS), which is installed in OPR1000 and APR1400 plants. It generates a trip signal to scram the reactor in case of low Departure from Nucleate Boiling Ratio (DNBR) or high Local Power Density (LPD). However, is a reactor trip necessary to protect the core? Or could a fast power reduction be enough to recover the DNBR/LPD without a scram? In order to analyze the online calculation of DNBR/LPD, and the use of fast power reduction as trip avoidance methodology, a concept of CPCS with fast power reduction function was developed in Matlab® Simulink using systems engineering approach. The system was validated with maximum of 0.2% deviation from the reference and the dynamic deviation was maximum of 12.65% for DNBR and 6.72% for LPD during a transient of 16,000 seconds.

Key words : CPCS, DNBR, LPD, core protection, nucleate boiling, trip avoidance.

Received: September 15, 2020 / **Revised**: November 19, 2020 / **Accepted**: November 24, 2020

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1. Introduction

Core protection systems are part of the plant protection system (PPS) addressed to protect the fuel pellets and cladding during normal operations and specific Anticipated Operational Occurrences (AOO). This main requirement of core protection is guided by the General Design Criteria GDC 10, 12, and 21 with obligations to assure that the Specified Acceptance Fuel Design Limits (SAFDL) will not be exceed.[1]

The Three Mile Island (TMI) accident showed that some additional requirements were necessary.[2] Thus, US Nuclear Regulatory Commission (USNRC) published the regulations for NPPs to provide instruments in the control room to indicate an inadequate core cooling condition.[3] Therefore, the core protection systems were developed to attend the SAFDL and trip the reactor in case of the limits exceeding. The core protection system is described in Tier 2, chapter 7, of an NPP's Final Safety Analysis Report (FSAR).[4]

Because the system must provide safety for the fuel, specifically to the cladding and to the fuel pellets, the value of departure from nucleate boiling ratio (DNBR) and the value of local power density (LPD) are monitored. These quantities are not directly obtained by sensors but calculated using thermal hydraulic magnitudes such as temperature, pressure, power, control rods positions, and coolant flow.

In this aspect, NPPs shall be operated within operational thermal margins to prevent fuel damage. The phenomenon of departure from nucleate boiling (DNB), which can damage the fuel cladding, and also the localized peaking power, which can cause fuel pellet centerline melting, have to be avoided, and a margin has to be applied.[5],[6]

The core protection system can use different approaches to calculate the DNBR and LPD. The system can be analog or digital. An analog system is the Westinghouse Overpower DT and Overtemperature DT (OPDT&OTDT) and a digital system is the Combustion Engineering, Inc Core Protection Calculator System (CPCS).[7]

I&C core protection systems are important for the operational performance. Firstly, the number of unnecessary reactor trips can be reduced by system with trip avoidance methodology. Secondly, reduced number of reactor trips permits increment on availability and on capability factor of the NPP. Finally, a reduction of unnecessary reactor trips reduces the components stress due a reactor trip.[8]

The Korea's nuclear industry publish its events by the Korea Institute of Nuclear Safety. Using the data available in its website is possible to verify which events are direct or indirectly related to the core protection system. Since 1986 until 2018, 31 reactor trips were related to core protection system.[10]

This paper proposes a concept of core protection calculator system with a method to avoid unnecessary reactor trips on Matlab® Simulink using a system engineering approach. Two main goals are pointed in this work, a development of core protection system to calculate DNBR and LPD and the use of reactor power cutback system (RPCS) as a first response of core protection system actuation using Matlab® Simulink.

The system engineering (SE) approach was used to conduct the development of a complex model and create a successful system that meets the requirements.

