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Verification of a Design Change to Remove PPS Signal Simulation Equipment Using an MMIS Digital Twin

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1. Introduction

Korea Hydro & Nuclear Power (KHNP) recently completed the development of a digital twin for the Korean Man-Machine Interface System (MMIS) using virtualization technology. This MMIS digital twin implements virtual hardware technology based on full virtualization to replicate the Programmable Logic Controllers (PLCs) and Distributed Control Systems (DCSs) currently in operation at nuclear power plants [1]. Through these technical features, the plant's real-time OS, firmware, and application software can be executed in the virtual environment without modification. Consequently, this ensures compatibility, allowing software verified in the digital twin to be directly deployed to the actual systems.

This paper proposes a design change for the Engineered Safety Features - Component Control System (ESF-CCS) to eliminate the need for Plant Protection System (PPS) signal simulation equipment, which is temporarily operated during Overhauls (OH). To verify the reliability of the proposed change, this study details the pre-verification process conducted within the MMIS digital twin environment [2].

2. Operating Status and Verification Environment

2.1 Status of PPS Signal Simulation Equipment

The PPS signal simulation equipment is used during OH. Its main purpose is to prevent unnecessary signals, generated during PPS testing or maintenance, from being transmitted to the lower-level ESF-CCS. This equipment generates normal signals and heartbeats instead of the actual PPS, allowing the ESF-CCS to maintain a normal standby condition and preventing the unintended operation of components when upper-level signals are absent.

In the Korean APR1400 MMIS, PPS signal simulation equipment is operated for each of the four channels. This equipment is installed and removed only during OH periods. This repetitive process increases the workload of maintenance personnel and presents a persistent risk of human errors, such as miswiring. Additionally, if the simulation equipment fails or loses power, the PPS signal for that channel is lost immediately, regardless of the external cable connection status. Consequently, this repetitive installation and removal process not only reduces maintenance efficiency but also potentially causes unnecessary reactions in the control system due to unexpected signal loss.

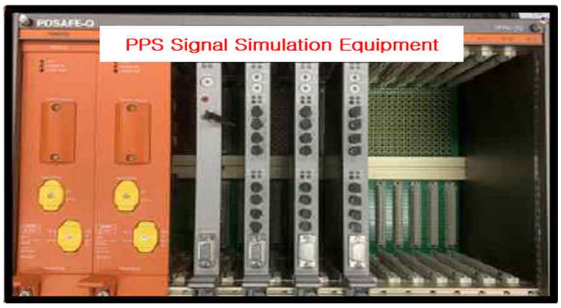

Fig. 1. PPS Signal Simulation Equipment

2.2 Digital Twin Testbed

In this study, the MMIS digital twin was used as a testbed to verify the reliability of the proposed design change. In particular, the MMIS digital twin goes beyond software logic simulation by providing hardware-level functions, such as terminal block jumper settings at the rear of the cabinet and power loss scenarios. Therefore, the digital twin served as a useful tool for reducing risks by effectively simulating hardware operations and fault scenarios that may occur during actual site implementation.

3. Proposed ESF-CCS Design Change

In this study, a Maintenance Mode recognition method using internal logic and hardware jumper settings was designed to eliminate the need for physical PPS simulation equipment.

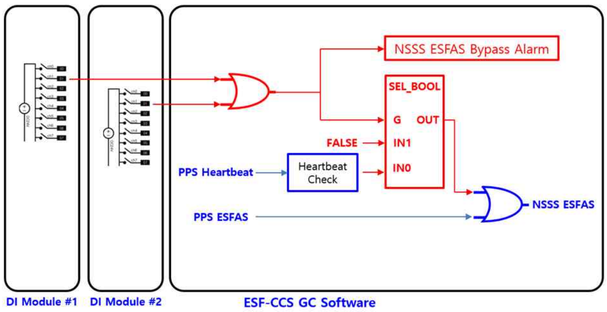

Fig. 2. Proposed design change to the ESF-CCS

As shown in Figure 2, a redundant dual-jumper input structure was implemented on the terminal block at the rear of the cabinet to safely recognize the OH status. This design is intended to prevent malfunctions caused by a single contact failure. The system enters Maintenance Mode only when both I/O module inputs are activated, thereby ensuring high design reliability.

