FPGA-Based Digital Twins for Real-Time Monitoring of Power Converters: A Review

Mridula M[1], Sree Sankar J[2], Aswani K [3]

[1] UG Scholar ,Department of ECE,NCERC,Thrissur , Kerala
[2] Assistant professor , Department of ECE,NCERC, Thrissur , Kerala
[3] Assistant professor , Department of ECE,NCERC, Thrissur , Kerala

---***---

Abstract - Power converters are critical components in modern power electronics, requiring robust real-time control to maintain stability under disturbances and random faults. Conventional cloud-based digital twins (DTs) offer advanced monitoring and analysis but face challenges such as high latency, privacy risks, and potential data loss due to large data transfers between the physical asset and the cloud. This review paper explores an edge-based alternative by implementing digital twins directly on field-programmable gate arrays (FPGAs) for real-time condition monitoring of power converters. The approach leverages FPGA's inherent parallelism, low latency, and enhanced data security to achieve effective monitoring and fault detection. Two case studies—a flyback converter and a DC-DC boost converter—illustrate the methodology. For the flyback converter, MATLAB/Simulink models were converted to HDL and deployed on FPGA to integrate PI control, PWM generation, ADC interfacing, and DT error calculation. In the boost converter, state-space modeling and discretization enabled real-time digital model execution on FPGA, while particle swarm optimization (PSO) was used to estimate health-related parameters. Comparative analysis between the DT and physical converters demonstrated close behavioral matching, low-latency performance, and the capability to detect sensor faults through error signal monitoring. The results confirm the feasibility of FPGA-based embedded DTs as a tool for smart, privacy-preserving monitoring and event detection in power electronics. However, the current implementations employ simplified models and are limited to basic voltage regulation tests. Future work aims to enhance predictive maintenance, expand diagnostic capabilities, integrate machine learning, and apply the framework to more complex converter systems. This review highlights FPGA-based DTs as a promising pathway toward intelligent, reliable, and secure power converter monitoring.

Key Words: Light Digital Twin, FPGA-based Monitoring, Power Converters, Real-Time Condition Monitoring

1.INTRODUCTION

Power converters are indispensable elements of modern energy and industrial infrastructures, enabling the conversion, conditioning, and regulation of electrical power for renewable generation, microgrids, transportation, and high-performance electronics. Their reliable operation under dynamic loads, disturbances, and aging conditions is essential for system stability and safety. Conventional monitoring and control methods, which rely on scheduled maintenance or isolated sensors, often fail to capture the real-time health and behaviour of these devices. In parallel, the concept of the digital twin (DT)—a virtual representation of a physical system updated in real time—has emerged as a transformative approach to predictive maintenance and intelligent control. Applying DT technology to power converters promises to provide continuous insight into internal states, fault precursors, and performance trends, thereby reducing downtime and enhancing efficiency.

Although cloud-hosted DT platforms offer high computational capacity and storage, they also introduce significant latency, privacy concerns, and potential data loss due to the continuous transfer of large data sets. These limitations are particularly critical in power electronic applications, where control loops operate at microsecond to millisecond timescales. Recent research, such as that surveyed in this paper, highlights the shift from centralized cloud implementations toward edge-embedded or FPGA-based DTs. Field-programmable gate arrays (FPGAs) offer massive parallelism, deterministic execution, and the ability to run control algorithms and DT models concurrently on the same hardware. By moving the DT closer to the physical asset, researchers aim to achieve low-latency monitoring, secure data handling, and higher reliability in mission-critical environments.

Beyond hardware migration, the literature shows a strong trend toward hybrid modeling strategies that combine physics-based representations with data-driven or machine-learning methods. Adaptive digital twins can track parameter variations in real time, while neural networks, optimization algorithms, and reinforcement learning enhance fault diagnosis and control performance. Hardware-in-the-loop (HIL) and power-hardware-in-the-loop (PHIL) platforms are increasingly used to validate these DTs under realistic operating conditions before deployment. This convergence of embedded hardware, hybrid modeling, and AI-driven adaptation signals a new phase of development for DTs in power electronics—one that seeks to balance model fidelity, computational cost, and real-time responsiveness.

Given the breadth and rapid growth of this research area, a systematic review of FPGA-based and edge-oriented digital twins for power converters is timely and necessary. This paper consolidates and compares recent studies ranging from FPGA-implemented DTs for transformers and DC–DC converters to hybrid simulation platforms for power system stability, reinforcement-learning-enabled twins, and FPGA-based sensing in manufacturing and renewable energy applications. By analysing their methodologies, key parameters, advantages, and limitations, the review identifies common themes and knowledge gaps—such as predictive maintenance, scalability to complex converter topologies, and integration of advanced AI models without overloading hardware resources. The resulting synthesis provides researchers and practitioners with a clearer understanding of current capabilities and future directions for real-time, embedded digital twins in power electronics.

