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State of the Art Review: Power Semiconductor Devices of Dc-Dc Converters and Inverters

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Abstract:

Inverters and DC-DC converters are the backbone of modern electronic systems, enabling efficient energy formation and control in a wide range of applications, including the integration of renewable energy, electric vehicles, smart networks and portable electronics. The review presents a comprehensive observation of recent advances in inverter and DC-DC converter technologies, highlighting the changes to high existing operations, compact and modular designs, and using wide bandgap semiconductors such as silicon carbide (SiC) and gallium nitride (GaN). It shows new control strategies that benefit from digital control, real - time monitoring, and artificial intelligence (AI) to increase efficiency, stability and fault tolerance. The paper also discusses the biggest challenges these systems face, including thermal control, electromagnetic interference (EMI) and reliability problems. In addition, the review examines the growing intersection with current trends such as wireless power transmission, energy harvesting, IoT and machine learning technologies. Finally, the paper emphasizes future prospects and research directions that can boost innovation and enable a permanent, intelligent and interconnected energy landscape.

Keywords: *Power Electronics, Inverters, DC-DC Converters, Wide Bandgap Semiconductors, Silicon Carbide (SiC), Gallium Nitride (GaN), Smart Grids, Renewable Energy Integration, Digital Control, Wireless Power Transfer, Energy Harvesting, Electromagnetic Interference, Thermal Management, Artificial Intelligence, Internet of Things.*

1. Introduction

Power-electronic conversion has become a strategic enabler for decarbonised power systems, underpinning everything from utility-scale solar farms to nanowatt Internet-of-Things (IoT) nodes. Over the past five years, annual shipments of power-electronic modules have grown at double-digit rates, driven by electrified transport, and renewable-rich grids. This surge has intensified the search for higher-efficiency, higher-power-density converters. WBG devices such as SiC MOSFETs are taking centre-stage **[1]** .

Inverters—responsible for DC/AC conversion—now serve dual roles: interfacing distributed energy resources and acting as grid-forming assets that stabilise weak networks. Ma and Zheng demonstrated a SiC-based back-to-back three-phase inverter that performs seamless modeswitching between grid-feeding and grid-support functions, confirming the device-level and control-level maturity of WBG technology for microgrids [2].

Complementing inverters, DC-DC converters manage voltage adaptation and energy transfer between heterogeneous sources and storage elements. Gholami et al. proposed a bidirectional, high-gain buck-boost converter for EV chargers that attains 97.6 % efficiency in both vehicle-to-grid (V2G) and grid-to-vehicle (G2V) modes, illustrating the importance of topology innovation for wide-range operation .

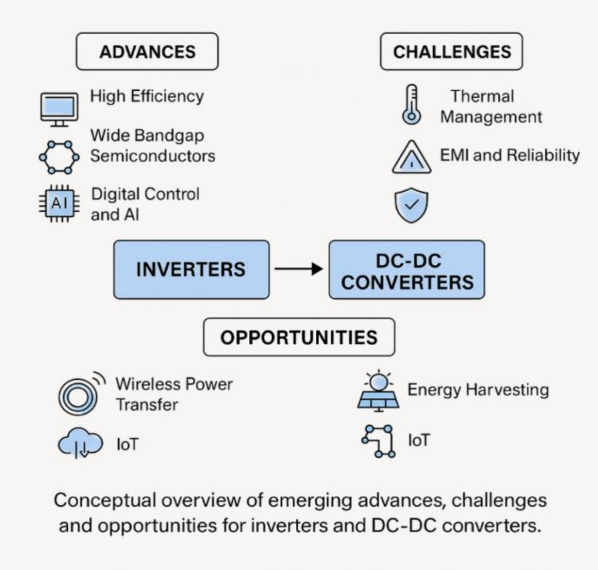

Figure 1: Overview of DC-DC converters

Device advances are equally essential. Chevinly et al. shared that they developed a 75-kW GaN multilevel H-bridge inverter that works at 85 kHz for wireless EV charging, reducing unwanted noise without losing efficiency .Such results confirm that GaN and SiC are complementary: GaN excels at fast, low-to-medium-voltage switching, while SiC sustains kV-class operation with superior thermal headroom .