Upon entering Maintenance Mode, the ESF-CCS software executes logic to block signals from the PPS and maintain an internally defined 'Safe State' signal. To ensure overall system stability, modifications to the existing logic were kept to a minimum. While the PPS signals are bypassed, the Radiation Monitoring System (RMS) signals remain independent to preserve essential safety functions during maintenance.

Additionally, the system immediately triggers an alarm in the Main Control Room (MCR) upon the activation of Maintenance Mode. The bypass status of the corresponding channel is also explicitly displayed through the Information Processing System (IPS). This allows operators to monitor the specific system status in real-time, preventing potential human errors and operational confusion.

4. Verification and Results

To verify the proposed design change, tests were conducted within an MMIS digital twin environment consisting of approximately 450 virtual machines (VMs). This process took place in a virtual testbed where all plant control systems, including the PPS and ESF-CCS, operate in an integrated manner. The study compared the performance of ESF-CCS Channel A, which implemented the new logic, with Channel B, which maintained the existing logic.

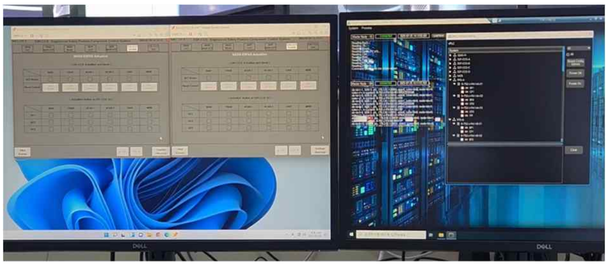

Fig. 3. PPS ESFAS signal bypass test screen based on MMIS digital twin

First, a test was performed to verify the PPS signal bypass and entry into Maintenance Mode. Using the Smart Engineering tool, jumper settings were simulated on the redundant I/O modules of Channel A. The results confirmed that Channel A successfully entered Maintenance Mode as designed. During this state, a signal loss was induced by intentionally cutting the power to the PPS. Channel B, operating with the existing logic, triggered an Engineered Safety Features Actuation Signal (ESFAS). In contrast, Channel A successfully bypassed the PPS signal and maintained its normal standby condition.

Subsequently, the verification focused on maintaining essential safety functions during Maintenance Mode. While Channel A was in Maintenance Mode, an actuation signal from the RMS was input. The results confirmed that the RMS-related components operated normally according to the design, even while the PPS signal was being bypassed.

These scenario-based tests validated that the proposed design change effectively blocks unnecessary interference from PPS signals while fully preserving essential safety functions. The verification was performed by precisely replicating actual hardware operations and system fault scenarios in a virtual environment through the digital twin. The integrity of the overall results was finalized and confirmed through simulation data analysis.

5. Conclusions

This paper proposes a design change for the ESF-CCS to eliminate the need for PPS signal simulation equipment and validates its feasibility using an MMIS digital twin. The MMIS digital twin, which accurately replicates the actual plant, confirmed the reliability of the dual-jumper based Maintenance Mode and software bypass logic. In particular, verifying the stability during a loss of PPS signals and the independence of RMS safety functions demonstrated that the new design fully meets all requirements without the need for PPS signal simulation equipment.

This design change eliminates the repetitive installation and removal of PPS simulation equipment during each OH, thereby fundamentally preventing human errors and maximizing maintenance efficiency. Furthermore, this verification case, which precisely replicated hardware manipulation scenarios, suggests the high utility value of digital twins for future MMIS design changes and pre-testing applications.

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