2. LITRETURE REVIEW

Xiong et al. [1] proposed an FPGA-based digital twin platform for real-time monitoring and fault diagnosis of power electronic transformers. The study emphasizes low-latency, on-edge diagnosis to overcome delays and data-transfer issues seen in cloud-based DTs. It includes detection of open-circuit and other operational faults, providing an embedded solution for critical power systems. Their methodology integrates FPGA's parallel processing with real-time data acquisition and model execution. The work highlights how embedded DTs improve privacy, reliability, and responsiveness in power electronics applications.

Jessie et al. [2] developed a digital twin framework specifically for DC–DC converters operating under varying parameters. Their approach uses adaptive, data-driven models such as NARX and recurrent neural networks to track state variables and estimate parameters online. Optimization algorithms allow the model to adapt to changes in converter conditions, maintaining high accuracy. This work demonstrates that combining physics-based modeling with adaptive algorithms enhances the robustness of DTs for power converters. It also shows how such DTs can support real-time control and predictive diagnostics in embedded systems.

Hueros-Barrios et al. [3] presented a five-dimensional digital twin architecture for photovoltaic (PV) plant DC–DC converters. The framework integrates model validation and machine learning techniques to detect faults such as switch and diode failures. They used evaluation metrics like ROC curves and precision–recall to quantify detection performance. This hybrid approach addresses both hardware faults and sensor-related anomalies such as false data injection attacks. The study demonstrates improved fault classification accuracy and reliability in PV converter monitoring.

Han et al. [4] developed a real-time hardware-in-the-loop (HIL) platform to prototype and test digital twins of distributed energy resources (DERs). Their platform allows testing under realistic operating conditions while measuring communication jitter and latency effects on DT performance. This HIL approach enables safe, controlled evaluation of DT models before deployment. The authors show that such platforms are essential for validating real-time synchronization between physical systems and their digital counterparts. The study highlights the importance of HIL in accelerating the adoption of DTs in power systems.

Khan et al. [5] surveyed FPGA-based sensors and their role in digital manufacturing and DT applications. The review highlights FPGA's advantages for near-real-time monitoring, edge data processing, and high-speed acquisition. It identifies trends in integrating FPGA-based sensing directly into DT frameworks for improved responsiveness and reliability. The authors also discuss challenges such as resource constraints and programming complexity on FPGAs. This review reinforces the growing role of reconfigurable hardware in enabling practical DT implementations.

Song et al. [6] reviewed multi-level digital twin applications spanning components, units, plants, and grid levels in future power systems. The paper highlights the need for real-time, embedded DTs using FPGA or DSP platforms for low-latency execution. It discusses bidirectional communication requirements and interoperability challenges across hierarchical DT layers. By identifying research gaps, the review provides a roadmap for integrating DTs into complex power networks. The authors conclude that edge-deployed DTs will be crucial for the next generation of resilient power systems.

Lopez et al. [7] proposed a real-time digital twin combined with neural network clusters to identify faults in microgrid power converters. The framework leverages hardware-in-the-loop and power-hardware-in-the-loop methods to validate performance under real-time constraints. Neural networks enhance fault detection capabilities beyond conventional model-based approaches. This work shows the potential of combining AI with DTs on embedded platforms for smarter diagnostics. It also underscores the importance of scalable, real-time architectures for microgrid applications.

Abo-Khalil et al. [8] introduced a hybrid simulation platform combining physics-based and data-driven models for power system stability analysis. Their DT framework enables real-time fault prediction and energy integration assessment. This approach improves modeling accuracy and resilience compared to purely physics-based or purely data-driven methods. The platform demonstrates the feasibility of hybrid DTs for monitoring large, complex systems under varying conditions. It highlights hybrid modeling as a promising pathway to enhance DT fidelity in stability studies.

Kafkes et al. [9] developed a digital twin of a gradient magnet power supply using LSTM networks and deployed it on FPGA hardware. They integrated reinforcement learning (Deep Q-Networks) with the DT to improve closed-loop control performance. This combination allowed the system to adapt to changing conditions and optimize control policies. The study demonstrates how DTs and RL can work together to enhance accelerator system reliability. It also showcases the practicality of FPGA deployment for high-speed, intelligent control.