2. Systems Engineering Approach

The systems engineering approach concentrates on development of a successful system that meets the user's requirements. The success of the system represents the balance of high performance with affordability and constraints.[9]

In attempting to develop the system it is important to understand exactly what the system is designed to do, how the system tasks will be performed, and what the boundaries of the system are.[9]

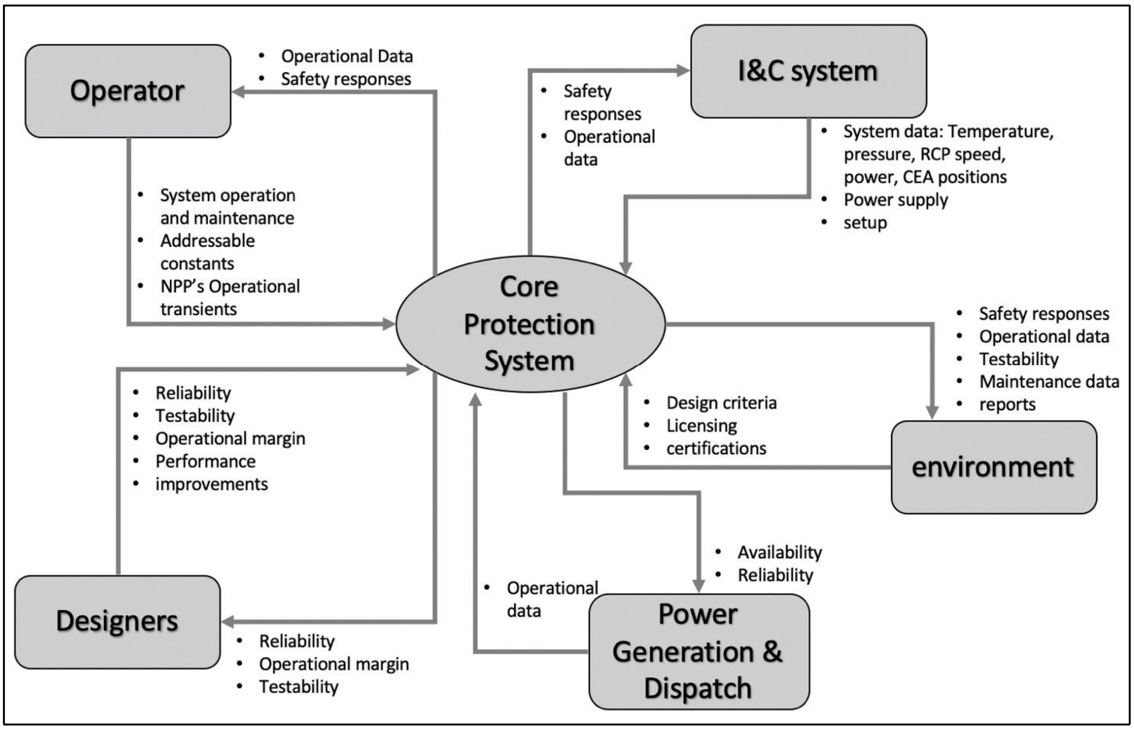
Everything starts with the requirements of the project. The success of the project is quite related to the precision of requirements description. Therefore, besides the requirements stablished by regulations as mentioned in the introduction, this work has as main user's requirements:

Concept development of a core protection system in Matlab® Simulink.

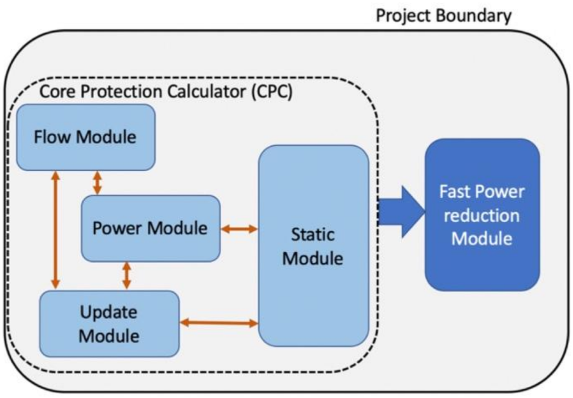
Unnecessary reactor trip avoidance function.

Then it is necessary to define the entities and boundaries. The Figure 1 shows the context diagram with the entities related to the core protection system, such as the general I&C system and the Power Generation & Dispatch.

The boundary of this work is stablished inside the core protection system as showed in Figure 2. Basically, the CPCS is combined by a core protection calculator (CPC) and a control element assembly calculator (CEAC). This



[Figure 1] Context diagram of the system work is focusing on the development of the CPC processor with an additional function of fast power reduction as showed in Figure 2. The CPC is responsible for the calculation of DNBR and LPD and the fast power reduction is used for trip avoidance methodology.

