Concept Development of Reactor Trip Avoidance Methodology using Improved Core Protection System

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1. Introduction

A core protection system is used to preserve the integrity of the core in Nuclear Power Plants (NPP). The heat created by nuclear fission inside the fuel is used to create steam and runs turbine-generators to produce electrical energy. However, if the same yield heat is not properly removed, it can damage the fuel causing a very serious accident. Therefore, the core protection system is used to monitor the condition of the core and shutdown the reactor if necessary.

Pressurized Water Reactors (PWR) use the core protection system to calculate the Departure from Nucleate Boiling Ratio (DNBR) and the Local Power Density (LPD) and generate a reactor trip when the Specified Acceptance Fuel Design Limits (SAFDL) are violated [1]. The system is used to maintain the core thermal margin to nuclear fuel design limits. The values of DNBR and LPD are continuously compared to the trip limits [2]. DNBR is determined by the ratio of calculated critical heat flux to the actual heat flux. The LPD is based on the core average power and the core power distribution [3].

Most of Westinghouse NPPs apply an analog core protection system, the overpower and overt temperature ΔT (OPΔT&OTΔT). The overpower ΔT is used to prevent fuel centerline meltdown (high LPD) and the overtemperature ΔT is used to prevent cladding damage (low DNBR). Nowadays, digital NPPs are using digital core protection systems, which is used to generate trip signals not only for low DNBR and high LPD, but also pre-trip signals and CEA withdrawal prohibit signal [4].

Anticipated Operational Transients (AOO) can be cause of reactor trip signals from the core protection system due to SAFDL violation. However, shutdown the reactor is not the only option to protect the core, because measures such as reduction of power can help the reactor stays within the SAFDL limits without a reactor trip and, therefore, enhance the plant availability [4].

Therefore, as the value of DNBR and LPD are been used to generate reactor trip signals, why they cannot be used as a feedback for power control? As the values of DNBR or LPD are following a path to reach the pre-trip or trip setpoint the regulating CEA groups could move to reduce the power and avoid the reactor trip.

Another possible measure to avoid low DNBR and/or high LPD is to reduce the inlet core temperature, object of this work. It can be achievable by open the heater bypass valve in the main feedwater system when a pre-trip signal is generated by the core protection system. The question that has been raised is: the reduction of coolant inlet temperature can an option to avoid low DNBR and/or high LPD?

This work is focused on reactor trip avoidance by (1) the reactor power cutback system, (2) by the regulating CEA groups movement, and (3) by the inlet coolant temperature reduction.

2. Core Protection Calculator System

The digital Core Protection Calculator System (CPCS) is used in APR1400 NPPs in Korea. It was firstly developed by C-E Combustion Company and now it is being enhanced by KAERI. It is designed to generate the low DNBR pre-trip and trip signals, high LPD pre-trip and trip signals, and the following auxiliary trips:

1. Less than 2 Reactor Coolant Pumps (RCP) running.
2. Hot leg temperature approaching to the saturation temperature, which prevent from substantial void.
3. Variable Overpower Trip (VOPT), which protect the core from sudden power increases.
4. Asymmetric Steam Generator Transient Trip (ASGT), which protect for instantaneous closure of the Main Steam Isolation Valves (MSIV) to a single steam generator.
5. Low pressure and low DNBR trip (LPLD).
6. Hardware malfunctions, when conditions like Test, Initialization, or internal fault are reached.

Besides, the CPCS sends a CEA withdrawal prohibit when any pre-trip signal is present. [5]

The AOO considered for CPCS design are:

1. Uncontrolled Xenon Oscillations.
2. Insertion or withdrawal of CEA groups, CEA subgroup, or a single CEA.
3. Excess heat removal.
4. Changed of forced RCS flow including simultaneous LOOP to RCP at 100% power.
5. Inadvertent depressurization of RCS including full spray flow.
6. Decreasing in heat transfer capabilities.
7. Complete loss of AC power to the station auxiliary.
8. Uncontrolled boron dilution.
9. Asymmetric steam generator transient due to an MSIV closure. [5]

The CPCS consists in six interdependent modules: FLOW, UPDATE, POWER, STATIC, TRIPSEQ, and CEAC. [1]

2.1. FLOW module

The FLOW module uses as input the Reactor Coolant Pumps (RCP) speeds, the Reactor Coolant System (RCS) pressure, RCS temperatures, and the updated DNBR to calculate the mass flow rate, the number of RCPs running, the flow adjusted DNBR, and the normalized specific volume [5]. This module runs in cycles of 50 milliseconds [1].

