

Power Electronics for Energy Transition and Renewable Energy Conversion Processes

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1. Introduction

The global energy transition has become an urgent engineering challenge rather than a distant aspiration. International commitment to carbon neutrality and the gradual reduction in fossil fuel generation have accelerated the deployment of renewable energy systems [1]. The continuous increase in installed capacity, primarily from wind and photovoltaic sources, has led to a structural transformation of electric power systems [2]. Despite this progress, the global target of tripling renewable energy capacity by 2030 remains elusive, highlighting the need for deeper technological innovation and systemic coordination [3,4].

Meanwhile, the electrification of transport and its infrastructure is advancing rapidly, creating a demand for robust charging systems [5,6]. Power electronics have become the enabling technology for this transition. It performs the conversion, control, and interconnection of heterogeneous energy sources with the electrical grid and end users [7–9]. Currently, a significant proportion of the world's electricity is produced by power converters, and it is projected that this proportion will steadily increase, reaching around 60% by 2030 [1,3,4]. This requirement has established power electronics as a key component of the electrical system [4].

However, the rapid expansion of inverter-based resources poses significant operational challenges. The displacement of traditional synchronous machines by non-synchronous renewable sources reduces system inertia and weakens frequency stability [7,8,10]. As inertia naturally buffers load and generation fluctuations, advanced control strategies are now required to emulate it, such as virtual inertia implementations, to maintain system robustness [4,9,10]. Grid-connected converters must, therefore, meet increasingly stringent standards for power quality and dynamic response to voltage disturbances. This meets the increasing requirements for efficiency, power density, and reliability in transportation, heating, and industrial electrification [4,9,11].

This Special Issue brings together recent research that addresses these challenges through advances in semiconductor technologies, converter architectures, control strategies, and system-level integration. The following sections summarize the main trends and research directions that define the current state of the field.

2. Technological Developments and Challenges

The evolution of power electronics is determined by progress in semiconductor materials, converter architectures, digital control, and system integration. These developments form an interdependent framework that defines present and future energy technologies.



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2.1. Semiconductor Devices

The transition from silicon devices to wide-bandgap (WBG) semiconductors, such as silicon carbide (SiC) and gallium nitride (GaN), represents a significant step in converter technology [4,9,12]. WBG devices enable higher switching frequencies, reduced conduction losses, and operation at elevated temperatures, resulting in higher efficiency and power density. Their use has expanded in electric vehicle chargers, renewable energy interfaces, and grid converters. Nevertheless, high device costs, packaging complexity, and the need to mitigate electromagnetic interference remain barriers to large-scale adoption. Ongoing research on ultra-wide-bandgap (UWBG) materials, including gallium oxide and diamond, promises further improvements in voltage capability for medium and high-voltage applications [9,12].

2.2. Converter Architectures and Integration

Novel converter topologies have been developed recently. Modular and impedance-source architectures offer inherent fault tolerance, single-stage voltage regulation, and flexible scalability [4]. These configurations eliminate shoot-through conditions and enable bidirectional energy transfer with simplified protection schemes [9].

Despite these advantages, the size reduction of power converters is limited by passive components. Progress in magnetic materials and capacitors limits the achievable energy density. Research therefore focuses on integrated magnetics, high-frequency cores, and three-dimensional heterogeneous packaging, in which semiconductor devices, passives, and control circuits are embedded in compact assemblies. This integration demands new design methodologies, shared manufacturing infrastructure, and standardized process models to reduce development costs and complexity [7].

2.3. Control, Digitalization, and Artificial Intelligence

Control strategies are evolving toward intelligent, adaptive, and data-driven approaches. Artificial intelligence (AI) and machine-learning algorithms support both design and operation phases [7,9,13]. During design, AI assists in topology selection, parameter optimization, and loss minimization. During operation, AI enables predictive maintenance and adaptive control, improving reliability under variable and uncertain conditions [14].

The concept of the digital twin extends these capabilities by replicating physical converters or power systems in real time, enabling virtual testing and predictive diagnostics [13]. Digital twins allow operators to validate control strategies before field deployment and optimize system behavior under dynamic grid conditions. They are becoming a fundamental component of future large-scale systems, providing the analytical foundation for autonomous, self-optimizing operations [14,15].

2.4. Grid Stability and Grid-Forming Control

As inverter-based resources replace synchronous generators, system inertia decreases and frequency stability deteriorates. Traditional grid-following converters depend on external voltage references and cannot sustain grid operation after disturbances. Grid-forming converters address this limitation by establishing their own voltage and frequency references, emulating the inertial and damping behavior of rotating machines [7,9,10].

Grid-forming (GFM) control strategies, including virtual synchronous machine control and droop-based techniques, allow converters to supply synthetic inertia and rapid frequency support. As renewable energy penetration increases, shifting from grid-following to grid-forming operation becomes necessary. Future research should focus on ensuring interoperability between multiple GFM units, scalability for extensive systems, and coordination to prevent oscillations caused by interactions [4,10].