Lucia et al. [10] proposed using deep learning to learn model predictive control (MPC) policies offline for resonant power converters. Their setup included a hardware-in-the-loop environment with FPGA-based control implementation. The study shows the feasibility of deploying deep learning–enabled MPC on reconfigurable hardware. This approach achieves real-time performance while retaining the benefits of MPC's optimality. It highlights the early integration of AI methods into FPGA-based converter control.

Alkhateeb et al. [11] presented a vision for multi-modal, real-time digital twins in wireless environments. Although not directly focused on FPGA implementations, the framework addresses key latency and sensing challenges relevant to edge-based DTs. It outlines how continuous updates and multi-modal sensing can support emerging 6G applications. This vision paper underscores the cross-domain applicability of DT principles beyond power systems. It provides insights into real-time requirements that also influence FPGA-based DT development.

Knebel et al. [12] explored a cloud–fog computing architecture to meet real-time requirements of digital twins. Their work shows how moving computation closer to the edge can reduce latency and improve responsiveness. It directly motivates the shift toward FPGA-based edge twins for time-critical applications. The architecture also addresses scalability and hierarchical control challenges. This study bridges cloud-level analytics with edge-level execution in DT frameworks.

Bergeron et al. [13] demonstrated a Unity 3D digital twin for real-time monitoring of supercomputing systems. The work highlights advanced visualization and real-time aggregation of diverse telemetry data. While the context is high-performance computing, the principles of real-time DT visualization are applicable to power systems. It illustrates how interactive DT environments can improve user understanding and decision-making. This study expands the scope of DTs to include immersive, user-focused interfaces.

Angelova et al. [14] reviewed digital twin modeling for photovoltaic installations, including FPGA-level deployments for maximum power point (MPP) tracking and monitoring. They evaluated real-environment testing of Artix-7 FPGA-based DTs for PV panels and converters. This review highlights practical challenges and successes in implementing DTs at the hardware level. It provides valuable benchmarks for future FPGA-based DT research in renewable energy systems. The work reinforces the relevance of embedded DTs in the clean energy transition.

Tao et al. [15] provided a seminal review of digital twin technology adoption across industries. The paper outlines a taxonomy of enabling technologies, applications, and challenges, forming a conceptual foundation for FPGA-based DTs. It identifies edge computing and embedded platforms as key for time-sensitive applications. This state-of-the-art review has influenced much of the subsequent research on embedded and real-time DTs. It underscores the importance of bridging theory and practice in DT development.

3. COMPARISIONS OF VARIOUS WORKS

Across the surveyed studies, a clear progression emerges from early conceptual reviews of digital twins toward increasingly specialized, real-time and FPGA-based implementations for power electronics. Xiong et al. (2022) and Khan et al. (2024) illustrate how FPGA hardware provides low-latency, privacy-preserving monitoring for power transformers and manufacturing systems, while Knebel et al. (2020) and Song et al. (2023) motivate this edge approach by documenting the latency and scalability limitations of cloud or fog DTs. Jessie et al. (2024), Hueros-Barrios et al. (2025), Lopez et al. (2022) and Abo-Khalil et al. (2023) extend the concept to DC–DC converters, PV installations, microgrids and system-stability studies, showing that hybrid physics–data models and adaptive or neural-network methods can track parameter changes and detect hardware or sensor faults more effectively than static models. Han et al. (2022) highlight the importance of hardware-in-the-loop platforms to validate these DTs under real-time constraints before deployment, while Kafkes et al. (2021) and Lucia et al. (2018) demonstrate that combining DTs with reinforcement learning or deep-learning-based MPC further enhances control performance on reconfigurable hardware. Meanwhile, vision papers such as Alkhateeb et al. (2023), Bergeron et al. (2024) and Tao et al. (2019) broaden the scope to multi-modal sensing, immersive visualization and industrial taxonomy, pointing to future directions in predictive maintenance, AI integration and scalable multi-level DT architectures. Taken together, these works show a convergence on edge-deployed, FPGA-accelerated DTs that blend physics-based models with data-driven intelligence to deliver secure, low-latency and adaptive monitoring of complex power-electronic systems.

