Multi-level DC–DC Converters for High-Voltage EV Battery Packs

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ABSTRACT

The increasing adoption of electric vehicles (EVs) has highlighted the need for efficient, reliable, and compact power conversion solutions capable of handling high-voltage battery packs. Multi-level DC–DC converters have emerged as a promising approach for enhancing voltage conversion efficiency, reducing electromagnetic interference (EMI), and improving overall system reliability. This paper reviews recent developments in multi-level DC–DC converter topologies, design strategies, and control methodologies specifically tailored for high-voltage EV battery applications. Key aspects such as modular design, soft-switching techniques, and fault-tolerant architectures are discussed. Comparative analysis with traditional two-level converters demonstrates the advantages of multi-level approaches in terms of efficiency, voltage stress distribution, and scalability. Finally, challenges and future research directions for next-generation EV power electronics are highlighted.

KEYWORDS: *DC–DC converter, multi-level topology, electric vehicle, high-voltage battery, power electronics, soft switching, modular converters.*

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INTRODUCTION

Electric vehicles (EVs) are rapidly transforming the transportation sector, driven by environmental concerns, government incentives, and advances in battery technology. High-voltage battery packs, typically ranging from 400 V to 800 V, are essential for achieving higher driving ranges and power outputs. Efficient power conversion between the battery and the vehicle's traction system is crucial for minimizing energy losses and maintaining battery health.

Traditional two-level DC–DC converters face limitations in high-voltage applications, including high voltage stress on switches, increased EMI, and reduced efficiency. Multi-level converters, originally developed for high-voltage AC systems, are now gaining attention in DC applications due to their ability to handle high voltage in a modular and scalable manner.
This paper reviews multi-level DC–DC converter topologies suitable for EV battery packs, focusing on design considerations, control strategies, and performance metrics.

OVERVIEW OF DC–DC CONVERTERS IN ELECTRIC VEHICLES

DC–DC converters play a critical role in modern electric vehicles (EVs) by ensuring efficient energy transfer between the high-voltage battery packs, the traction motor, and auxiliary systems. The primary function of a DC–DC converter is to regulate voltage levels to meet the specific requirements of different vehicle subsystems while minimizing energy losses. The efficiency, reliability, and compactness of DC–DC converters directly impact the overall performance, range, and lifetime of an EV.

High-voltage EV battery packs typically operate between 400 V and 800 V, with next-generation systems exceeding 1000 V for high-performance vehicles. However, various vehicle components such as electric motors, power inverters, onboard chargers, and low-voltage electronics require different voltage levels. This voltage mismatch necessitates the use of DC–DC converters for voltage step-up, step-down, and stabilization.

DC–DC converters in EVs generally serve three major purposes:

1. Traction DC–DC Conversion

Traction systems are the primary consumers of high-voltage energy in EVs. The electric motor inverter requires a stable and regulated DC voltage for efficient operation. Traction DC–DC

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converters are responsible for either stepping down or stepping up the battery voltage to match the requirements of the motor drive system.

For example:

- A 800 V battery pack may need to be converted to 400 V for a specific motor inverter designed for mid-voltage operation.
- Conversely, step-up conversion may be required in systems where multiple motor stages are used in series.

Key design considerations for traction DC–DC converters include:

- **High power handling**: Typical traction converters handle power levels from 20 kW to over 200 kW.
- **Fast dynamic response**: The converter must quickly adapt to acceleration, regenerative braking, and transient load changes.
- **Low losses**: High efficiency (>95%) is essential to maximize driving range.

Modern high-voltage traction converters often employ multi-level topologies, such as cascaded H-bridge or flying-capacitor converters, to reduce voltage stress on semiconductors, minimize EMI, and improve reliability.

2.2 Auxiliary DC–DC Conversion

While the traction system dominates energy consumption, EVs also contain a variety of low-voltage subsystems that require stable power. These include lighting, infotainment, climate control, sensors, and the vehicle control unit (VCU). Auxiliary DC–DC converters step down the high-voltage battery output (400–800 V) to conventional low-voltage levels, typically 12 V or 48 V, used by these components.

Key features of auxiliary converters include:

- **Isolation**: To ensure safety and protect low-voltage electronics from high-voltage battery faults.
- **Compact design**: Due to space constraints within the vehicle.
- **High reliability**: These systems operate continuously, even when the vehicle is stationary.

In modern EV architectures, a 48 V auxiliary system is gaining popularity due to higher power requirements for electric turbochargers, active suspensions, and advanced driver-assistance

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systems (ADAS). This trend requires DC–DC converters capable of efficiently stepping down from 400–800 V to 48 V with minimal losses.

