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Design Improvement of Diverse Protection System in OPR1000

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1. Introduction

The digital safety I&C systems include the Digital Plant Protection System (DPPS) and the Plant Control System (PCS), which perform primary protection functions when a Design Basis Accident (DBA) occurs. The Diverse Protection System (DPS), which is diverse from the digital safety I&C system, provides secondary protection functions to ensure the safe operation of the Nuclear Power Plants (NPPs) in the event of an Anticipated Transient Without Scram (ATWS) or a DBA occurring simultaneously with Common Cause Failures (CCFs) of digital safety I&C systems [1][4]. Despite this diversity, new vulnerabilities—such as potential failures caused by the increasing complexity of digital systems and software issues that undermine the defense-in-depth provisions of digital safety I&C systems—have been continuously identified and reviewed.

One such vulnerability is a Steam Line Break (SLB) outside containment occurring concurrently with CCFs (hereafter SLB with CCF). When the SLB with CCF occurs, depressurization of the secondary side can lead to reactor core power excursions. To protect the reactor core during the SLB with CCF, it is necessary to implement a newly introduced protection function capable of initiating an immediate reactor trip to ensure the safety of the NPPs. As a countermeasure, a design improvement has been implemented in the DPS of the OPR1000 to enable reactor trip, including for Hanul Nuclear Power Plant Units 5&6, Shin-Kori Units 1&2, and Shin-Wolsong Units 1&2.

This paper discusses a design improvement of DPS by incorporating a new reactor trip signal, aiming to mitigate the SLB with CCF.

2. Justification for the Reinforcement of the DPS

During the SLB with CCF, the rapid depressurization of the Steam Generator (SG) induces a rapid cooldown in the Reactor Coolant System (RCS), which in turn leads to a significant increase in reactor core power due to positive reactivity insertion mechanisms. This sustained high-power operation poses a critical safety concern, as excessive core power excursions may result in conditions approaching the fuel melting threshold.

The DPS has a reactor trip signal initiated by high pressurizer pressure. However, the reactor trip signal initiated by high pressurizer pressure in the DPS was activated approximately 850 seconds after the SLB with CCF event. By that time, the fuel centerline temperature had approached the fuel melting threshold, posing a severe safety risk. A rapid reactor trip is crucial to minimize the impact of the SLB with CCF and enhance overall plant safety. To prevent fuel melting, an additional reactor trip signal initiated by Low Steam Generator Pressure (LSGP) was introduced into the DPS of OPR1000 to ensure an earlier reactor shutdown.

The reactor trip signal generated by LSGP in the DPS enables an immediate and automatic reactor trip upon detecting the rapid depressurization of the secondary side, thereby preventing core power excursions. Extensive sensitivity analyses have been conducted to optimize the trip setpoint, ensuring that the reactor trip is initiated within approximately 10 seconds after the SLB with CCF. The integration of the DPS LSGP reactor trip function represents a significant advancement in the safety of OPR1000, providing a robust countermeasure specifically addressing the SLB with CCF-induced reactivity excursions [2].

3. Implementation of the Design Reinforcement

The DPS has two channels and is classified as a non-safety-related system. It consists of the measurement channels, trip recognition logic, coincidence logic, and initiation circuitry. The DPS cabinet is equipped with a controller, I/O modules, switches, and a Maintenance and Test Panel (MTP).

In order to protect the reactor core from reactivity excursions caused by the SLB with CCF, a new LSGP reactor trip function has been implemented in the DPS.

3.1 DPS Controller

Obsolete analog and digital hardware platforms in NPPs are commonly replaced with Programmable Logic Controllers (PLCs) and Distributed Control Systems (DCSs). Field-Programmable Gate Arrays (FPGAs) have been highlighted as an alternative to outdated hardware platforms. The DPS Controller has already been replaced with an FPGA-based Logic Controller (FLC) [3]. The FLC includes an FPGA chip programmed with an FPGA application developed using VHSIC Hardware Description Language (VHDL). A new reactor trip function, initiated by LSGP has been incorporated into the FPGA application. After the implementation of the updated FPGA application onto the FPGA chip, a series of tests-including unit, integration, and V&V tests-is conducted to verify its functionality. The FLC functionality was verified through unit, integration, and V&V tests, the results of which are documented separately. Fig. 1 shows the simplified configuration of the DPS cabinet incorporating the LSGP logic.