2.5. Power Quality, Reliability, and Adaptive Operation

Maintaining power quality in inverter-dominated grids requires advanced control and filtering solutions. Active Power Filters (APFs) and multifunctional inverters integrate harmonic compensation, reactive power support, and voltage regulation into a unified system. Adaptive controllers based on resonant or predictive algorithms mitigate harmonic resonance in weak grids [4,9].

Model-reference adaptive control (MRAC) and other model-free techniques have shown strong performance under nonlinear, time-varying conditions, reducing the need for precise system identification. These approaches enable “plug-and-play” operation, in which converters can automatically adjust their parameters to maintain stability and compliance with grid codes [7,11].

Reliability at the component level is also critical. Novel topologies, such as stacked switched-capacitor (SSC) circuits for active-power decoupling, replace electrolytic capacitors with long-life film capacitors, improving lifespan and power density. Modular redundancy and intelligent fault management further increase system availability [4,11].

2.6. Power-to-X Integration

Expanding beyond grid applications, power electronics are now necessary in the interface between renewable energy and new energy carriers. In Power-to-Hydrogen and broader Power-to-X (P2X) applications, converters interface renewable energy sources with electrolyzer systems to produce green hydrogen. These applications require converter designs capable of delivering high-current, low-ripple DC power with high efficiency and reliability [16,17].

Economic analyses indicate that the Levelized Cost of Hydrogen (LCOH) is dominated by electrolyzer capital costs rather than electricity prices, making converter optimization essential for overall cost reduction [18]. Power electronics thus operate as the technological bridge between renewable electricity and chemical energy sources, supporting the development of a fully decarbonized economy [16,17].

3. Contributions of the Special Issue

The nine articles that comprise this Special Issue directly address the knowledge gaps identified in the previous section. They represent a cross-section of the critical research areas, from high-power converters to intelligent system control, as presented in Table 1, which provides a concise overview of each contribution. In the subsequent subsections, summaries of each article are provided.

Table 1. Summary of Contributions in the Special Issue.

Article Reference	Theme	Problem Addressed	Key Contribution
Rajendran et al. [19]	Wind Energy Systems	Technology scaling for multi-megawatt wind turbines (>6 MW).	Review of trends in generators and power converters (transition to medium voltage and modular multilevel converters) for large-scale turbines.
Deng et al. [20]	Power-to-Hydrogen	Integration of green hydrogen into a dense urban power system (Shenzhen).	Analysis of scenarios involving offshore wind and nuclear energy, identifying key challenges for coupling hydrogen systems with the electrical grid.

Table 1. *Cont.*

Article Reference	Theme	Problem Addressed	Key Contribution
Muñoz Díaz et al. [21]	Green Hydrogen Economics	Economic feasibility and cost optimization of green hydrogen production.	Modeling and simulation of the LCOH, identifying electrolyzer CAPEX as the dominant cost factor.
Dash & Sadhu [22]	Power Quality	Harmonic mitigation in grid-connected renewable systems.	Comprehensive review of Active Power Filter (APF) topologies, emphasizing switch-count reduction and multifunctional inverter designs for cost and size reduction.
Travieso-Torres et al. [23]	Advanced Control Systems	Control of nonlinear, time-varying renewable systems with unknown parameters.	Proposal of a Robust Cascade MRAC method that eliminates the need for linearization or parameter estimation, ensuring system stability.
Rodríguez-Benítez et al. [24]	PV System Reliability	Power pulsation and reliability issues in single-phase PV inverters.	Review of Active Power Decoupling (APD) techniques, highlighting SSC as a viable replacement for electrolytic capacitors.
Wang et al. [25]	Grid Stability (Weak Grids)	Parallel harmonic resonance in weak grids with hybrid compensation (APF + TSC).	Adaptive composite control strategy using SOGI-FLL to detect resonance and dynamically adjust damping.
Barrueto Guzmán et al. [26]	Grid Stability (Low Inertia)	Stability of interconnected, multi-area power systems with low inertia.	Stability analysis demonstrating that decentralized synthetic inertia control maintains global stability.
Loulijat et al. [27]	System Reliability (Faults)	DFIG vulnerability during balanced voltage dips (LVRT capability).	Modified Protection Scheme that prevents rotor-side converter disconnection during faults, maintaining power control and improving DFIG performance.

3.1. Converters, Stability, and Resilience

As renewable power plants increase in capacity to replace conventional power stations, specific challenges emerge related to high-power hardware and system stability. Three articles in this Special Issue address these aspects in the context of large-scale wind farms.

