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Intelligent Control of Electric Vehicle (EV) Charging Infrastructure Using IoT-Enabled Power Electronics and V2G Technology

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15. Intelligent Control of Electric Vehicle (EV) Charging Infrastructure Using IoT-Enabled Power Electronics and V2G Technology

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Abstract

The rapid growth of EVs and the increasing integration of renewable energy sources (RES) necessitate intelligent control strategies to enhance the efficiency, reliability, and sustainability of EV charging infrastructure. IoT-enabled power electronics, combined with Vehicle-to-Grid (V2G) technology, play a pivotal role in enabling bidirectional energy flow, real-time demand-response management, and optimized charging strategies. This book chapter explores the convergence of smart grid technologies, AI-driven forecasting models, and energy storage solutions to facilitate seamless grid interaction and enhance the stability of renewable-powered EV charging networks. Digital Twin technology was introduced as a transformative approach for real-time monitoring, predictive analytics, and adaptive control, ensuring the efficient utilization of distributed renewable energy resources. The integration of hybrid renewable energy systems, supercapacitors, and AI-based load forecasting techniques further strengthens grid resilience while addressing key challenges such as energy intermittency, peak demand fluctuations, and grid congestion. The chapter also examines the role of advanced energy storage solutions, including battery management systems, in mitigating power fluctuations and improving the overall efficiency of smart EV charging networks. Cybersecurity, interoperability, and regulatory considerations for large-scale deployment are also discussed, along with future research directions for enhancing the intelligence and scalability of next-generation EV charging systems.

Keywords: Smart EV Charging, IoT-Enabled Power Electronics, Vehicle-to-Grid (V2G), Digital Twin, Renewable Energy Integration, AI-Based Load Forecasting.

Introduction

The rapid electrification of transportation and the increasing deployment of renewable energy sources (RES) are reshaping the energy landscape, necessitating the development of intelligent electric vehicle (EV) charging infrastructure [1,2]. Conventional EV charging networks primarily rely on grid-based power, which often leads to challenges such as peak demand fluctuations, grid congestion, and increased reliance on non-renewable energy sources [3]. Integrating RES such as solar and wind into EV charging infrastructure offers a sustainable solution to mitigate these

challenges. The intermittent and variable nature of renewables presents complexities in maintaining a stable and efficient charging network [4]. The adoption of intelligent control strategies, leveraging IoT-enabled power electronics and Vehicle-to-Grid (V2G) technology, was critical to optimizing energy distribution, balancing demand and supply, and enhancing the resilience of smart charging networks [5,6].

IoT-enabled power electronics facilitate real-time monitoring, predictive analytics, and automated energy management within EV charging stations [7]. These technologies enable adaptive load balancing by dynamically adjusting charging rates based on grid conditions, renewable energy availability, and user preferences [8]. The ability to collect and process vast amounts of energy-related data enhances decision-making capabilities, allowing for improved demand response strategies and more efficient utilization of distributed energy resources [9-11]. The integration of AI-driven forecasting models enables more accurate predictions of energy generation and consumption patterns, ensuring that charging infrastructure can effectively accommodate fluctuating renewable inputs while maintaining grid stability [12].

V2G technology plays a crucial role in transforming EVs from passive energy consumers into active participants in the energy ecosystem [13]. Through bidirectional energy transfer, EVs can discharge surplus energy back to the grid during peak demand periods, thereby alleviating grid stress and enhancing overall energy efficiency [14]. This capability allows for better load management, reduces dependency on conventional power generation, and fosters a decentralized energy infrastructure. Additionally, the combination of V2G and battery storage technologies optimizes energy distribution, enabling EVs to serve as mobile energy storage units that contribute to grid resilience and stability [15]. The implementation of such intelligent energy exchange mechanisms supports the long-term sustainability of EV adoption while addressing the challenges of renewable energy intermittency.

To further enhance the reliability of renewable-powered EV charging networks, the integration of hybrid renewable energy systems was essential [16]. A combination of solar PV and wind energy can provide a more stable and diversified energy supply, reducing the risk of power shortages caused by weather-related fluctuations [17]. The inclusion of advanced energy storage solutions, such as lithium-ion batteries and supercapacitors, further strengthens system reliability by mitigating power variability and ensuring uninterrupted charging services [18]. Digital twin technology was emerging as a powerful tool for real-time system monitoring, predictive maintenance, and performance optimization [19]. By creating virtual models of physical charging infrastructure, digital twins enable continuous analysis and proactive decision-making to maximize operational efficiency [20].

Several challenges remain in the widespread deployment of intelligent EV charging infrastructure. Issues such as interoperability between charging systems, cybersecurity threats, and regulatory barriers must be addressed to ensure seamless integration with existing grid infrastructure [21,22]. Standardized communication protocols, robust data security measures, and supportive policy frameworks are essential to fostering large-scale adoption [23]. Future research efforts must focus on developing scalable, cost-effective, and highly efficient charging solutions that leverage AI, IoT, and smart grid technologies [24]. By addressing these challenges, the transition toward a more intelligent and sustainable EV charging ecosystem can be accelerated, supporting global efforts to achieve decarbonization and energy resilience [25].