2.2. UPDATE module

The UPDATE module uses as input many variables from the other modules. For example, the number of RCPs running and normalized mass flow rate from FLOW module; the relative power in each axial node of pseudo hot pin and the average of hot pin power distribution from POWER module; the static quality at node of minimum DNBR and CEA deviation penalty factor for DNBR from STATIC module; and DNBR penalty factor from CEAC module. [5]

As output the module sends, for example, the updated DNBR, the update quality margin, the calibrated neutron flux power, and the Reactor Power Cutback Flag [5]. This module runs in cycle of 100 milliseconds [1].

2.3. POWER module

The POWER module uses as input, from FLOW module, the normalized core coolant mass flow and the normalized average cold leg specific volume. From UPDATE module, it uses the raw ex-core neutron flux detectors values read from A/D converter, the temperature shadowing factor, and the Reactor power cutback flag. [5]

As output, the POWER module generates, for instance, the maximum peaking factor, the neutron flux power normalization factor – corrected by shape annealing and CEA shadowing factor –, and the average of the hot pin distribution [5]. This module runs in cycles of 1 second [1].

2.4. STATIC module

The STATIC module uses many variables from the modules FLOW, POWER, and UPDATE. For instance, 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 [5]. This module runs in cycles of 2 seconds [1].

2.5. TRIPSEQ module

Different of other modules, TRIPSEQ module has as output only the pre-trip and trip signals, and the CEA withdrawal prohibit signal. As input it receives many variables from each module, such as the reactor power cutback flag, the saturation temperature of water, the groups out-of-sequence and subgroup deviation warning flag, and the flow adjusted DNBR [5]. This module does not present a cycle of calculation, because it is not used to calculate, but to conduct the signals.

2.6. CEAC module

This module is not inside the same processor of core protection processor. It is used to calculate the penalty factors related to CEA positions. The inputs are signals from the Reed Switch Position Transmitters (RSPT). As output of CEAC module are, for example, the LPD and DNBR penalty factors for each CEA subgroup [5].

3. Core Inlet Temperature Influence – Barakah Full Scope Simulator

What is the influence of each input in the core protection system? The values of DNBR and LPD are influenced by each input, but how is the behavior of them when the inputs change?

Heaters bypass valve FW065 opening was performed in the Barakah APR1400 full scope simulator. The aim of this simulation was to verify the cold leg temperature, reactor power, and the DNBR values during the transient. In Figure 1 and Figure 2 are showing the power and average temperature and the cold legs temperature, respectively.

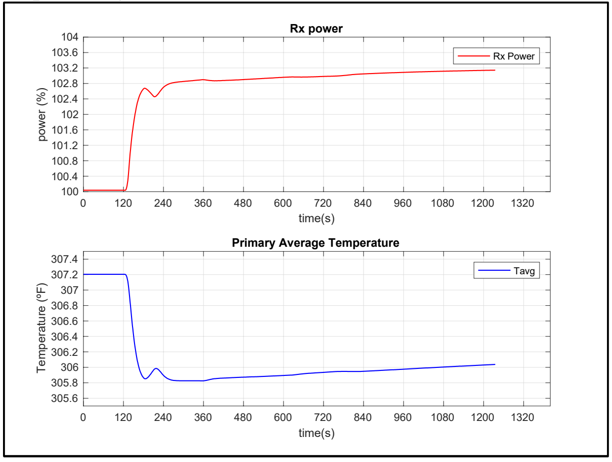

Figure 1: Power and RCS Average Temperature.

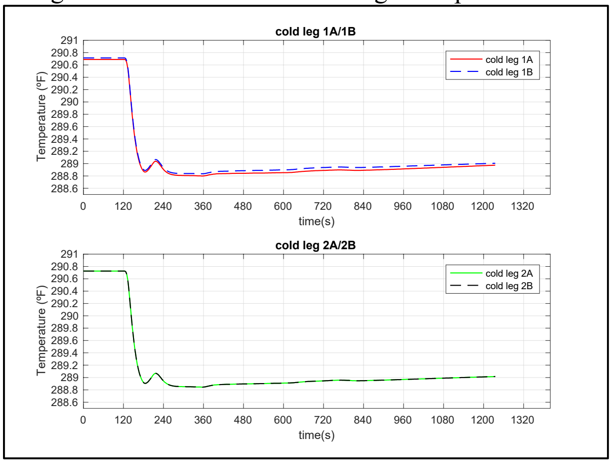

Figure 2: Cold Legs temperature.

The reduction of coolant temperature should contribute to **increase** the DNBR value, but it is not what it is showed in the simulation. In the Figure 3 is showing the DNBR trending during the same transient. The DNBR from each CPCS channel is decreasing just after the valve opening.