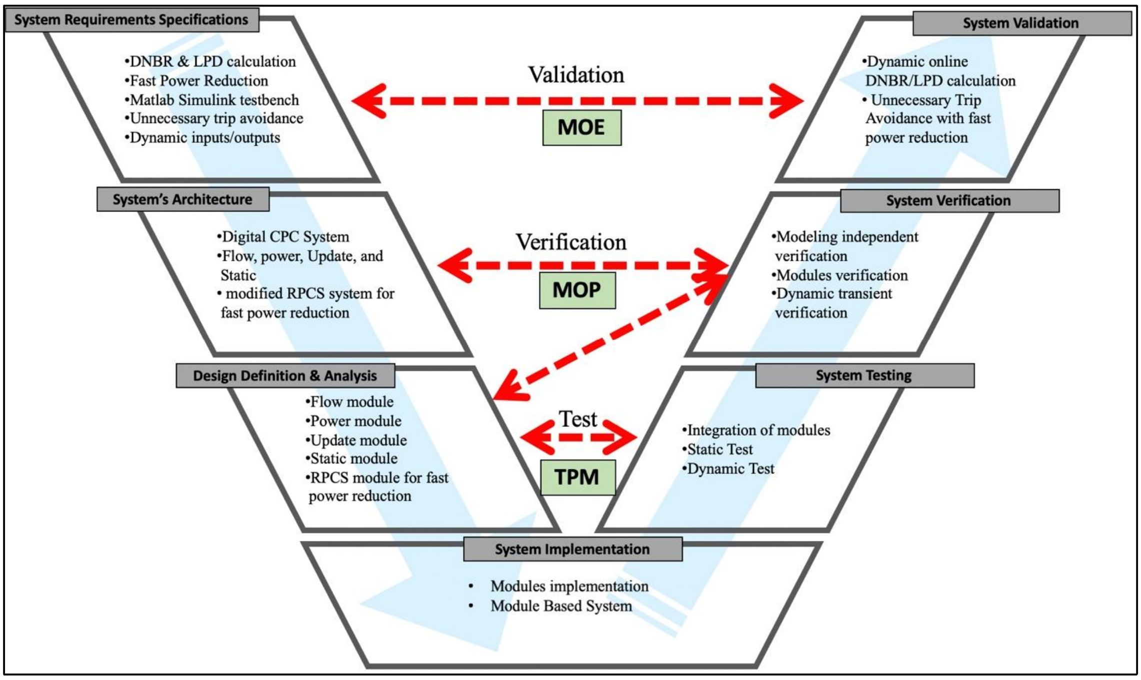


[Figure 2] Boundary of the work

The V-model for the whole system is developed using the concept of operation of the system. As mentioned before CPC calculates the value of DNBR and LPD and sends a trip signal in case they reach the setpoint. The V-model gives the step-by-step from the requirements until the acceptance criteria of the system.

The first leg of the V-model decomposes the concept of the system into very specific goals and functions, which transforms the stakeholder's expectation into technical requirements. The decomposition generates design criteria of the subsystems and their specifications to be implemented. The second leg of the V-model uses the baseline of requirements to test, verify and validate the subsystems individually and integrally. The end of the V-model is the validation of the whole system using the acceptance criteria.

This work utilizes the V-model to develop a concept of core protection system with trip avoidance methodology in Matlab® Simulink as showed in Figure 3.



[Figure 3] Concept Development V-model of Core Protection System

The defined problem is how to develop a concept of CPC with a function to fast reduce the power and recover to a safety value of DNBR and LPD. Therefore, the purposes of this work are (1) to develop a concept of CPCS in a testbench simulator; (2) develop a function of fast power reduction; and (3) integrate the CPCS and the power reduction function to as avoidance methodology.

The test, verification, and validation were performed using as reference the facility of KEPCO E&C and the KINGS' simulator results using the same inputs.

The test of the modules was divided in 2 tests. First, a static test using preselect random values of inputs. Second, a dynamic test using a dynamic transient signal as input. The test was performed to check if the system works properly and without any simulation errors.