3. Bidirectional Operation for Regenerative Braking and Vehicle-to-Grid (V2G)

Advanced DC–DC converters in EVs often support **bidirectional operation**, allowing energy to flow both from the battery to the load and from the regenerative source back to the battery. This capability is essential for:

1. **Regenerative braking**: During braking, the motor acts as a generator, converting kinetic energy back into electrical energy. Bidirectional DC–DC converters ensure this recovered energy is efficiently stored in the high-voltage battery.
2. **Vehicle-to-grid (V2G) applications**: Bidirectional converters enable energy transfer from the vehicle to the grid during peak demand, providing grid stabilization and potential economic benefits for EV owners.

Bidirectional converters require careful design to maintain high efficiency in both power flow directions and to ensure smooth transitions between motoring and regenerative modes. Multi-level converter topologies and wide-bandgap semiconductors (SiC, GaN) are increasingly used to reduce switching losses and improve performance in these applications.

4. Emerging Trends in EV DC–DC Conversion

Recent advances in EV power electronics include:

- **High-voltage, high-power multi-level converters**: Reducing voltage stress on components and increasing modularity.
- **Integration with battery management systems (BMS)**: Enabling more precise control over charging, discharging, and balancing.
- **Soft-switching and resonant techniques**: Enhancing efficiency at high frequencies while reducing EMI.
- **Compact and lightweight designs**: Using advanced packaging, liquid cooling, and wide-bandgap devices for better thermal performance.

These trends demonstrate that DC–DC converters are no longer simple voltage regulators but central components of energy management systems in EVs.

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Figure 1 illustrates a simplified EV powertrain with multi-level DC–DC conversion stages.

Converter Type	Input Voltage	Output Voltage	Typical Efficiency	Application
Two-level Buck	400–800 V	12–48 V	92–95%	Auxiliary power
Multi-level Boost	400–800 V	800–1200 V	96–98%	Traction inverter
Modular Half-Bridge	400–800 V	400–800 V	97%	Bidirectional EV charger

MULTI-LEVEL DC–DC CONVERTER TOPOLOGIES

Multi-level DC–DC converters have emerged as a key technology for high-voltage electric vehicle (EV) battery packs due to their ability to **divide a high voltage into multiple smaller voltage levels**. This voltage division offers several benefits:

- **Reduced voltage stress on semiconductor devices** – enabling the use of lower-voltage MOSFETs or IGBTs with faster switching speeds.
- **Lower electromagnetic interference (EMI)** – since each switch operates at a fraction of the total voltage.
- **Improved efficiency and reliability** – by allowing modular design and distributing thermal load among multiple components.

Multi-level topologies can be classified based on their structure and method of voltage level generation. The most commonly used topologies in EV DC–DC applications include **Cascaded H-Bridge (CHB), Neutral-Point Clamped (NPC), and Flying Capacitor (FC) converters**.

1. Cascaded H-Bridge (CHB) Converter

The Cascaded H-Bridge topology consists of multiple H-bridge modules connected in series at the output. Each module can operate at a lower DC voltage level, and the combined output voltage is the sum of all individual module outputs.

Structure and Operation:

- Each H-bridge cell has four switches arranged in an H configuration.
- By controlling the switches, each cell can output positive, negative, or zero voltage.

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- Multiple cells connected in series allow the output voltage to reach high levels while keeping individual switch voltage stress low.

Advantages:

- **Modularity:** Cells can be added or removed to scale voltage levels according to battery pack requirements.
- **Reduced voltage stress on switches:** Each switch only sees a fraction of the total voltage, allowing smaller, faster, and lower-cost semiconductors.
- **High efficiency at partial load:** CHB converters maintain efficiency over a wide load range due to independent module operation.
- **Ease of fault tolerance:** Faulty cells can sometimes be bypassed without shutting down the entire system.

Challenges:

- **Complex control for voltage balancing:** Each module must maintain equal voltage contribution to prevent overvoltage stress.
- **Increased component count:** More switches and drivers increase the complexity, weight, and cost.
- **Synchronization requirements:** Precise timing is required to ensure proper waveform generation and reduce harmonics.

Applications: CHB converters are ideal for high-voltage traction applications in EVs (400–800 V or higher) where modularity, scalability, and efficiency are critical.

2. Neutral-Point Clamped (NPC) DC–DC Converter

The Neutral-Point Clamped topology, also known as a diode-clamped converter, uses **clamping diodes** to create multiple voltage levels at the output. Unlike CHB, NPC converters do not require fully independent H-bridge modules but use a central neutral point to generate three or more levels.

Structure and Operation:

- NPC converters typically use three-level (or higher-level) designs.

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- Diodes connected to the neutral point allow the voltage across each switch to be limited to half (or a fraction) of the total DC-link voltage.
- Switching patterns determine which voltage level appears at the output.