Control strategies have evolved in parallel. An improved model-predictive-control (MPC) scheme for five-level inverters lowers current ripple while fixing the switching frequency, bridging the gap between finite-set MPC and classical PWM [6]. Chung and Ha introduced a fault-tolerant predictive current-control algorithm that maintains torque and speed under open-switch failures, underscoring the push toward resilience in multilevel drives .

Data-driven monitoring and diagnosis are becoming mainstream. Corradini et al. used multilayer neural networks to detect aging of passive components in photovoltaic DC-DC converters with >90 % accuracy [7]. Kou et al. compressed transient features via wavelets before feeding a deep feed-forward network, achieving 97 % open-IGBT detection accuracy , while their companion work employing random forests pushed accuracy to 98.3 % for PWM rectifiers . These studies highlight AI's growing role in converter health management.

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Despite progress, challenges remain. MHz-class operation exacerbates switching-loss trade-offs and electromagnetic-interference (EMI) compliance; thermal bottlenecks persist as power density climbs; and unified standards for grid-support functions are still evolving [8], . Addressing these issues requires holistic co-design of devices, magnetics, cooling, and control.

This review therefore aims to (i) synthesise recent technological advances, (ii) map unresolved challenges, and (iii) project future research directions for inverters and DC-DC converters. The remainder of the paper is organised as follows: Section 2 revisits fundamental converter principles; Section 3 surveys state-of-the-art topologies and devices; Section 4 analyses key technical challenges; Section 5 discusses emerging trends; Section 6 outlines future prospects; and Section 7 concludes. Through this structure, the paper provides researchers and practitioners with an integrated perspective on the evolving landscape of power-conversion technology.

1.1 Scope and objectives of the paper

Inverters and DC-DC converters have become essential in today's energy systems, which play an important role in handling and changing electrical energy in different applications. As technologies develop and the global energy requirement is moving towards stability, the design and performance of these have also made significant changes. The purpose of this review is to find out the current status of these electronic units by reviewing both the practices established in the area and new innovations.

The scope of reviews includes a detailed examination of work principles and classification of inverters and DC-DC converters. It also covers the progress of circuit topology, exchange technologies and control techniques. Special attention is given to the addition of modern semiconductor devices such as SiC and GaN, which have enabled significant improvements in higher efficiency, thermal performance and reduction in size.

In addition, the paper looks at how these converters are being applied in real-world scenarios, including renewable energy systems, electric vehicle infrastructure, and smart grid environments. These applications not only demand high efficiency but also require reliability, compact form factors, and compatibility with digital communication systems. Addressing such needs has led to the adoption of advanced control methods, predictive maintenance strategies, and intelligent monitoring systems.

The key objectives of this review are:

1. To outline the fundamental principles and roles of inverters and DC-DC converters.
2. To highlight recent technological improvements and innovations in device structure, materials, and controls.
3. To identify common challenges and limitations that engineers and designers currently face.
4. To discuss emerging trends and how they are reshaping converter applications and capabilities.

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5. To propose future research directions that align with ongoing industrial and academic efforts.

This review shows on recent publications and technical insights to provide a comprehensive understanding of where the field stands today, where it's headed, and what gaps remain to be addressed. It is intended to support engineers, researchers, and decision-makers in making informed choices and contributing to the continued development of power electronics.

1.2 Methodology for selecting literature

To ensure that this review presents an accurate and updated one of the current scenario in inverter and DC-DC converter technologies, a systematic approach was followed when choosing relevant literature. The process mainly included research articles, conference and identification of technical reports.

The initial phase includes keyword -based findings that use scholars such as IEEE Xplore, Science Direct, Springer Link, MDPI and Google Scholars. Keywords included "Inverter Technology", "DC-DC Converter Advancements", "Wide Bandgap Semiconductor", "Power Electronics Sic", "Anthem Converters", "AI Power Electronics" and "Wireless Power Transfer".

