Real-Time Digital-Twin for Synergistic Interaction of SMRs and Sustainable Power Systems

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Amid the challenges of digitalization, coordination complexities, and uncertainty in integrating diverse energy sources, digital-twin technology and small modular reactors (SMRs) are increasingly emerging as cutting-edge tools and technical pathways to address these issues. Against this backdrop, this paper proposes a modular, scalable real-time digital-twin (RTDT) and surrogate physical-twin (SPT) collaborative hardware framework that predicts and responds to anomalies six times faster-than-real- time, while also addressing simulation interface issues across multiple physics modalities. The proposed system, deployed on a multi-embedded field-programmable gate arrays (FPGAs) platform, facilitates communication via the Aurora 64b/66b protocol and gigabit Ethernet based on IEEE 802.3, evaluating the impact of latency and data integrity on real-time performance. The SPT case study explores interactions among SMRs, the IEEE 39-bus system, and the CIGRE B4 DC grid with wind farms. The RTDT-SPT platform highlights the advantages of integrating next generation advanced nuclear technology, renewable energy, and digital management systems by enhancing the coordination of SMRs in primary and secondary frequency control, reactor-leading mode, and turbine-leading modes, effectively smoothing the volatility of wind power generation.

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