The verification was divided in (1) model verification and (2) model dynamic response verification. Two independent verifiers checked the models and compared with the reference [10] with functional design requirements of CPCS. This verification was performed using tables of contents with all the equations and iterations of each module. The dynamic response verification was performed by using a set of inputs from the Barakah simulator during a power reduction from 100% to 75% power.

The validation of the system was divided in the CPC validation and the trip avoidance validation. The CPC validation was performed by data response of each module from KEPCO E&C. This validation was only in a static calculation, because the system in KEPCO E&C cannot run with a signal as input. The trip avoidance validation was performed by a transient data from Barakah simulator.

3. Concept Development

The main concept of the core protection system has already been developed by the functional design requirements.[11] It is an electronic device designed to calculate the DNBR and the LPD and trip the reactor, which assures that the SAFDL will not be exceed. However, what are the needs to develop the system? The concept used for this work is development of the system by using a model to calculate DNBR and LPD with an additional function of trip avoidance.

3.1 Requirements Analysis

As the system has been used in industry the main requirements have already been applied to the current system. The criteria of GDC are applied on this work as requirements from the regulatory body.[1],[2] Additionally, some requirements for the concept are being considered.

The first requirement is related to that the Specified Acceptance Fuel Design Limits (SAFDL) will not be exceed by any AOO. In order to meet this criterion, is necessary to assure at least a 95% probability at a 95% confidence level that the fuel will not experience a DNB during normal operation or AOO.[1],[2]

The regulator pointed out that NPPs have to provide instruments in the control room to indicate an inadequate core cooling condition.[1],[2] This can be shown by the values of DNBR and LPD during the operation.

The system shall be designed for high functional reliability and inservice testability. The use of redundancy shall be applied to avoid single failures that results in loss of protection function.[1]

The operational margin shall be greater or equal than the current system. The improvement in the system will not make the operational margin decrease.[1]

The code script and models for the system shall be simplified and easy to comprehend. The current system uses a complex algorithm and hard traceability of all calculations performed by the software. The improvement shall use easy comprehension of the software algorithm with high reliability.[8]

The system is designed to improve the availability of the NPP. A trip avoidance methodology shall be applied to the system to avoid unnecessary reactor trips. The concept of reactor power cutback system will be used as first response of the core protection system.

3.2 System Architecture

The core protection systems used in these Korean NPPs are presented in table 1.[14],[15],[16],[17]

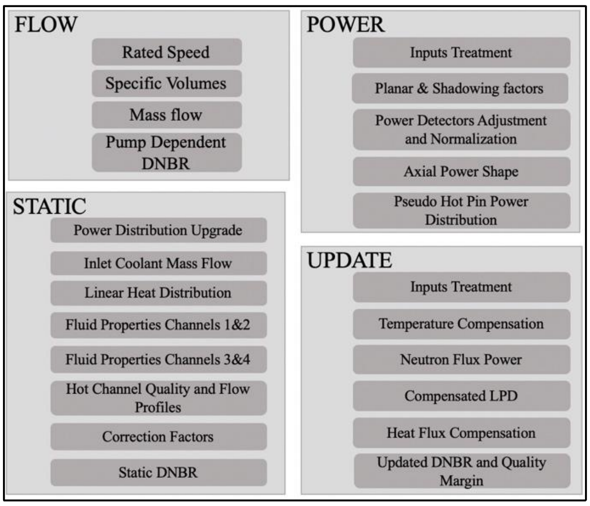
<Table 1> Korean NPPs and Core Protection Systems

Type of core protection system	NPP models
Analogical OPDT&OTDT	WH-F and FRANCE CPI
Digital CPCS	OPR-1000
Digital Common Q CPCS	APR-1400
Regional Overpower Protection System (ROP)	CANDU-6

The analogical system OPDT&OTDT are applied in some Westinghouse models. Digital CPCS system is applied in OPR1000 and the Common-Q CPCS is applied in APR1400. Lately, CANDU reactors use a concept of core protection system named regional overpower protection system.

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). The Common Q CPCS is an improved CPCS used in APR1400 reactors. This improvement was motivated by undesirable trips occurred in the CPCS system because of improper penalty factors and failures of the CEA position processor.[14],[19]

The current CPC architecture proposed for this work is a concept development of the Flow, Power, Static, and Update modules as showed in figure 4.