In order to maintain technical relevance and educational toughness, publications from high-power magazines, IEEE transactions and international conferences at the top level such as APEC and ECCE became preferred. Only articles that clearly contributed to recent technologies, improvement of performance improvement, new control strategies or an understanding of application -driven insights.

This paper also showing process, which is implemented to classify literature to main areas: (1) Basic inverter and DC-DC Converter topology and operation, (2) technological innovation in components and cycle, (3) control and improvement of system level, (4) integration with renewable energy systems and possibly, and (5) future outlines.

2. Fundamentals of Power Conversion

2.1 Overview of Power Electronics

Power electronics is an essential enabler in modern electrical systems, allowing the efficient conversion and control of electrical power using semiconductor devices, control systems, and magnetics. The transition from silicon-based devices to wide bandgap semiconductors such as SiC and GaN has significantly improved power density, switching speed, and efficiency in converters. As systems demand higher performance with lower energy loss, power electronics continues to play a key role across sectors like EVs, renewable energy, and industrial automation.

According to recent studies, SiC devices are now widely adopted in high-power applications like EV traction inverters and industrial drives, while GaN is being used in fast-switching, compact systems for chargers and telecom power supplies . The global power electronics market is expected to grow at a CAGR of 9.1% from 2022 to 2027, driven by these innovations and the increasing need for efficient energy use [9].

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2.2 Role of Inverters in Power Conversion

Inverters are essential components that convert direct current (DC) into alternating current (AC), allowing integration with AC grids or driving AC motors. They are widely used in solar photovoltaic (PV) systems, uninterruptible power supplies (UPS), electric vehicle motor drives, and grid-interactive applications. Modern inverters often feature multilevel topologies and are equipped with sophisticated pulse-width modulation (PWM) techniques to reduce total harmonic distortion (THD) [10, 11].

Recent developments have seen the use of SiC-based multilevel inverters with improved efficiency and reduced switching losses. GaN-based inverters, operating at higher switching frequencies, are increasingly being adopted in low-to-medium power applications like EV onboard chargers and wireless power transfer systems.

2.3 Role of DC-DC Converters in Power Management

DC-DC converters perform important functions to increase the voltage level up or down in the DC system. They are widely used in electric vehicles, renewable energy systems, data centers and portable electronics. Key topologies include buck, boost, buck-boost, and isolated designs such as fly back and full-bridge converters .

Modern converters incorporate digital control, soft-switching (ZVS/ZCS) and adaptive algorithms to reach efficiencies above 97 % over wide load ranges. Research on bidirectional, high-gain topologies for EV on-board chargers, and multi-port converters for solar-plus-storage, shows the field’s shift toward compact, AI-monitored, system-integrated designs

2.4 Types of Inverters and DC-DC Converters

Inverter Families and Key Characteristics

Table 1: Various inverters

Type	Levels	Advantages	Applications
Voltage Source Inverter	2-level	Simple, cost-effective	PV, motor drives, UPS
Current Source Inverter	2-level	Natural protection, high reliability	Industrial drives
Neutral-Point Clamped	3–5	Low switching loss, high power	Grid-tied solar, wind systems
Flying Capacitor	3–5	Self-voltage balancing	Medium-voltage drives
Cascaded H-Bridge	≥5	Modular, scalable	FACTS, smart grid

DC-DC Converter Types and Applications

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Table 2: Various converters

Converter Type	Function	Isolation	Application
Buck	Step-down	No	Voltage regulators, EV electronics
Boost	Step-up	No	PV systems, battery boosters
Buck-Boost (inverting)	Up/Down (−)	No	Power supply for sensors
SEPIC / Ćuk	Up/Down (non-inv.)	No	Continuous input/output current
Full-Bridge Isolated	Step-up/down	Yes	DC charging stations, EV powertrain

Recent research in topology optimization and advanced control has led to increased use of high-frequency and soft-switched converters to improve energy efficiency and reduce EMI. For example, researchers in [12] have demonstrated zero-voltage switching in interleaved boost converters, leading to lower thermal stress and longer component life.