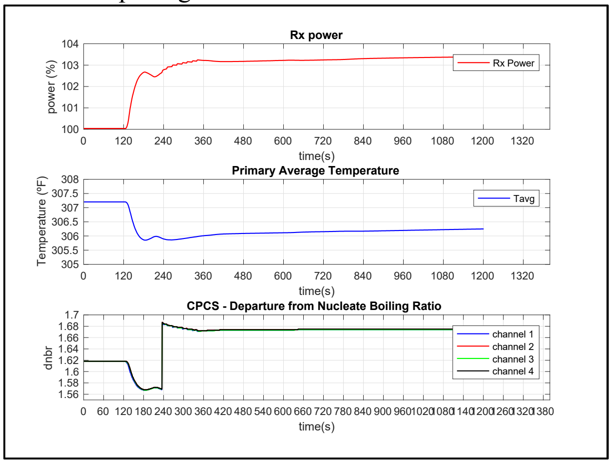

Figure 3: Power, average temperature, and DNBR.

Moreover, it shows an interesting sharp step increasing of DNBR output when the regulating CEA group 5 starts to move as showed in figure 4. The question is: why the DNBR output sharply moves to a higher value? This is one of the questions to be answered by this research.

The regulation observed by CEA group withdrawal is supposed to be due to the difference from average temperature and reference temperature. As the power is increased by the reactivity inserted by the negative moderator coefficient, the Reactor Regulating System (RRS) will withdrawal the regulating groups to move the average temperature to the same value of reference temperature [6].

Another phenomenon observed in this case is the value of DNBR decreasing as the CEA regulating group 5 withdrawal.

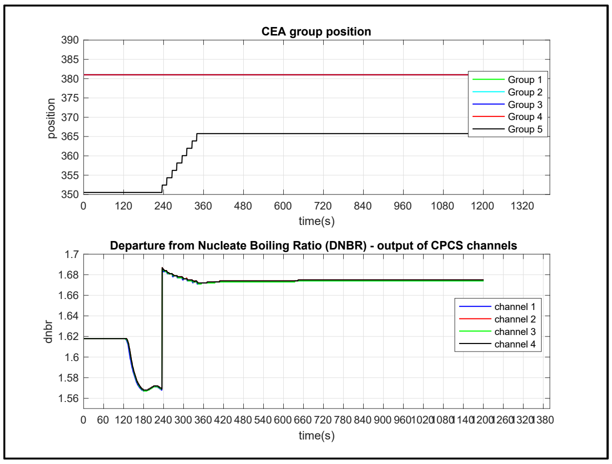

Figure 4: CEA regulating group position and DNBR outputs from CPCS channels.

4. Research Path

First, using the CPCS algorithm, it is necessary to analyze how each input cause influence in the trip signals. Holding all the other inputs and changing only one input, the values of DNBR and LPD will be analyzed.

Second, the RPCS actuation will be used for each AOO mentioned above with the goal to avoid a trip signal. The objective is checking weather RPCS is able to decrease the power to avoid the trip signal.

Third, analyze if of core inlet temperature reduction can avoid a trip signal generated by CPCS during a transient.

Forth, the CPCS can have interface with RRS not only with the withdrawal prohibit signal, but also using CPCS DNBR and LPD values as input to regulate the power and avoid an unnecessary reactor trip.

Finally, the results and analysis will be criticized and a conclusion will be presented.

The path of the research proposed is showed in figure 4 below.

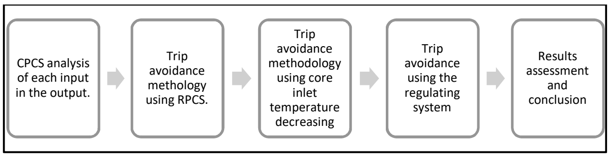

Figure 4: Research path.

5. Conclusion

Avoid unnecessary trips of CPCS system, guaranteeing the same safety requirements, is desired because it can enhance the availability of the NPP. The RPCS can be used to drop the power during a transient, what brings the core to a safety condition without a reactor trip.

Additionally, using the same approach, it was expected that the reduction of core inlet coolant temperature can be used to avoid a CPCS trip signal bringing the core to a safe condition without a reactor trip, what is not confirmed by the simulation above. However, the DNBR calculation in the Barakah simulator shows an inconsistent calculation when the DNBR output sharply goes to a higher value. Besides, another inconsistence is showed the value of DNBR is decreasing as the regulating group 5 is withdrawing.

Therefore, this study can contribute with a detailed analysis about the CPCS system. Mainly, it can present a method to avoid unnecessary reactor trips from CPCS system.

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