[Figure 4] CPC architecture developed in Matlab®

The Flow module is responsible to calculate the core mass flow using as input the reactor coolant pumps (RCP) speed, the reactor coolant system (RCS) pressure, RCS temperatures.[11]

The Update module is responsible to update the value of DNBR and quality margin as well as the value of LPD. The module uses many variables from the other modules as input and sensors.[11]

The Power module is responsible for axial power distribution and planar & shadowing penalty factors. It uses as inputs the excore power detectors and the CEA positions. Thus, using a spline function it calculates the axial power distribution.[11]

The Static module is responsible to apply the thermohydraulic equations for DNBR calculation using the subchannel approach. As input it uses the normalized core coolant mass flow rate, the CEA deviation penalty factor for DNBR, and relative power in each axial node of the pseudo hot pin.[11]

4. Engineering Development

The development of this work used the following sequence:

1) Modeling design for Matlab® Simulink.
2) Model implementation on Matlab® Simulink.
3) Model testing and verification.
4) Model validation.
5) Project Transition.

4.1 Modeling Design for Matlab® Simulink

The design of the systems is based on the functional design requirements of CPCS.[11] Using the algorithm description and information from KEPCO E&C, each module was designed using the tools available on Matlab® Simulink.

4.1.1 Flow Module

The speed sensors of RCPs are treated to convert the counts per seconds into rated speed or rpm. Then, the speeds are used to check and account the RCPs running. Next, the temperature and pressure are used to calculate the specific volumes and, therefore, the core mass flow.

4.1.2 Power Module

The power module calculates the planar and shadowing factor based on CEA positions and calculates the axial power distribution. The hot pin axial power distribution is calculated using the upper, middle, and lower excore power detectors combined in a spline function. The penalty factor is applied to adjust the pseudo hot pin power distribution.

4.1.3 Static Module

The static module calculates the hot assembly fluid properties. Using a thermohydraulic correlation based on CETOP and TORC the local and maximum heat fluxes are calculates in each of 20 core's axial nodes. The correlation is used in lumped channels to calculates the minimum DNBR.[20]

4.1.4 Update Module

The update module first treats the temperature, excore power detectors, and pressure signals from their sensors. Next, it compensates the neutron flux power, the heat flux, and the local power density (LPD). Then, the value of DNBR and quality margin calculated in static module are updated.

4.1.5 Fast Power Reduction Module

The fast power reduction module is where the methodology of trip avoidance is applied. As the method to protect the core is the reactor trip, a small trip could be enough to protect the core as well as maintain the plant operating. Therefore, in order to fast reduce the power, the concept of reactor power cutback system was used in this module.

In case of the DNBR rate is lower than −0.2 compared with the previous 10th calculation or the absolute value of DNBR becomes lower than 1.6 the reactor power cutback system is activated. These values need to be verified and validated according to thermohydraulic safety analysis. As a matter of fact, the I&C system is designed for any setpoint value and addressable constants can be considered for the limits application.

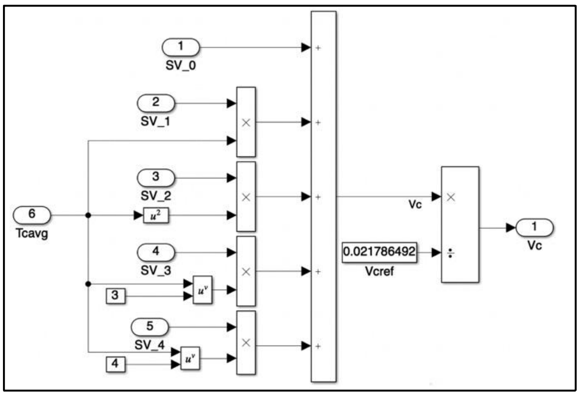
4.2 Model implementation on Matlab® Simulink.

The models were implemented in the Simulink using mathematic blocks and script code blocks. The equations and iterations described in the algorithm were applied using the tools on Matlab® Simulink. Each submodule corresponds to a subitem of the algorithm.

4.2.1 Flow Module Implementation

The inputs signals are RCPs' speeds, cold and hot legs temperatures, and primary pressure. The outputs are the number of RCPs running, the pump dependent DNBR, the pump dependent LPD factor, and the mass flow. The module uses thermohydraulic and design constants from KEPCO E&C and Shin Kori 3 and 4 as reference.