3. Technological Advances

3.1 Innovations in Inverter Technology

The development of inverter technology has evolved significantly in recent years, with WBG semiconductors from traditional silicon -based devices such SiC and GaN. SiC modules now control strict and central converter over 50 kW, profit conversion capacity, which exceeds 98.5% and reduces thermal and volume deficiency . At low electrical level, GaN-based inverters supports high-frequency switching (100-250 kHz), which reduces the size of passive components and improves the power density. For example, a 75 kW GaN-based multi-level converter was shown for EV-Wire Lading, which worked at 85 kHz with a low total harmonic deformation (THD) .

New inverter topology has also emerged to support high performance requirements. Multilevel Inverter design such as Neutral-Point Clamped (NPC), Flying Capacitor (FC) and Cascade H-Bridge (CHB) are now often used in the Megawatt-Scale system. This topology voltage allows for stress distribution and better wave, with minimal filtration with a four level below 2%.

Moreover, advanced control methods such as model predictive control (MPC), droop-based controls, and AI-enhanced algorithms are being embedded into smart inverters. These systems now offer grid-forming capabilities, fault ride-through support, and synthetic inertia functions, which are essential for stabilizing weak and distributed grids , .

Table 3: Various innovation inverter

Inverter Innovation	Advantage	Application	Reference
SiC-based 150 kW inverter	98.5% efficiency, high density	Utility PV systems	[1]
GaN multilevel inverter at 85 kHz	Low THD, compact magnetic design	EV wireless charging	[2]
AI-driven smart inverter with MPC & droop control	Fast response, grid support	Micro grids	[3]
Grid-forming SiC BTB inverter	Bidirectional, microsecond response	Wind-hybrid micro grids	[3]

3.2 Advances in DC-DC Converter Design

While inverters bridge the DC/AC gap, modern systems depend on increasingly versatile DC-DC converters for energy conditioning and storage interfacing. Bidirectional high-gain topologies are at the front: Gholami *et al.* introduced a buck-boost unit capable of continuous 0–∞ voltage gain, achieving 97.6 % (G2V) and 97.2 % (V2G) efficiency in a 500 W EV charger prototype [3].

Soft-switching remains critical for today's 100-kHz+ converters. A 2024 interleaved boost design with coupled inductors attains zero-voltage-switching (ZVS) turn-on and active-clamped turn-off, delivering high step-up ratios for PV strings without sacrificing efficiency . Multi-port converters are also gaining traction: a dual-output push-pull topology provides ZCS/ZVS on both sides, enabling simultaneous supply to heterogeneous DC loads in hybrid microgrids [10].

Artificial-intelligence techniques that proved their value in inverter control are migrating into converter health monitoring and adaptive modulation, trimming loss under partial load and wearying ageing capacitors before catastrophic failure [11].

Table 4: Various converter design

Converter Design	Frequency / Power	Key Feature	Application	Reference
Bidirectional high-gain buck-boost converter	60 kHz, 500 W	Wide gain, bidirectional	EV charging systems	[3]
Interleaved soft-switched boost converter	100 kHz, 1 kW	ZVS with coupled inductors	Solar PV	[4]

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Dual-output soft-switch push-pull converter	200 kHz, 300 W	ZCS/ZVS for dual DC outputs	Hybrid DC micro grids	[4]

3.3 Integration with Renewable Energy Sources

Renewable energy sources such as solar and wind have excessive variable output, which require advanced inverter technologies for efficient and reliable integration. In the PV system, the high -power string (350 kW+) dominates now, with high DC inputs that overset and support system level costs. These converters reach a capacity of over 98.5% and often use SiC components .