- The work of Rajendran et al. [19] presents a detailed review of the state of the art in multi-megawatt wind turbines. Their analysis identifies a consistent industrial trend toward Permanent Magnet Synchronous Generators (PMSGs) combined with full-scale power converters. The study emphasizes the ongoing transition to medium-voltage converters, particularly Modular Multilevel Converters (MMCs), as the preferred architecture for managing power levels exceeding 15 MW. This hardware evolution is essential for ensuring the efficient and reliable scaling of offshore and onshore wind generation.
- Barrueto Guzmán et al. [26] presents a study related to the increasing prevalence of inverter-based generation. This paper extends beyond single-area analyzes by considering the dynamics of a two-area interconnected system. Simulation demonstrates that decentralized synthetic inertia control, optimized for each local area, maintains global system stability even under varying interconnection strengths. This result provides important insight for transmission system operators, showing that modular inertia control schemes can preserve grid stability while supporting grid-forming converter operation.

- Loulijat et al. [27] focus on improving the Low-Voltage Ride-Through (LVRT) capability of Doubly-Fed Induction Generator (DFIGs), a widely used configuration. The authors propose an MPS that enhances traditional crowbar approaches. The main contribution is the ability of the generator to retain control of power flow during grid faults without disconnecting the rotor-side converter. This feature enables the continuous provision of grid-supporting services during voltage disturbances, thereby improving the resilience and grid value of DFIG-based wind farms.

3.2. Power Quality and Grid Intelligence

The transition toward an inverter-dominated grid demands greater intelligence and adaptability in control systems to ensure power quality and stability. Three articles in this Special Issue address these aspects in the context of inverter-dominated grids:

- Dash and Sadhu [22] present a paper in the field of power quality and APFs. Their analysis highlights the trend of integrating filtering capabilities into renewable energy inverters, enabling the development of multifunctional inverters. Emphasis is placed on converter topologies with reduced component counts, addressing the industrial demand for cost-effective, high-power-density solutions that meet the stringent harmonic distortion requirements set by modern grid codes.
- Wang et al. [25] study the phenomenon of parallel harmonic resonance, which is commonly found in weak grids. This condition occurs when APFs operate in conjunction with reactive power compensation devices, such as Thyristor-Switched Capacitors (TSCs), forming a resonant circuit that may be excited by nonlinear load harmonics. The authors propose an adaptive control method based on a Second-Order Generalized Integrator–Frequency-Locked Loop that identifies resonance conditions in real time and dynamically adjusts a virtual damping loop. This approach exemplifies intelligent control strategies that respond to evolving grid dynamics, aligning with the current research direction toward adaptive and resilient converter control.
- Travieso-Torres et al. [23] extend this adaptive control paradigm through a cascade MRAC scheme. The method can regulate nonlinear and time-varying systems without requiring precise modeling or detailed parameter knowledge. This contribution represents a critical step toward autonomous, or “plug-and-play,” renewable generation units capable of connecting to the grid and self-tuning for stable operation. This concept embodies the emerging *AI for Power* framework, in which controllers learn and adapt to system behavior, thereby enhancing reliability and performance in complex grid environments.

3.3. Power System and New Energy Vectors

Recent innovations in power electronics include advances in component design and new energy models. The Special Issue contributions covering these topics are detailed below:

- Rodríguez-Benítez et al. [24] present a comprehensive review on APD, addressing a key reliability issue in single-phase inverters that are widely used in residential photovoltaic systems. The inherent power pulsation at twice the grid frequency in these converters requires large electrolytic capacitors in the DC link, which are typically the weakest link in terms of lifetime. Their analysis emphasizes that architectures based on SSCs can effectively substitute these components with long-life film capacitors, increasing both power density and system durability.
- Deng et al. [20] and Muñoz Díaz et al. [21] explore the connection between power electronics and the emerging P2X framework. The work of Deng et al. [20] examines this concept within the dense urban context of Shenzhen, modeling scenarios for

green hydrogen production from renewable and nuclear energy sources. Their study demonstrates that power electronic converters act as a technological bridge linking the electric grid with the industrial and transportation sectors, enabling the conversion of electrical energy into chemical fuels.

- The study by Muñoz Díaz et al. [21] considers a P2X techno-economic analysis by estimating the LCOH. Their results indicate that capital expenditure (CAPEX) for electrolyzers currently exerts a stronger influence on hydrogen costs than the electricity price under power purchase agreements (PPAs). This conclusion provides an important guideline for policy and investment decisions, highlighting that innovation efforts must prioritize cost reduction in electrolyzer technologies.

4. Conclusions

Power electronics is the fundamental technology driving the global energy transition. Its influence spans renewable energy production, grid integration, electric vehicles, and hydrogen generation. The research featured in this Special Issue underscores the advancement and scope of power electronics, highlighting the significant link between semiconductor science, control theory, and systems engineering.

Advancements in the future rely on ongoing cooperation between academia and industry to create dependable, innovative, and affordable power-conversion technologies. The editors acknowledge the authors and reviewers for their valuable contributions, which collectively pave the way toward a future of secure and sustainable energy.

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