The mass flows are calculated using the values of specific volume and the RCPs' speed. The specific volumes are calculated using temperature and pressure of the system and the correspondent constants from a curve fit. An example of specific volume factor based on pressure and temperature is showed in figure 5.



[Figure 5] Specific volume calculation

4.2.2 Power Module Implementation

The implementation of power module is according to the equations and conditions described in the algorithm. The inputs are the CEA positions and the excore power detectors. The output are the axial power distribution, the maximum peak power, and the average power. In a nutshell, the synthesis of the axial power shape is computed by the selection of splines and their amplitudes.[11]

4.2.3 Static module implementation

The inputs are in summary the power distribution, the enthalpies calculated in Update, the RCS's temperatures and pressure, and the core mass flow. As output of the module are in summary the minimum static DNBR, the local heat flux rate, the static differential enthalpy across the core, the correction factor, and the static quality.

All the values generated as output are from the same node of the minimum DNBR. Therefore, the module calculates the value of DNBR in all 20 nodes and the minimum is selected. All the other values are from the same node of minimum DNBR.

4.2.4 Update Module Implementation

The inputs of Update module are the RCS temperatures and pressure, the excore power detectors, the core and legs mass flows, the axial power distribution, and the enthalpy temperature ratios. The outputs of Update are the LPD, the update DNBR, the update quality margin, and the core enthalpies.

4.2.5 Fast Power Reduction Module Implementation

Finally, the implementation of fast power reduction module is a modified RPCS. Besides the current inputs, this module has the value of DNBR and LPD with its respective rates. The figure 5 is showing the module of fast power reduction with code script implemented.

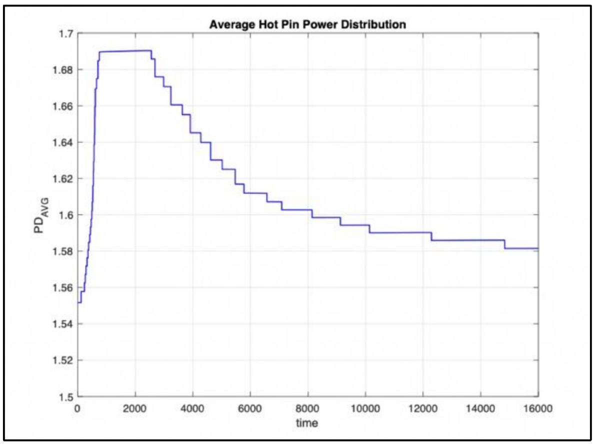
```
% Thiago Nascimento
% KEPCO International Nuclear Graduate School - 2020

% Fast power reduction
function [G5,G4,CPCS_1,CPCS_2] = fcn(DNBR,LPD,DNBR_grad,LPD_grad)

if DNBR < 1.6 || LPD > 350
    CPCS_1 = 1;
else
    CPCS_1 = 0;
end
if DNBR_grad < -0.03 || LPD_grad > 5
    CPCS_2 = 1;
else
    CPCS_2 = 0;
end
if DNBR < 1.6 && DNBR_grad < - 0.03 || LPD > 350 && LPD_grad > 5
    G5 = 1;
    G4 = 1;
else
    G5 = 1;
    G4 = 0;
end
```

[Figure 6] fast power reduction code script.

4.3 Test and Verification

All the modules were successfully tested during the development using random values as input. The tests were performed to check the models running. Each submodule was tested using a static value as input, then a transient input was used to test the processing of the module.

The verification was divided in two steps: model design verification and dynamic response verification. The first step is to check if all the equations from the algorithm are applied correctly in the model. This process was conducted by two independent verifiers using tables sheets of each model separately. The second step was conducted by dynamic signals as input in all the modules separately. The figure 7 shows one of the responses, the average of hot pin power distribution (PDAVG) during a transient of power reduction from 100% to 75% power.



[Figure 7] Average hot pin power distribution

4.4 Validation

The validation process was performed by

static input in each submodule. The table II shows the deviation of each submodule using the reference values of KEPCO E&C.

