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Application Methodology and Effect of Digital Twin Technology for Innovative Small Modular Reactors

Innovative Small Modular Reactors (i-SMRs) introduce fundamentally different design characteristics compared to conventional large-scale nuclear power plants, including integral reactor configurations, compact steel containment, multi-module deployment, extended fuel cycles, and flexible load-following capabilities. In particular, i-SMRs are inherently designed for multi-module operation, where coordinated control and monitoring of multiple reactor units are essential for achieving operational efficiency and safety. While these features enhance inherent safety and operational flexibility, they also introduce new challenges such as limited accessibility for instrumentation, increased system complexity, and the need for advanced monitoring and maintenance strategies.

This study proposes a systematic methodology for integrating digital twin technology into i-SMR design and operation within the framework of Industry 4.0. Unlike conventional approaches that apply digital twins primarily during operation, this study emphasizes the early adoption of digital twin concepts from the design phase to maximize lifecycle benefits. The proposed approach defines a hybrid digital twin architecture that combines physics-based high-fidelity safety analysis models with data-driven models for real-time monitoring and predictive analytics. The methodology is structured along three layers: (1) plant-level digital twin for integrated multi-module operation and load-following optimization, (2) system-level digital twin for critical systems such as reactor coolant systems and instrumentation and control (I&C), and (3) component-level digital twin for condition-based maintenance of key equipment. Special emphasis is placed on addressing i-SMR-specific constraints, including limited sensor deployment, indirect measurement environments, and the need for robust virtual sensing techniques.

The study further evaluates the expected benefits of digital twin implementation in i-SMRs. From a multi-module perspective, digital twins enable coordinated operation strategies, fleet-level optimization, and enhanced load-following performance across modules. Key outcomes include enhanced situational awareness under both normal and transient conditions, improved predictive maintenance through early fault detection, support for human-in-the-loop operation under high automation environments, and optimization of multi-module coordinated control. Moreover, early integration of digital twin technology during the design phase is expected to improve design verification, reduce uncertainties in system interactions, and support design-for-operability and maintainability. In addition, the role of digital twins in supporting licensing activities —such as verification and validation (V&V), safety analysis support, and risk-informed decision-making—is discussed, highlighting their potential to complement but not replace traditional safety analysis models.

The results suggest that digital twin technology can serve as a core enabler for achieving safe, flexible, and economically competitive operation of i-SMRs, provided that clear boundaries are established between safety-critical deterministic analyses and data-driven operational support functions. Particularly, its value is maximized when integrated from the early design stage and aligned with the requirements of multi-module operation. This work contributes to bridging the gap between advanced reactor design and Industry 4.0 technologies by providing a structured integration framework tailored to i-SMR characteristics.

Special/ Invited session

Classification

Mainly application

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i-SMR, Digital Twin

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