Advantages:

- **Low EMI:** Reduced voltage steps lead to smoother output waveforms, decreasing electromagnetic interference.
- **Soft-switching compatibility:** NPC designs can integrate resonant or zero-voltage-switching techniques to minimize switching losses.
- **High efficiency:** Particularly effective at moderate to high power levels.

Challenges:

- **Diode voltage balancing issues:** Unequal currents in clamping diodes can lead to overvoltage stress on certain switches.
- **Limited scalability:** Unlike modular CHB converters, NPC designs are less flexible for very high-voltage applications.
- **Complex gate drive design:** Requires precise control of switches and clamping diodes for correct operation.

Applications: NPC converters are widely used in medium-to-high voltage EV traction systems and fast-charging DC–DC converters, where efficiency and reduced EMI are prioritized.

3. Flying Capacitor (FC) Converter

Flying Capacitor converters generate multiple voltage levels by storing intermediate voltages on capacitors. Unlike CHB, FC converters do **not require series-connected modules**, but instead rely on capacitor voltage division to achieve multi-level operation.

Structure and Operation:

- Each stage has capacitors connected in series with switches.
- By selectively connecting capacitors to the output through switches, multiple voltage levels are synthesized.
- Capacitor voltages must be actively controlled to maintain the desired level and waveform quality.

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Advantages:

- **High-quality voltage waveform:** FC converters produce smooth voltage steps with low ripple, reducing filtering requirements.
- **Flexibility in level selection:** Adding more capacitors increases the number of voltage levels without major structural changes.
- **Reduces voltage stress:** Switches only handle a fraction of the total output voltage.

Challenges:

- **Complex capacitor voltage balancing:** Requires precise control algorithms to prevent overcharging or discharging of individual capacitors.
- **Higher component count:** Capacitors and switches increase system complexity, weight, and cost.
- **Thermal management issues:** Multiple capacitors generate localized heating and require careful thermal design.

Applications: FC converters are suitable for high-voltage EV battery packs, particularly in bidirectional converters for V2G applications, regenerative braking, and high-performance auxiliary DC–DC stages.

DESIGN CONSIDERATIONS FOR HIGH-VOLTAGE EV BATTERY PACKS

Designing multi-level DC–DC converters for high-voltage EV battery packs is a complex task that involves **balancing efficiency, reliability, thermal performance, and electromagnetic compatibility**. Unlike low-voltage converters, high-voltage EV applications introduce unique challenges due to high energy density, safety requirements, and the need for long-term reliability. The following design considerations are critical for achieving optimal performance.

1. Voltage Stress Distribution

High-voltage battery packs, ranging from 400 V to over 800 V in modern EVs, impose significant stress on semiconductor devices such as MOSFETs, IGBTs, and diodes. In traditional two-level converters, each switch must withstand the full bus voltage, which limits the choice of devices and increases switching losses.

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Multi-level converter design mitigates this challenge by dividing the total voltage across multiple switches or modules:

- **Cascaded H-Bridge (CHB) Converters:** Each H-bridge module operates at a fraction of the total voltage, reducing stress on individual switches.
- **Neutral-Point Clamped (NPC) Converters:** Clamping diodes split voltage across switches, preventing overvoltage conditions.
- **Flying Capacitor (FC) Converters:** Capacitor voltage levels are controlled to ensure each switch sees only a portion of the total voltage.

Proper voltage distribution improves **device reliability**, allows the use of **faster low-voltage semiconductors**, and reduces the risk of **electrical breakdown**. Designers must also account for voltage transients during switching and load variations to prevent overstressing switches or capacitors.

2. Efficiency Optimization

Efficiency is a critical parameter in EV applications, as any energy loss directly reduces driving range and increases thermal load. The main contributors to losses in multi-level converters are **switching losses** (due to turning devices on and off) and **conduction losses** (due to current flowing through resistive components).

Several techniques can improve efficiency:

1. **Soft-Switching Techniques:**
- Methods like Zero Voltage Switching (ZVS) and Zero Current Switching (ZCS) reduce switching losses by ensuring that devices switch when voltage or current is near zero.
- Particularly effective in high-frequency multi-level converters where hard switching would generate excessive losses.
2. **Synchronous Rectification:**
- Replacing diodes with actively controlled MOSFETs in the rectification stage reduces forward voltage drops and conduction losses.
3. **Resonant Converters:**
- Resonant topologies allow energy to oscillate between inductive and capacitive elements, minimizing overlap between voltage and current during switching events.
4. **High-Frequency Operation:**

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- Higher switching frequencies allow smaller passive components (inductors and capacitors), reducing overall size and weight. However, frequency must be optimized to avoid excessive switching losses or EMI.

