Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 7-8, 2026

Autonomous Normal Operation in SMRs: A Conceptual Design Integrating Models and HMI

Ji Woo Hong*, Ji Hun Park, Ji Hyeon Shin, Seo Ryong Koo
Korea Atomic Energy Research Institute, 111, Daedeok-daero 989beon-gil, Yuseong-gu, Daejeon, Republic of Korea
**Corresponding author: jiw00@kaeri.re.kr*

Keywords : small modular reactor, normal operation, autonomous operation, integral pressurized water reactor

1. Introduction

With the rapid advances in artificial intelligence (AI), autonomous operation that minimizes human intervention has become a key focus across various industries, including the automotive sector. This contributes to enhanced operator support and increased economic efficiency. The application of more advanced autonomous systems is anticipated in the future.

In the nuclear power plants (NPPs), increasing interest in small modular reactors (SMRs) has led to active research on integrated control and autonomous operation for multi-module reactor systems. Because SMRs consist of multiple modules operated simultaneously, high-level automation technologies are essential to ensure diverse operation strategies with a limited number of operators. In addition, increasing expansion of renewable energy generation and rising electricity demand require SMRs to support flexible operations such as power maneuvering and load-following. Advanced automation technologies in SMRs are expected to enhance safety and operational efficiency, while also improving economic competitiveness through reduced human error and lower operating costs.

This study presents the development of a normal operation autonomous model for SMRs using an integral pressurized water reactor (iPWR) simulator, along with a human-machine interface (HMI) designed to support autonomous operation. The results provide a technical foundation for the future application of high-level autonomous operation technologies in SMRs.

2. Power maneuvering automation model

To develop an autonomous operation system for SMRs, we need intelligent operation automation functions for normal operations [1]. Accordingly, this study developed an automation model for power maneuvering operation at the single-module level under normal operating conditions.

In this study, reactor power rise from 0% to 100%, reactor power decrease from 100% to 0%, and load maneuvering (100%-90%, 90%-100%) in the iPWR simulator environment were selected as targets for automatic operation. As summarized in Table II, automation strategies were derived through procedure-level analysis [2]. Each procedure was decomposed into subtasks and categorized based on action verbs. Subtasks that were previously performed manually by the operator were identified as automation tasks.

Fig. 1. Levels of automation for SMRs operation and scope of this study.

The automation model developed in this study follows automation Level 3, which is conditional autonomous operation, as shown in Fig. 1. At this level, the automation model automatically performs operations step by step. These operations require operator approval and intervention. As the automation level advances, the operator's role is expected to be gradually reduced, with the autonomous operation system assuming a more central function.

Table I: Description of action verb

Action Verb	Description	Automation Target
Input	Input target values	Intelligent automation
Ensure	Verification to achieve target values	Simple/Intelligent automation
Check	Verification of equipment and process variable status	Simple automation
Monitor	Continuous monitoring	Monitoring of cautions and operational limitations

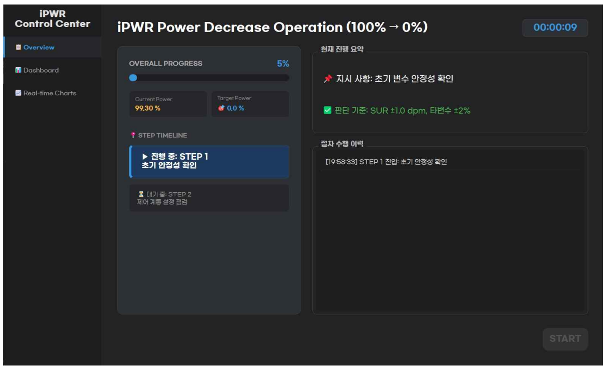
Table II: Excerpt of reactor power decrease procedure-level task analysis (Steps 1-3 of 20)

Step	Main Task	Subtask	Action Verb
1	Check the following variables are stable	Neutron power	Check
		Start-up rate	Check
		Thermal power	Check
		Generator load	Check
		Average temperature	Check
		Pressurizer level	Check
		Pressurizer pressure	Check
		Condenser pressure	Check
		Steam line pressure 1	Check
		Steam line pressure 2	Check
		Feedwater flow 1	Check
		Feedwater flow 2	Check
		Feedwater temperature 1	Check
		Feedwater temperature 2	Check
2	Verify proper status of the main plant controls	Plant in turbine leading mode	Check
		Rod control in auto	Check
		Main steam bypass is controlling average temperature	Check
		Feedwater system in auto	Check
		Circulating water and condenser systems in service	Check
		No active alarm	Check
3	Start turbine load reduction to 15%	Introduce turbine load demand and turbine load rate	Input
		Press Go	Press
		Check turbine control valve begins to close	Check
		Check generator power begins to lower	Check

