Development of online and offline simulation services for small modular reactor (SMR) technology

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1. Introduction

2.1 Background

Introduction to SMR technology and its significance in the future of sustainable energy. Discussion on the current state of nuclear simulation technology and its limitations.

2.2 Purpose

To develop a scalable simulation service that supports both online and offline environments, aimed at enhancing the accessibility of SMR technology for research, training, and operational optimization.

2.3 Objectives

The primary objective of this study is to design and implement an online platform specifically for Small Modular Reactor (SMR) simulation. This platform will enable real-time analysis, providing valuable operational insights and improving the decision-making process during reactor operation. Additionally, offline simulation modules will be developed to support on-site training and research activities. These modules will allow users to engage in practical learning and system testing across various operational scenarios, offering a robust environment for both educational and experimental purposes. Furthermore, this project aims to integrate artificial intelligence (AI) and big data analytics into the platform. By doing so, the system will enhance decision-making processes and ensure operational safety by providing predictive insights and optimization of reactor performance. The combination of these technologies will contribute significantly to improving the overall safety and efficiency of nuclear power plant operations.

2. Literature Review

A review of existing literature on Small Modular Reactor (SMR) technology highlights key aspects of its design, advantages, and challenges. SMRs offer significant benefits over traditional large reactors, including economic viability, enhanced safety features, and flexibility in deployment. However, there remain several challenges that need to be addressed for the widespread commercialization of SMR technology.

Simulation technology in nuclear engineering has played a crucial role in improving the accuracy of plant design and safety analysis. Historically, simulation was limited by computational capacity, allowing only basic modeling. However, recent advancements have enabled real-time simulations of complex systems, significantly enhancing the safety and efficiency of nuclear power plants.

Moreover, the integration of digital twin technology and artificial intelligence (AI) has introduced significant improvements in nuclear simulations. Digital twins provide virtual replicas of physical systems, enabling real-time data analysis and predictive maintenance. AI further enhances this process by optimizing the analysis and decision-making capabilities. These technologies have the potential to improve operational efficiency and prevent accidents in the nuclear industry.

In summary, SMR technology, simulation advancements, and the integration of digital twins and AI represent critical elements shaping the future of nuclear engineering.

3. Methodology

This study aims to develop a simulation platform using Small Modular Reactor (SMR) design data or similar data from the early to the final stages of design. The platform is built upon MSP-Pro applied technology, enabling the verification of system performance in both static and dynamic states. To ensure accuracy in the simulation, the model is based on Point Kinetics to accurately replicate the reactor core's behavior, and Pressurized Water Reactor (PWR) data is used as a reference to simulate the behavior of SMRs.

3.1 System Modeling

System modeling is carried out using SMR design data to model various equipment, facilities, or systems. The design data or similar data is utilized to model key components such as the reactor, heat exchanger, and power systems, all of which are integrated with the high-precision simulation provided by MSP-Pro applied technology.

Each system is designed to simulate physical behavior and functionality, first verifying normal operation in a static state (steady state) before assessing expected behavior under dynamic conditions. For example, system variables such as voltage, pressure, and flow are measured in the static state, and the system’s response to normal or abnormal situations is then validated through dynamic simulation.

3.2 Simulation Data Utilization and Performance Verification

The simulation platform measures and analyzes a variety of input/output data to verify system performance. By using data from the early design stage to the final stage, the performance of each system is evaluated to simulate behavior in actual operational environments. The performance verification process compares the predicted system responses in static states and dynamic states under abnormal conditions.

Moreover, MSP-Pro's multi-core computing capabilities allow for large-scale simulations to be performed efficiently in offline environments. Offline simulations can analyze performance based on pre-configured scenarios without the need for real-time data input, and they accurately replicate the system's dynamic behavior.

3.3 Offline Simulation Modules for Training and Research

Offline simulation modules are designed for on-site training and research, optimized to simulate various operational scenarios of SMRs. These modules support AI-assisted learning and real-time data analysis, enabling users to further develop expertise in their respective fields(Development of online a…). By simulating the actual behavior of the system, the offline modules can be utilized in educational and research settings, allowing users to practice under different operational conditions and enhance their understanding of complex system dynamics and control abilities.

4. Implementation

The current online/offline simulation systems are under construction, and the Full scope SMR simulator will be developed in the future once the necessary design data becomes available. The current focus of this project is to establish the development environment, build a generic PWR simulator, develop sample training modules, and create a sample big data generation system.

4.1 Development Environment Setup

The development environment provides the foundation for the online/offline simulation system based on MSP-Pro applied technology, leveraging multi-core computing resources to handle large-scale simulations efficiently. This environment is designed to be scalable for the future development of the Full scope SMR simulator and offers flexibility to accommodate different reactor designs.