Overall, careful selection of semiconductor devices, switching strategies, and control algorithms ensures **high efficiency (>95%)** across varying load conditions.

3. Thermal Management

High-voltage multi-level converters operate at **high power densities**, often exceeding 20 kW per module in EV traction applications. Without proper thermal management, devices can overheat, reducing efficiency and shortening lifespan.

Common thermal management strategies include:

1. **Heatsinks:**
- Aluminum or copper heatsinks attached to semiconductor devices conduct heat away from the junctions.
2. **Liquid Cooling:**
- High-power modules often integrate liquid-cooled cold plates or channels for uniform temperature distribution.
3. **Integrated Thermal Interfaces:**
- Thermal pads, gap fillers, or phase-change materials enhance heat transfer between devices and heat sinks or enclosures.
4. **Thermal Modeling:**
- Designers simulate temperature distribution using finite-element analysis (FEA) to predict hot spots and optimize cooling paths.

Proper thermal design ensures **reliable operation**, prevents thermal runaway, and allows higher power density without compromising device lifetime.

4. Electromagnetic Interference (EMI) Mitigation

Fast-switching multi-level converters can generate **high-frequency EMI**, which may interfere with vehicle electronics, sensors, and communication systems. EMI mitigation is therefore a key design consideration.

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Common solutions include:

1. **Multi-Level PWM (Pulse Width Modulation):**

- Spreads voltage transitions across multiple levels to reduce sharp voltage changes and high-frequency harmonics.

2. **Snubber Circuits:**

- RC, RCD, or active snubbers absorb voltage spikes caused by parasitic inductances during switching events.

3. **PCB Layout and Grounding Techniques:**

- Proper separation of power and signal grounds, short trace lengths, and shielding reduce EMI coupling.

4. **Filter Design:**

- Input/output LC or LCL filters suppress conducted EMI on power lines.

By combining multi-level topologies with **careful switching control and layout optimization**, EMI can be reduced without significantly affecting efficiency or cost.

CONTROL STRATEGIES

Multi-level DC–DC converters require sophisticated control algorithms for stable operation, voltage balancing, and dynamic response.

1. Pulse Width Modulation (PWM)

- **Phase-shifted PWM:** Reduces output ripple and EMI.
- **Multilevel PWM:** Controls individual levels for balanced voltage distribution.

2. Model Predictive Control (MPC)

MPC predicts future states of the converter and selects optimal switch positions to maintain voltage levels and minimize losses.

3. Voltage Balancing Techniques

For CHB and FC converters, voltage balancing between modules/capacitors is critical. Methods include:

- Passive balancing resistors.
- Active capacitor switching.
- Digital controllers for predictive balancing.

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FAULT-TOLERANT AND MODULAR ARCHITECTURES

EV reliability requires fault-tolerant converter designs. Strategies include:

- **Redundant modules:** Extra H-bridge cells that can take over in case of failure.
- **Hot-swappable modules:** Allow maintenance without shutting down the entire system.
- **Adaptive control:** Reconfigures converter topology in real time under fault conditions.

Comparative Analysis

Parameter	Two-Level Converter	Multi-Level Converter	Remarks
Voltage Stress	High	Low	Multi-level reduces stress per switch
EMI	High	Low	Smaller voltage steps
Efficiency	92–95%	96–98%	Soft-switching improves efficiency
Scalability	Limited	High	Modular design allows expansion
Cost	Low	Moderate	More components, higher cost

APPLICATIONS IN HIGH-VOLTAGE EVS

- **Traction inverters:** Multi-level DC–DC converters provide stable high-voltage input to the motor.
- **Vehicle-to-Grid (V2G):** Bidirectional converters enable energy exchange with the grid.
- **Fast charging stations:** Multi-level converters step up or step down voltage efficiently for fast charging.

CHALLENGES AND FUTURE DIRECTIONS

Despite their advantages, multi-level DC–DC converters face challenges:

- High component count increases complexity and cost.
- Voltage/capacitor balancing remains a design challenge.
- Integration with battery management systems (BMS) requires advanced control.
- Future research includes wide-bandgap semiconductors (SiC, GaN), higher switching frequencies, and AI-based predictive control.

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CONCLUSION

Multi-level DC–DC converters offer significant advantages for high-voltage EV battery packs, including improved efficiency, reduced voltage stress, and scalability. Among the topologies, CHB, NPC, and FC converters show promise in modular and fault-tolerant designs. Control strategies such as PWM, MPC, and active balancing are crucial for reliable operation. While challenges remain in cost, complexity, and integration, advancements in wide-bandgap semiconductors and intelligent control algorithms are expected to drive the adoption of multi-level converters in next-generation EVs.

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