Table 1. Comparison of various works

Journal Ref. No.	Year	Authors (main)	Short title (or topic)	What the paper suggests / proposes
[1]	2022	J. Xiong et al.	FPGA-digital twin for power-electronic transformer	Proposes an FPGA-based digital-twin platform for real-time monitoring and fault diagnosis of power-electronic transformers (low latency, on-edge diagnosis).
[2]	2025	B. Jessie et al.	Digital Twin for DC-DC converters	Develops a DT for parameter-varying DC-DC buck converters, using data-

				driven / adaptive models (NARX/RNN style) for state estimation and online adaptation.
[3]	2025	P. J. Hueros-Barrios et al.	DT for PV plant DC-DC converter fault diagnosis	Proposes a hybrid DT + ML fault diagnosis framework for PV DC-DC converters (hardware faults + sensor FDIAs), showing detection/classification performance.
[4]	2022	J. Han et al.	Real-time HIL platform for DTs of DERs	Presents a real-time HIL prototyping & testing platform for digital twins of distributed energy resources — explores communication jitter and HIL validation.
[5]	2024	L. Khan et al.	FPGA-based sensors for digital manufacturing	Survey of FPGA-based sensing and edge processing for digital manufacturing / DTs — highlights FPGA advantages for near-real-time monitoring.
[6]	2023	Z. Song et al.	Digital twins for future power systems	Reviews multi-level DT applications in power systems, gaps, and future directions — emphasizes the need for real-time, embedded/edge DT (including FPGA/DSP options).
[7]	2022	J. R. Lopez et al.	Real-time DT + neural net clusters for microgrid converters	Proposes a real-time DT + neural-net cluster framework for fault identification in microgrid power converters; uses HIL/real-time constraints.
[8]	2023	A. G. Abo-Khalil et al.	Real-time hybrid DT simulation platform for power stability	Presents a hybrid (physics + data) DT simulation platform for power system stability and fault prediction — focuses on hybrid modeling for accurate real-time analysis.
[9]	2021	D. Kafkes et al.	DT + RL for Fermilab Booster	Builds a digital twin (LSTM) of a gradient magnet power supply and integrates FPGA deployment + RL for improved closed-loop control of accelerator power supplies.
[10]	2018	S. Lucia et al.	Deep-learning MPC for resonant power converters	Proposes learning the MPC policy offline with deep networks for resonant power converters; demonstrates feasibility of DL-based MPC and HIL/FPGA-style deployment.

[11]	2023	A. Alkhateeb et al.	Real-time DTs for 6G	Lays out a vision for real-time digital twins of wireless environments (multi-modal sensing, continuous updates) — relevant for DT latency/real-time constraints and edge implementations.
[12]	2020	F. P. Knebel et al.	Cloud-fog architecture for real-time DTs	Shows that a cloud–fog (edge) architecture can reduce latency and meet real-time DT requirements — motivates edge/FPGA twins to avoid cloud delays.
[13]	2024	W. Bergeron et al.	Supercomputer 3D DT for real-time monitoring	Demonstrates a Unity 3D digital twin for real-time monitoring of supercomputing systems — emphasizes visualization + real-time aggregation of diverse telemetry.
[14]	2024	D. D. Angelova et al.	Review: DTs for photovoltaic installations	Reviews DT modeling/implementations for PV installations (including converter DTs and FPGA-level deployments for MPP tracking / monitoring).
[15]	2019	Fei Tao, He Zhang, Ang Liu, A. Y. C. Nee	Digital Twin in industry — state-of-the-art	Seminal industry review: taxonomy, enabling technologies, applications and challenges for DT in industry (foundational background for FPGA/edge DT choices)

4. DISCUSSIONS

The reviewed literature highlights the rapid advancement of digital twin (DT) technologies for real-time monitoring of power electronic systems, with particular focus on FPGA-based implementations. Tao et al. (2019) laid the groundwork by classifying DT technologies and emphasizing edge computing and embedded platforms as key enablers for latency-sensitive applications. Building on this, Xiong et al. (2022) introduced FPGA-based DTs for power-electronic transformers, demonstrating the advantages of on-edge fault diagnosis and low-latency monitoring over traditional cloud-based DTs, which are prone to latency and privacy issues (Knebel et al., 2020). FPGA hardware emerges as a robust platform for embedded DT execution.

A major trend is the integration of hybrid and adaptive modeling techniques. Jessie et al. (2025) used NARX and recurrent neural networks for online adaptation in DC–DC converters, while Abo-Khalil et al. (2023) applied hybrid physics–data methods for power system stability prediction. Similarly, Hueros-Barrios et al. (2025) combined machine learning with DTs to detect hardware faults and false data injection attacks. These approaches underline the value of physics-based models coupled with data-driven techniques for accurate, robust, real-time fault detection.

Hardware-in-the-loop (HIL) platforms further enable real-time validation of DTs, as shown by Han et al. (2022) and Lopez et al. (2022) for microgrid and distributed energy resources, allowing assessment of communication jitter, synchronization, and neural network deployment feasibility. Future directions include multi-level DT integration, predictive maintenance, and 6G-enabled DTs (Song et al., 2023; Angelova et al., 2024). Despite progress, challenges remain in scaling to complex converter topologies, handling non-linearities, and integrating advanced AI without overloading FPGA resources, which is critical for fully deployable, intelligent DT systems in power electronics..