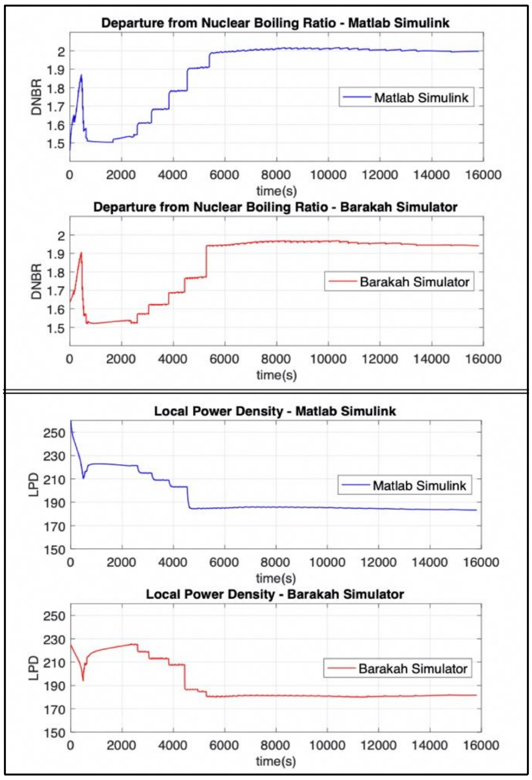
<Table 2> Modules validation and deviations (D)

Module		D(%)
Flow	Speed conversion	0.0%
	Specific volumes	0.0%
	Core and legs mass flow	0.0%
	Pump dependent DNBR	0.0%
Power	CEA inputs treatment	0.0%
	Shadowing correction factor	0.0%
	Adjusted normalized detector response	0.0%
	Adjusted detector responses	0.0%
	Power vector for spline amplitudes	0.0%
	Spline amplitudes	0.0%
	Axial power shape	0.0%
	ASI dependent parameters	0.0%
	Pseudo hot pin power distribution	0.0%
Update	Sensor inputs treatment	0.0%
	Temperature compensation	0.0%
	Neutron Flux Power	0.0%
	Compensated LPD	0.0%
	Heat flux compensation	0.0%
	Updated DNBR and Quality Margin	0.0%
static	Power Distribution DNBR Calculation	0.0%
	Inlet Coolant Mass Flux	0.0%
	Calculation of Linear Heat Distributions	0.0%
	Fluid Properties for Channels 1 and 2	*
	Fluid Properties for Channels 3 and 4	0.0%
	Hot Channel Quality and Flow Profiles	0.0%
	Hot Channel Heat Flux Distributions	0.0%
	Correction Factors	0.2%
	Static DNBR	0.0%

* This submodule gives response different of the reference. However, comparing the result of Matlab® model with the reference FORTRAN code script, the responses are the same, with deviation equal to zero.

The validation was not 100% successful due to different addressable constants and static inputs. As the system uses corrections with previous steps computations, a static value depends on the initial condition of each delay block. Therefore, as the access to the model of current CPCS was not possible, the exact value used as initial condition was not available.

The dynamic validation of the integrated system was performed using a transient data from Barakah simulator. The transient selected was a power reduction from 100% to 75% in normal condition. The values of DNBR and LPD calculated by the simulator and the system developed in this work are showed in figure 8. The deviation from the simulator was maximum of 12.65% in DNBR and 6.72% in LPD during a transient of 16,000 seconds.



[Figure 8] DNBR and LPD dynamic validation

4.5 Project Transition

The transition of this project is to the I&C lab of the School. The system can be used for future improvements and new applications.

5. Conclusion

The user's requirements of the concept development of core protection system with a function of unnecessary reactor trip avoidance was successfully accomplished. The system was divided in 5 modules and each module was divided by multiple submodules according to their specific functions.

A shrewd test and verification were performed in the entire system. Two independent verifiers checked each equation from the algorithm on the system. Using randomized inputs, the system was successfully tested.

The validation was performed using KEPCO E&C reference and the Barakah full scope simulator. The results were reasonable in both of references. The static reference of KEPCO E&C resulted in 100% fidelity and the dynamic validation with Barakah simulator resulted in maximum deviation of 12.65% for DNBR and 6.72% for LPD.

Acknowledgement

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

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