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RADemics

Silicon Carbide (SiC) and Gallium Nitride (GaN)- Based Wide Bandgap Power Electronics for High-Efficiency IoT-Integrated Grid Applications

A decorative graphic consisting of several thin, curved lines in shades of blue and grey, originating from the bottom left and extending upwards and to the right, partially overlapping the vertical bar and the main text area.

Kalangiri Manohar, S. Hariprasath
SVR Engineering College, Velalar College
of Engineering and Technology

7. Silicon Carbide (SiC) and Gallium Nitride (GaN)-Based Wide Bandgap Power Electronics for High-Efficiency IoT-Integrated Grid Applications

¹Kalangiri Manohar, Assistant Professor, Department of Electrical and Electronics Engineering, SVR Engineering College, Nandyal, Kurnool District, Andhra Pradesh, India kalangirimanoahar22@gmail.com

²S. Hariprasath, Assistant Professor, Department of Electrical and Electronics Engineering, Velalar College of Engineering and Technology, Erode, Tamil Nadu, India, hariprasaths@live.com

Abstract

The rapid evolution of power electronics, driven by Silicon Carbide (SiC) and Gallium Nitride (GaN) wide bandgap (WBG) semiconductors, has revolutionized the efficiency, reliability, and scalability of modern energy systems. The integration of these advanced power devices with the IoT and AI-driven smart grid infrastructure enables real-time monitoring, predictive analytics, and self-healing capabilities, significantly enhancing grid performance. The increasing complexity of IoT-integrated power systems presents critical challenges in data processing, cybersecurity, predictive maintenance, and system optimization. This book chapter explores cutting-edge advancements in SiC- and GaN-based power electronics, focusing on their role in high-efficiency grid applications. Key topics include AI-powered predictive maintenance for fault detection, digital twin technology for real-time performance optimization, and scalable big data analytics for enhancing grid intelligence. Additionally, AI-driven cybersecurity frameworks and self-healing mechanisms are examined to ensure the resilience of smart grid components against cyber threats and operational anomalies. The convergence of SiC and GaN power electronics with IoT and AI not only optimizes energy conversion efficiency but also fosters the development of autonomous, self-adaptive energy networks. Future research directions emphasize hybrid edge-cloud computing architectures, federated learning for decentralized intelligence, and advanced machine learning models for real-time power system optimization. The insights presented in this chapter provide a foundation for accelerating the adoption of SiC- and GaN-based power electronics in next-generation smart grids, driving the transition toward more sustainable, intelligent, and resilient energy infrastructure.

Keywords: SiC power electronics, GaN power devices, IoT-enabled smart grids, AI-driven predictive maintenance, big data analytics, cybersecurity resilience.

Introduction

The evolution of power electronics has been driven by the demand for higher efficiency, better performance, and improved reliability in energy systems [1]. Traditional silicon-based power semiconductor devices have reached their operational limits in high-power and high-frequency applications, necessitating the adoption of wide bandgap (WBG) materials such as Silicon Carbide (SiC) and Gallium Nitride (GaN) [2,3]. These advanced semiconductors offer superior electrical and thermal properties, enabling reduced switching losses, higher breakdown voltages, and enhanced thermal conductivity [4]. As a result, SiC and GaN power devices are widely adopted in renewable energy systems, electric vehicle (EV) charging stations, industrial motor drives, and high-voltage transmission networks [5]. The ability of these materials to operate at higher temperatures and switching frequencies compared to traditional silicon-based devices makes them ideal for next-generation power grids that require greater efficiency and resilience [6-8].

The integration of SiC and GaN power electronics with the IoT has further transformed modern energy systems by enabling real-time data exchange, remote monitoring, and intelligent control [9]. IoT-enabled sensors embedded within power converters, transformers, and distribution networks continuously collect operational data, allowing for real-time analysis and decision-making [10]. This connectivity enhances the efficiency of energy distribution, reduces losses, and facilitates predictive maintenance strategies that minimize downtime and operational costs. In addition, the deployment of AI in IoT-integrated power electronics enables advanced data analytics, fault detection, and self-healing mechanisms that ensure grid stability [11]. These intelligent capabilities allow smart grids to dynamically adapt to changing demand patterns, optimize power flow, and enhance system reliability [12].

IoT-integrated SiC and GaN power electronics, several challenges must be addressed to fully exploit their potential in smart grid applications. One of the primary concerns was the large volume of real-time data generated by interconnected devices, which necessitates the development of scalable and high-performance big data analytics platforms [13]. Edge computing and cloud-based architectures have emerged as essential solutions to manage, process, and analyze this data with minimal latency [14]. Edge computing facilitates localized decision-making by reducing dependency on centralized cloud servers, whereas cloud computing enables large-scale data aggregation and deep learning-based optimization strategies [15]. The synergy between these computational frameworks plays a critical role in enhancing the efficiency and responsiveness of smart grids [16].

Another major challenge in IoT-integrated power electronics was cybersecurity. As power grids become increasingly digitized, become more vulnerable to cyberattacks, including data breaches, distributed denial-of-service (DDoS) attacks, and AI-driven adversarial threats [17]. Protecting SiC and GaN-based smart grid components from cyber risks requires the implementation of AI-enhanced security frameworks, blockchain-based authentication, and encrypted communication protocols [18]. AI-driven threat detection models can analyze network traffic patterns, identify anomalies, and mitigate security breaches in real-time. Additionally, the integration of digital twins in cybersecurity strategies allows for proactive risk assessment, enabling grid operators to simulate attack scenarios and develop robust countermeasures. Strengthening the cybersecurity resilience of IoT-integrated power systems was crucial to ensuring uninterrupted energy supply and safeguarding critical infrastructure [19-21].

The role of SiC and GaN power electronics in modern energy systems extends beyond efficiency improvements to encompass sustainability, resilience, and intelligent automation [22]. The continuous advancements in AI-driven predictive maintenance, self-healing mechanisms, and big data analytics are shaping the future of power grids, making them more adaptive and autonomous [23]. The integration of hybrid edge-cloud computing architectures, federated learning models, and AI-enhanced control strategies further enhance the performance of smart grid applications [24]. As research in this field progresses, the development of standardized protocols, interoperable frameworks, and scalable security solutions be essential in accelerating the widespread adoption of IoT-enabled SiC and GaN power electronics [25]. This chapter provides an in-depth exploration of these key advancements, addressing the opportunities, challenges, and future directions in high-efficiency, intelligent power systems.