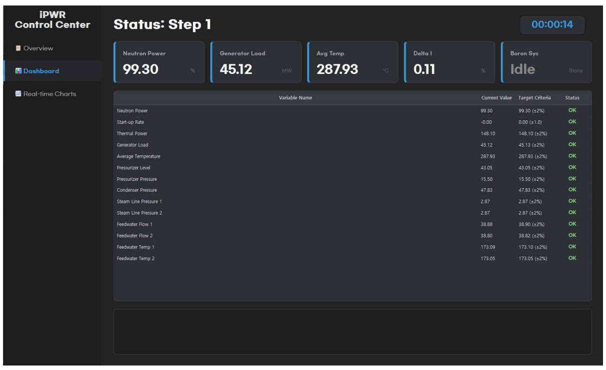
3. Normal operation automation HMI

The normal operation automation HMI was developed to intuitively present the operational status of the power maneuvering automation model to the operator. The HMI aims to clearly show the current state of the automation model and to effectively support the operator's monitoring and approval roles in a conditional autonomous operation (Level 3) environment.

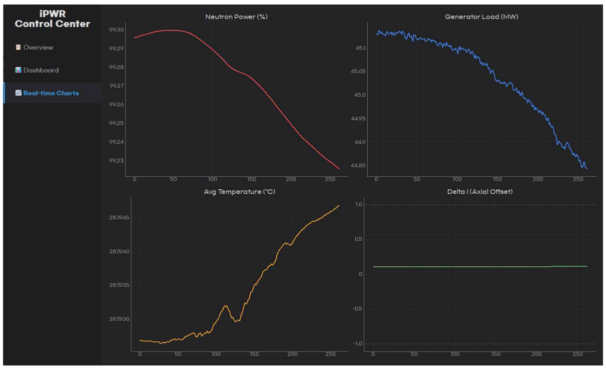
The HMI comprises two displays: a fixed display for continuous monitoring of the automation model and a dynamic display for step-based automated operation execution. The fixed display area applies a dark background color to reduce visual fatigue in long-term monitoring conditions. In contrast, the dynamic display area uses a bright background color to ensure immediate recognition and clear distinction from the fixed area [3].



(a) Main procedure overview



(b) Step progress status



(c) Real-time parameter monitoring

Fig. 2. Configuration of fixed display HMI for normal operation.

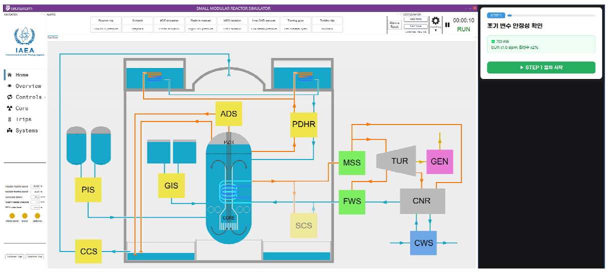


Fig. 3. Configuration of dynamic display with iPWR simulator.

Fig. 2 shows the fixed display of the power maneuvering automation model HMI. The fixed display comprises three tabs: the first displays a procedure overview, indicating the current step within the overall operating procedure; the second displays the progress of each step; and the third displays real-time monitoring data for key operating variables. As shown in Fig. 3, the dynamic display appears as a pop-up at the beginning of each step in the automation model and provides information on the corresponding actions. After confirming the displayed information, the operator starts step-based automated operation through the execution command.

4. Conclusions

This study constitutes a foundational effort toward integrated multi-module operation of SMRs by developing a power maneuvering automation model for a single module in normal conditions. A step-based automated operation logic was implemented, and the applicability of automation operation system was verified using the iPWR simulator. In addition, assuming a conditional autonomous operation environment (Level 3), the roles of the automation model and the operator were clearly defined, and an HMI was designed to effectively support the operator. The developed HMI intuitively presents step-based automated operation execution and monitoring information, thereby supporting operator intervention in automated operations. The proposed automation model is expected to provide a technical foundation for future expansion towards higher levels of autonomous operation (Level 4).

In future studies, we will focus on developing automation models for an integrated control center in multi-module SMRs. In addition, the automation level will be extended towards Level 4 to minimize operator intervention, and the proposed approaches will be validated using a virtual reactor platform which is to be developed in the future.

ACKNOWLEDGEMENTS

This research was supported by the National Research Council of Science & Technology(NST) grant by the Korea government (MSIT) (No. GTL24031-000).

REFERENCES

[1] J. H. Shin, J. M. Kim, and S. R. Koo, Insights into Simulation and Required Functions for Developing Normal Operation Autonomous Models of SMRs, in: Proceedings of the Korean Nuclear Society Autumn Meeting, Changwon, Korea, October, 2025.

[2] H. J. Lee, D. Lee, and J. Kim, Automating power-increase operation for small modular reactors based on task analysis with proximal policy optimization, Nuclear Engineering and Technology, 103767, 2025.

[3] Korea Hydro & Nuclear Power Company, “Standard Safety Analysis Report for APR1400”, 2002.