4.2 Development of the Generic PWR Simulator

A generic PWR simulator is currently under development and will serve as the standard platform for nuclear power plant simulation until the SMR design is complete. The PWR simulator accurately simulates the core behavior of the reactor and supports performance verification in both static and dynamic states.

4.3 Development of Sample Training Modules

Training modules are being developed to explain key concepts and operational scenarios. These sample modules are designed for educational and training purposes within the SMR simulation environment. The aim is to enhance learning efficiency by integrating AI-based learning and real-time data analysis.

4.4 Development of the Sample Big Data Generation System

The sample big data generation system focuses on building a framework to generate and analyze data from simulation results. This system will enable the analysis of data generated from various scenarios, supporting future operational optimization and decision-making processes.

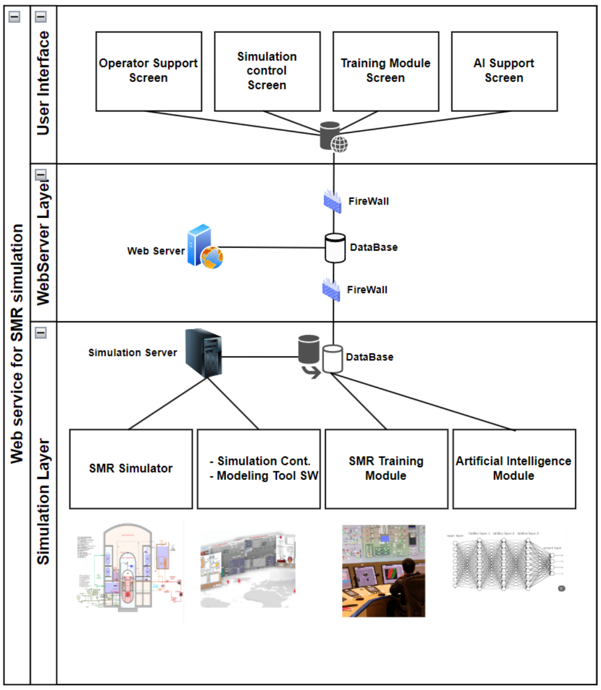

Fig. 1. Conceptual Diagram of the Development of Online and Offline Simulation Services for Small Modular Reactor (SMR)

5. Results and Discussion

5.1 Performance Analysis of the Simulation System

The online/offline simulation systems under construction have undergone a series of tests for performance validation. The generic PWR simulator was evaluated for reactor stability in static conditions, while dynamic tests focused on response times and accuracy in complex scenarios. Initial results indicate that the simulation platform can process data within expected time frames and produce accurate simulation outcomes. Notably, performance optimization in the multi-core environment has effectively supported large-scale simulation tasks.

5.2 Impact on Training and Research

The sample training modules developed thus far have received positive feedback in educational and training environments. The integration of AI-based learning has enhanced learner comprehension, and real-time data analysis features have provided a more efficient learning experience. These modules are expected to become essential tools for training future SMR operators. Moreover, the high-precision modeling of the power plant protection system will play a significant role in research and development. By accurately simulating the protection system, researchers will be able to verify the safety and efficiency of the system, providing critical data for future design optimization and operational improvements. This high-precision modeling will contribute to important safety-related research and play a crucial role in enhancing the design and operational efficiency of future nuclear power plants.

5.3 Technical Challenges and Limitations

Several technical and operational challenges have been encountered during the development process. One major constraint is the lack of design data necessary for the full implementation of the SMR simulator. Additionally, the absence of real-time data in offline environments presents a challenge for ensuring the reliability of simulation results. Potential solutions include acquiring more design data and further strengthening the data generation system to improve the credibility of the simulations.

6. Conclusion

Summary of Findings: Recap of the key findings from This study marks the initial phase in the development of a simulation system for Small Modular Reactor (SMR) technology, focusing on building the online/offline simulation system, designing a generic PWR simulator, and creating sample training modules and a big data generation framework.

The generic PWR simulator successfully replicates the static and dynamic behavior of reactors, providing a valid platform until the SMR simulator is fully developed. Additionally, the sample training modules and big data generation system have laid a solid foundation for education and research.

Notably, the high-precision modeling of the power plant protection system is expected to make significant contributions to research and development. It will allow for the evaluation of system safety and efficiency, providing critical data for future nuclear power plant design and operational optimization. These models will also serve as essential tools for enhancing the effectiveness of training and education.

Future work includes completing the Full scope SMR simulator once the necessary design data becomes available, as well as continuously expanding and improving the current development environment. Further integration of big data analysis and artificial intelligence (AI) will enhance operational optimization and system safety. Through these efforts, the commercialization and safety of SMR technology will be further strengthened.

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