Real-Time Digital-Twin of Thorium-Based Molten Salt Breeder Reactor for Closed-Loop Controller
Testing Applications

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Molten Salt Breeder Reactors (MSBRs), which utilize molten fluoride salts as both fuel and coolant, are currently being researched and designed worldwide, offering inherent safety features, efficient fuel utilization, and the potential for thorium-based fuel cycles. Given the advanced development status of MSBRs, real-time emulation is essential for dynamic analysis studies, accommodating more detailed models and advanced control strategies. This paper proposes a real-time digital-twin (RTDT) based on a hardware-in-the-loop (HIL) emulation on a field-programmable gate array (FPGA) for a multi-domain two-fluid Molten Salt Breeder Reactor (MSBR) model with a designed controller for validation and testing. A nonlinear explicit numerical solution with an appropriate step-size and ordinary differential equation (ODE) solver is carried out in a non-iterative fashion to achieve the required accuracy and real-time execution. The MSBR hardware emulation and closed-loop controller tests have been implemented on the parallel hardware architecture of the FPGA in real-time for dynamic analysis and performance evaluation. The FPGA-based hardware emulation has achieved an ultra-low latency of 2.34 μs, providing a remarkable 427-fold acceleration in faster-than-real-time (FTRT) performance. The designed controller performs well under transient and steady-state operating conditions, effectively stabilizing the MSBR system under perturbations, as validated on the RTDT.

979-8-3315-8138-1