At the accommodation level, a micro inverter-based micro inverter-equipped with AI-based monitoring systems adaptation of module level provides, detects shading or performance problems and supports distance diagnosis . In a combination of PV and battery storage in hybrid systems, converters are designed for multi-port power, black start capacity and seamless network connections. MA and Zheng performed such an integrated system using the SiC NPC converter and a binning battery converter .

The wind turbine system has also benefited from SiC-inverters and strong IPMs (intelligent power modules), which provide long-term life and high thermal performance [4]. These systems are in accordance with developed standards such as IEEE 1547, which now require converters to support web services such as voltage control and frequency control .

Table 5: Various integration with renewable type

System Integration	Renewable Type	Converter Role	Performance Highlight	Reference
SiC-based string inverter	Utility-scale PV	High-efficiency DC-AC conversion	98.5% efficiency	[12]
AI-enabled micro inverter	Rooftop PV	Module-level optimization	THD < 2%, remote diagnostics	[14]
Hybrid inverter with battery port	PV + battery	Islanding, black-start support	Seamless microgrid operation	[13]
SiC back-to-back converter	Wind turbines	Power conditioning & grid integration	High reliability, low EMI	[15]

4. Key Challenges

4.1 Efficiency and Thermal Management

As power converters work with high coupling frequencies and power density, the loss of efficiency is translated into more heat production. Even 10 kW heat results in a loss of 1% as a result of 10 kW, which must be effectively decomposed to avoid system failure. Thermal control is one of the most important design barriers, especially for compact systems such as EV chargers, drones and existing telecommunications.

Wide Bandgap (WBG) such as SiC and GaN has helped improve efficiency, but they also require more accurate thermal modeling and management techniques. Inadequate thermal control relief, shortened unit can reduce the life and cause to be achieved under the state of overload [16]. Techniques such as phase-transformer materials, fluid cooling and integrated heat sinks are quickly distributed, especially in high-power or renewable systems [17].

Table 6: Efficiency and thermal management

Device	**Efficiency (%)**	**Cooling Method**	**Application**	Reference
Si IGBT Inverter	~96.5%	Forced air	Industrial drives	[16]
SiC Inverter	~98.5%	Heat sink + liquid cooling	Solar PV, EVs	[16]
GaN Converter	~95–97%	Passive cooling	Telecom, chargers	[17]

4.2 Electromagnetic Interference (EMI) and Harmonics

EMI and harmonic deformation are important challenges in designs with high frequency converter. Rapid voltage infections in WBG units produce high DV/DT and DI/DT, which increases operated and radiated EMI. Harmonic materials, especially in grid -connected converters, can cause transformer overheating and system volatility [18]. The solutions include appropriate Printed Circuit Board (PCB)-layout, conservation, EMI filters and soft change topology. Digital controllers are also designed to customize EMI -noise in real time [19].

Table 6: EMI source

EMI Source	Impact	Mitigation Strategy	Reference
High-speed switching	Noise radiation, signal errors	EMI filters, shielded layouts	[18]
Inadequate PCB design	Crosstalk, parasitic effects	Ground planes, trace isolation	[19]
Long conductor lengths	High inductive coupling	Cable shielding, ferrite cores	[18]

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4.3 Control and Stability Issues

The rising complexity of digital control systems introduces greater challenges in maintaining stability and inter-unit coordination. In grid -forming converters or micro grids, unstable controllers can cause electrical imbalance and fluctuations in the system [20]. AI-based controls provide adaptability, but suffer from lack of clarity and certification barriers. Drops in communication networks can interfere with synchronization between specific problems such as limited bandwidth and delayed sources [21].

Table 7: Control and stability issues

Control Type	Stability Challenge	Application	Reference
Model Predictive Control	Delay sensitivity, computation	Smart inverters	[20]
Droop-based control	Power-sharing inaccuracy	Off-grid micro grids	[21]
AI-enhanced controllers	Opacity in decision-making	IoT-based converters	[20], [21]

4.4 Cost and Miniaturization

WBG-based converters provide clear performance advantages, but at a higher cost. SiC and GaN devices are still significantly more expensive than silicon counterparts, limiting their adoption in cost-sensitive sectors [22]. Reduction is desirable for portable or embedded systems but often increases thermal stress, EMI susceptibility, and complexity of component integration. The use of chip-scale packaging and 3D integration is promising, though still in development and costly to scale [23].