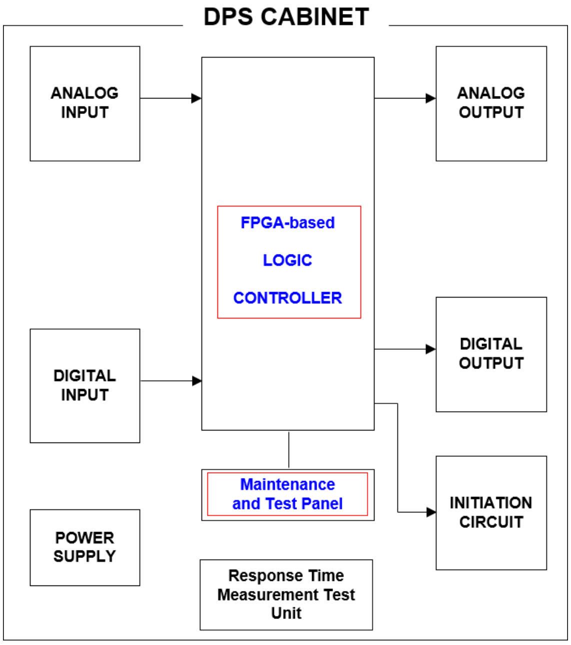

Fig. 1 Configuration of the DPS cabinet

3.2 DPS Reactor Trip Function

The DPS automatically initiates a reactor trip when either the pressurizer pressure or the containment pressure reaches its respective high setpoint. Two pressurizer pressure channels are monitored, one in each DPS channel, and similarly, two containment pressure channels perform the same function. The DPS initiates a reactor trip on a 2-out-of-2 coincidence logic when both inputs reach the trip condition. The DPS is not classified as a safety system, and its safety function is not required to operate in the event of a single failure. However, it is designed on 2-out-of-2 to prevent malfunctions caused by spurious actuation. Additionally, the DPS automatically initiates a reactor trip when either SG 1 pressure or SG 2 pressure reaches a low setpoint. Fig. 2 illustrates the reactor trip initiation logic, incorporating the SG pressure signal.

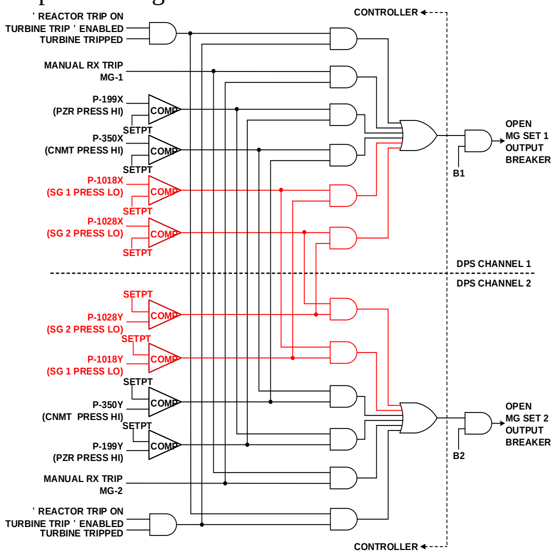

Fig. 2. Initiation logic of the DPS Reactor trip

3.3 DPS MTP

The DPS cabinet contains the MTP, which displays system status and alarm information. The addition of the SG signals has led to a modification to the MTP. Fig. 3 presents the DPS MTP main screen, incorporating the SG pressure signal.

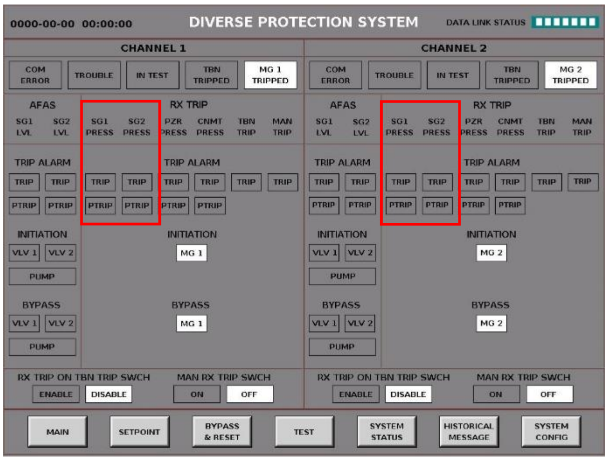

Fig. 3. Main Screen of the DPS MTP

4. Conclusion

This paper presents the results of the addition of the LSGP reactor trip function implemented in the DPS of the OPR1000. Incorporation of the LSGP reactor trip signal into the DPS constitutes an enhancement to the safety of the OPR1000 by offering a reliable protective measure against the SLB with CCF. Furthermore, consideration should be given to incorporating an automatic reactor trip signal based on LSGP into the Advanced Power Reactor (APR) 1400, an advanced nuclear reactor model developed in Korea. These findings not only contribute to the field of DPS optimization but also provide a framework for future research aimed at enhancing the safety and operational reliability of advanced nuclear reactor designs.

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