5. CONCLUSIONS

This review has examined the rapid evolution of digital twin technologies from conceptual frameworks toward specialized, real-time implementations on reconfigurable hardware for power electronic systems. Across the surveyed studies, a consistent pattern emerges: FPGA-based platforms offer a unique combination of parallelism, determinism, and embedded execution that directly addresses the latency, privacy, and reliability challenges inherent in cloud-hosted DTs. Researchers have demonstrated that such platforms can host both converter control loops and high-fidelity digital models concurrently, enabling immediate comparison between predicted and measured behaviour for fault diagnosis, performance assessment, and event detection. Hybrid approaches that combine physics-based Modeling with machine learning or optimization algorithms have further improved adaptability to parameter variations and the detection of subtle degradation modes, while hardware-in-the-loop validation has ensured real-time feasibility before deployment. At the same time, the literature highlights remaining challenges and opportunities. Most current implementations simplify models to fit FPGA resources and focus on limited converter types or single-fault scenarios. Scaling these techniques to multiphase converters, grid-tied systems, and complex sensor networks will require more efficient architectures and careful trade-offs between model fidelity and computational cost. Integrating predictive maintenance, reinforcement learning, and advanced AI within constrained embedded platforms represents another active frontier. Nevertheless, the collective evidence reviewed here shows that FPGA-accelerated, edge-based digital twins are moving from promising prototypes toward practical tools for intelligent, secure, and low-latency monitoring of power converters. Continued research along these lines is likely to deliver the next generation of smart, fault-aware, and self-optimizing power electronic systems.

REFERENCES

1. J. Xiong, et al., "A monitoring and diagnostics method based on FPGA-digital twin for power electronic transformer," *Electric Power Systems Research*, vol. 210, p. 108111, Sept. 2022.
2. B. Jessie, et al., "Development of digital twin for DC–DC converters under varying parameter conditions," *Electronics*, vol. 14, no. 13, p. 2549, 2025.
3. P. J. Hueros-Barrios, et al., "Digital twin approach for fault diagnosis in photovoltaic plant DC–DC converters," *Sensors*, vol. 25, no. 14, p. 4323, 2025.
4. J. Han, et al., "Real-time hardware-in-the-loop platform for digital twins of distributed energy resources," *Energies*, vol. 15, no. 11, p. 4062, 2022.
5. L. Khan, et al., "FPGA-based sensors and edge processing for digital manufacturing: A review," *Journal of Manufacturing Systems*, 2024.
6. Z. Song, et al., "Digital twins for future power systems: Challenges, applications, and research directions," *Renewable and Sustainable Energy Reviews*, vol. 174, p. 113126, 2023.
7. J. R. Lopez, et al., "A real-time digital twin and neural-net cluster-based framework for fault identification in power converters of microgrids," *Energies*, vol. 15, no. 19, p. 7306, 2022.
8. G. Abo-Khalil, et al., "Real-time hybrid digital twin simulation platform for power system stability and fault prediction," *IEEE Access*, vol. 11, pp. 136542–136556, 2023.
9. D. Kafkes, et al., "Developing robust digital twins and reinforcement learning for accelerator control systems at the Fermilab Booster," *arXiv preprint*, arXiv:2105.12847, 2021.
10. S. Lucia, et al., "Deep learning-based model predictive control for resonant power converters," *arXiv preprint*, arXiv:1810.04872, 2018.
11. Alkhateeb, et al., "Real-time digital twins for 6G wireless systems: Vision and research challenges," *IEEE Communications Magazine*, vol. 61, no. 5, pp. 86–92, 2023.
12. F. P. Knebel, et al., "Cloud–fog computing architecture for real-time digital twins," *arXiv preprint*, arXiv:2007.05625, 2020.
13. W. Bergeron, et al., "A supercomputer 3D digital twin for real-time monitoring," *arXiv preprint*, arXiv:2402.01876, 2024.
14. D. D. Angelova, et al., "Digital twin modeling for photovoltaic installations: A review," *Energies*, vol. 17, no. 6, p. 2150, 2024.
15. F. Tao, H. Zhang, A. Liu, and A. Y. C. Nee, "Digital twin in industry: State-of-the-art," *IEEE Transactions on Industrial Informatics*, vol. 15, no. 4, pp. 2405–2415, Apr. 2019.