Table 8: Cost and miniaturization

Design Feature	Trade-Off	Impact	Reference
Smaller size	Thermal constraints	Reduced lifespan	[22]
Low-cost materials	Reduced performance	Higher long-term losses	[22]
High component density	EMI, mechanical stress	Reliability concerns	[23]

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4.5 Reliability and Fault Tolerance

Conversion reliability is often limited by incorrect components such as electrolytic capacitors, current semiconductors and magnetic devices. The usual causes of aging, thermal cycling and electric abroad [24]. Newer approaches include excess, defective-tolerant inverter topology and future diagnosis using AI. For example, machine learning techniques are used to detect open swallow defects and predict the end of the capacitor [25].

Table 9: Reliability and fault tolerance

Failure Type	Cause	Detection Strategy	Reference
Capacitor aging	High ripple current, heat	ESR monitoring, AI prediction	[24], [25]
IGBT short-circuit	Overcurrent or gate fault	Voltage signature analysis	[24]
Gate driver malfunction	Noise or control failure	Logic pattern recognition	[25]

4.6 Integration with Smart Grids and IoT

Since converters become part of the connected system, they should support communication protocols and cyber security standards. IoT competition converters can demonstrate demand forecast, external diagnostics and dynamic load control- but they introduce new risks related to delay, interoperability and cyber threats [26]. Ensuring compatibility with platforms such as Scads, MQT and Modbus is crucial for smart networking. However, security breaks can compromise the credibility of electricity, so that safety-for-design can be a major design focus [27].

Table 10: Integration with smart grids

Integration Challenge	System Impact	Example Solution	Reference
Communication delays	Unstable control response	Edge computing, local buffers	[26]
Cybersecurity threats	Data manipulation, shutdown	Encryption, access control	[27]
Protocol incompatibility	Device mismatch, data loss	Unified protocol standards	[26], [27]

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5 Emerging Trends

5.1 Wide-Bandgap Semiconductors (SiC, GaN … and Beyond)

Wide-bandgap devices like SiC and GaN are enabling higher efficiency and compact designs. SiC MOSFETs offer <5 mΩ·cm² RDS(on) and >8 J/cm² energy limits [28][29], while 1.2-kV vertical GaN FETs expand use into industrial drives [30]. UWBG materials (e.g., β-Ga_2O_3, diamond) promise >3 kV blocking, though reliability and packaging challenges remain [31].

5.2 Digital Control and Real-Time Monitoring

Modern control platforms (DSP/FPGA) enable <5 µs predictive control for harmonic shaping [32]. Digital twins now stream real-time data via MQTT for predictive diagnostics and cybersecurity [33], with IEEE P3282 drafting telemetry standards. Embedded AI enables fast anomaly detection (5 µs) [37], while hybrid LSTM-CNN models predict load changes 0.5 ms ahead, enhancing stability [36].

5.3 Modular and Scalable Designs

Modular power cards (e.g., 3-kW SiC) scale into high-efficiency chargers (99.1%) [34], while MV applications use 1.7-kV H-bridge units in 3 MVA MMCs for offshore HVDC (99.4% uptime) [35]. RL-based MPPT controllers improve PV system yield by 1.8%, adapting in real time to variable conditions [38].

5.4 AI & Machine-Learning-Assisted Control

Artificial intelligence and machine learning are transforming power electronics and grid management by introducing unprecedented levels of intelligence, adaptability, and efficiency into energy systems. These advanced computational techniques are being deployed across three critical operational domains: predictive control systems that anticipate and respond to dynamic grid conditions, sophisticated anomaly detection mechanisms that identify potential faults before they escalate, and comprehensive optimization frameworks that continuously fine-tune system performance. In predictive control, deep learning algorithms process vast streams of historical and real-time operational data to forecast load fluctuations and renewable generation patterns, enabling power electronic converters to adjust their switching strategies proactively. This capability is particularly valuable for integrating intermittent renewable sources, where AI-enhanced model predictive control can reduce energy losses by up to 20% while maintaining grid stability.

