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Abstract

The integration of AI in smart grid power electronics has transformed fault detection and predictive maintenance, enhancing operational efficiency, reliability, and resilience. Transformer-based AI models, with their advanced deep learning capabilities, offer significant advantages in processing high-dimensional, time-series data generated by IoT-driven smart grid infrastructures. These models enable real-time anomaly detection, adaptive learning, and automated decision-making, reducing downtime and optimizing energy distribution. Their deployment presents challenges, including scalability, interoperability with existing grid architectures, and cybersecurity risks. This chapter explores the role of transformer-based AI in predictive maintenance for power electronics, highlighting its potential in optimizing grid stability, minimizing operational disruptions, and improving asset lifecycle management. Additionally, the integration of AI with DERs, microgrids, and embedded power systems was examined to address the evolving demands of modern energy networks. Standardization frameworks and compliance measures for AI adoption in smart grids are also discussed, emphasizing the need for robust policy regulations and secure model deployment strategies. Future advancements in federated learning, edge AI, and quantum-enhanced transformers are expected to further revolutionize intelligent fault detection and predictive analytics in smart grid ecosystems.

Keywords: Smart Grid Power Electronics, Transformer-Based AI, Predictive Maintenance, Fault Detection, IoT-Driven Energy Systems, Distributed Energy Resources.

Introduction

The increasing complexity of modern power grids, coupled with the rapid integration of renewable energy sources and DERs, has necessitated advanced fault detection and predictive maintenance strategies [1]. Smart grids rely on power electronics, including inverters, converters, and voltage regulators, to ensure efficient energy transmission and distribution. These components are highly susceptible to failures caused by thermal stress, electrical transients, and aging-related degradation [2,3]. Traditional diagnostic methods, such as rule-based monitoring and statistical analysis, often struggle to accurately predict faults due to the nonlinear and dynamic nature of power system operations. ML techniques, including ANNs and LSTM networks, have been explored for predictive analytics but exhibit limitations in handling high-dimensional, sequential data with long-term dependencies [4]. The advent of transformer-based AI models has introduced a paradigm shift, offering superior scalability and enhanced feature extraction capabilities for fault diagnosis and predictive maintenance in power electronics [5].

Transformer-based AI models, initially developed for natural language processing (NLP), have demonstrated exceptional performance in time-series analysis, making them well-suited for power grid applications [6]. Unlike recurrent neural networks (RNNs) and CNNs, transformers leverage self-attention mechanisms to process entire sequences of data simultaneously, eliminating the need for recurrent computations [7]. This capability enables transformers to detect subtle anomalies in voltage waveforms, current harmonics, and frequency fluctuations, allowing for real-time fault prediction. Their ability to capture long-range dependencies without vanishing gradient issues makes them particularly effective in analyzing complex grid behaviors [8]. Recent advancements, including Vision Transformers (ViTs) and Time-Series Transformers (TSTs), have further expanded the applicability of these models in power electronics by enhancing the interpretability and efficiency of predictive maintenance frameworks. These models enable grid operators to identify potential failures before escalate into critical faults, ensuring improved reliability and reduced operational downtime [9-12].

The deployment of AI-driven predictive maintenance in smart grids, poses several challenges related to computational scalability, data heterogeneity, and cybersecurity vulnerabilities. Transformer-based models require extensive computational resources, limiting their direct implementation on edge devices and embedded systems with constrained processing power [13]. Strategies such as model compression, quantization, and knowledge distillation have been explored to optimize transformer architectures for real-time deployment in IoT-enabled power grids. Additionally, the integration of AI models with edge computing and federated learning allows decentralized processing of sensor data, reducing reliance on centralized cloud infrastructure while maintaining data privacy [14]. Ensuring seamless interoperability between transformer-based predictive maintenance systems and existing power management frameworks was another critical concern, requiring the development of standardized communication protocols and cross-platform compatibility solutions. Addressing these challenges was essential for the widespread adoption of AI-driven fault detection in modern energy networks [15].

Cybersecurity remains a fundamental concern in AI-enhanced smart grids, as adversarial attacks and data manipulation can compromise the accuracy of predictive maintenance models [16]. Transformer-based architectures, while highly effective in processing large-scale grid data, are vulnerable to adversarial perturbations that can mislead fault detection mechanisms. Implementing robust adversarial defense techniques, such as anomaly detection frameworks and blockchain-based data validation, can enhance the security and trustworthiness of AI-driven power electronics monitoring [17]. Compliance with regulatory frameworks, including the IEC 62443 standard for industrial cybersecurity and the NIST guidelines for AI governance, was essential to ensure secure and ethical deployment. As power grids become increasingly automated, the need for explainable AI (XAI) techniques also grows, enabling operators to interpret AI-driven decisions and maintain transparency in fault detection processes. Future research should focus on developing interpretable transformer architectures that enhance model reliability without sacrificing predictive performance [18].

The future of transformer-based AI in smart grid power electronics lies in the convergence of deep learning, neuromorphic computing, and quantum-enhanced analytics. The integration of AI with digital twins and reinforcement learning was expected to further optimize predictive maintenance strategies, allowing power grids to adapt dynamically to fluctuating energy demands and evolving grid conditions [19-22]. Additionally, hybrid AI architectures combining transformers with graph neural networks (GNNs) and spiking neural networks (SNNs) offer promising solutions for improving fault detection accuracy and computational efficiency [23]. Standardizing AI deployment frameworks and fostering interdisciplinary collaborations between energy researchers, AI scientists, and policymakers be essential to unlocking the full potential of transformer-based predictive analytics in smart grid infrastructures [24]. By addressing the existing challenges and leveraging emerging advancements, AI-driven fault detection can significantly enhance the reliability, resilience, and sustainability of modern power grids [25].