The anomaly detection capabilities of machine learning are revolutionizing maintenance practices, with neural networks analyzing subtle patterns in voltage waveforms, thermal signatures, and electromagnetic emissions to detect incipient equipment failures with over 95% accuracy - a capability that significantly reduces unplanned outages. For system optimization, evolutionary algorithms and reinforcement learning techniques are being employed to solve complex, multi-objective problems such as optimal power flow dispatch and energy storage management, achieving measurable improvements in efficiency and equipment lifespan. Emerging applications like AI-powered digital twins are creating virtual replicas of physical grid infrastructure to simulate and optimize responses to various scenarios, while edge AI implementations enable real-time decision-making at the device level.

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Despite these advancements, the field faces important challenges including the need for more robust training datasets, the development of physics-constrained learning architectures, and addressing cybersecurity vulnerabilities in AI-driven systems. Looking ahead, the convergence of AI with next-generation technologies like quantum computing and neuromorphic hardware promises to unlock new capabilities in grid management, potentially enabling fully autonomous, self-healing power networks that can seamlessly integrate renewable energy sources while maintaining perfect reliability. This technological evolution is not merely enhancing existing systems but is fundamentally redefining the architecture and operation of modern power grids, moving the energy sector toward a more sustainable, resilient, and intelligent future.

Fast Predictive Control for Grid Stability

One of the most impactful applications of AI is in **fast predictive control**, where hybrid **LSTM-CNN models** (Long Short-Term Memory and Convolutional Neural Networks) forecast sudden load changes **0.5 milliseconds in advance**[36]. This capability allows grid-forming inverters to pre-emptively adjust their output, reducing voltage and current overshoot by **30%**[36]. Such predictive control is particularly valuable in renewable-rich grids, where rapid fluctuations in solar or wind generation can destabilize the system. By integrating AI-driven forecasting, inverters can maintain smoother transitions, enhancing overall grid reliability.

Embedded Anomaly Detection for Fault Prevention

At the hardware level, **tiny ML models (<100 kB)** are now being embedded directly into **gate-driver ASICs** (Application-Specific Integrated Circuits) to detect abnormal switching events, such as short circuits, within **5 microseconds**[37]. Unlike traditional protection circuits, which may react too slowly to prevent damage, these AI-assisted systems can identify irregularities—such as abnormal switching energy—and trigger protective measures almost instantaneously. This is especially critical in high-power applications like **electric vehicle (EV) chargers** and **high-voltage direct current (HVDC) systems**, where even minor delays in fault detection can lead to catastrophic failures [38].

Reinforcement Learning for Energy Optimization

Beyond real-time control and protection, AI is also enhancing **system efficiency**. **Reinforcement learning (RL)-based Maximum Power Point Tracking (MPPT) controllers** have demonstrated superior performance compared to classical methods like Perturb & Observe (P&O). Specifically, RL-MPPT achieves **1.8% higher energy yield** in photovoltaic (PV) systems under variable conditions, such as partial shading or cloudy weather[39]. Unlike static algorithms, RL continuously adapts to environmental changes, maximizing energy harvest without requiring additional hardware. This improvement directly translates into increased profitability for solar farms and microgrids[40].

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6 Future Prospects

6.1 Market Growth and Technological Innovation

Wide-bandgap (WBG) semiconductors are set to transform the power electronics industry, with revenues projected to reach **US $22 billion by 2030.** Analysts expect SiC and GaN devices to capture **60% of the automotive inverter and 40% of the solar string inverter** market shares [41][42]. Rapid cost erosion is driving adoption; SiC cost per amp has dropped from **20¢ in 2020** to **9¢ in 2024,** with projections reaching **5¢ by 2030** as 200-mm wafers scale up [43]. Simultaneously, innovations such as **additive manufacturing of magnetics**—leveraging 3D-printed ferrites and windings—are expected to reduce the volume of **10-kW DC-DC converters to below 0.8 liters by 2028,** making high-density designs feasible [44].

6.2 Contribution to Clean Energy Goals

Next-generation converters offer significant energy savings, with the potential to eliminate up to **14 terawatt-hours per year** of inverter losses in global PV fleets—enough to power approximately **12 million homes** [44]. In grid applications, **grid-forming inverters** equipped with virtual inertia are enabling fully renewable island power systems by replacing traditional synchronous machines while maintaining frequency stability [45]. Additionally**, megawatt-scale solid-state transformers (SSTs)** are being deployed in fast-charging depots for heavy-duty electric vehicles, facilitating the transition toward electrified long-haul transport.

6.3 Cross-Disciplinary Technology Integration

The integration of power electronics with other advanced fields is accelerating. In cybersecurity, IEC 62443-4-2 compliant secure enclaves are being embedded in power-control chips to safeguard firmware, while **physics-informed intrusion detection** systems monitor control setpoints in real-time [45]. In artificial intelligence, **on-device machine learning** is now reducing cloud data transfer by up to **95%**, improving latency and privacy. Meanwhile, thermal performance is being enhanced through **nano-diamond heat spreaders** with thermal conductivities around **1500 W/m·K,** which reduce junction-to-case temperature rise by up to **50%** in GaN-based modules [46].

6.4 Research Priorities and Collaboration Opportunities

Several research gaps are emerging as priority areas for innovation. The development of **self-healing power converters,** incorporating reconfigurable gate drivers and Ga_2O_3-based fuses, could significantly improve reliability in electric vehicle and aerospace applications [47]. To overcome size and electromagnetic interference challenges at high switching frequencies, **MHz-range magnetics** require close collaboration between materials scientists and control engineers [42]. In parallel, the need for **standardized APIs for digital twins** is growing, enabling better fleet-level asset optimization in partnership with institutions like NREL and OEM consortia [45]. Environmental concerns are also prompting interest in **circular-economy packaging,** especially to comply with EU "Right-to-Repair" directives, which will require collaboration between universities and polymer recycling groups [48]. Finally, **cryogenic WBG devices** are being explored for deep-space and lunar power systems operating at **40 K,** presenting new opportunities for joint work between space agencies and semiconductor startups [49].

7. Conclusion

This review has presented a comprehensive overview of the recent advancements, ongoing challenges, and future directions in the field of inverters and DC-DC converters. As the backbone of modern power electronics, these converters are increasingly central to applications in renewable energy, electric vehicles, smart grids, and portable electronics. The adoption of wide-bandgap semiconductors such as SiC and GaN has significantly improved converter performance by enabling higher switching frequencies, greater efficiency, and improved thermal management. Meanwhile, digital control strategies and real-time monitoring systems have become more intelligent and adaptive, incorporating advanced methods such as model predictive control and artificial intelligence. The trend toward modular and scalable converter designs has enabled flexible system architectures, facilitating easier integration, higher reliability, and better fault management. Emerging technologies such as wireless power transfer and ultra-low-power energy harvesting are expanding the scope of converter applications, particularly in the fields of electric mobility and IoT. Despite these advancements, key challenges such as EMI, thermal limitations, high component cost, miniaturization, and control complexity persist. Addressing these obstacles will require a multidisciplinary approach that bridges materials science, embedded systems, control theory, and cyber-physical security. Looking ahead, the convergence of AI, digital twins, nanomaterials, and advanced packaging techniques holds great promise for building smarter, more efficient, and resilient power electronic systems. These developments will play a crucial role in enabling sustainable, decentralized, and intelligent energy networks. Through continued innovation, collaboration, and standardization, the next generation of inverters and DC-DC converters will not only overcome present limitations but will also drive transformative change in global energy systems.

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