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A Comprehensive Review of DC-DC Converter Topologies and Control Compensation for Battery Charging Applications

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Abstract—The exponential growth of energy storage systems and electric mobility requires highly efficient, reliable, and power- dense battery charging infrastructure. Central to these systems is the DC-DC converter, which must accommodate wide battery voltage variations across different states of charge (SOC). This review paper systematically categorizes and evaluates advanced DC-DC converter topologies utilized in battery chargers, rang- ing from fundamental non-isolated architectures (Buck, Boost, Buck-Boost) and high-order networks (SEPIC, Cuk, Zeta) to galvanically isolated systems (Flyback, Forward, Push-Pull, DAB, and LLC Resonant). Furthermore, this paper provides a rig- orous mathematical analysis of closed-loop control challenges, specifically addressing the destabilizing Right-Half-Plane (RHP) zero prevalent in continuous conduction mode (CCM). By syn- thesizing compensation techniques, topological tradeoffs, and power-transfer mathematics, this review establishes a definitive framework for optimizing modern battery charging systems.

Index Terms—Battery Charger, DC-DC Converter, Dual Active Bridge (DAB), LLC Resonant, SEPIC, Cuk, Flyback, Continuous Conduction Mode (CCM), Loop Compensation, Right-Half-Plane (RHP) Zero.

I. Introduction

As the global energy paradigm shifts toward sustainable storage and electrified transportation, the engineering of high-performance battery charging systems has become a critical focal point of power electronics research **[1]**. Batteries present a highly dynamic and unique electrical load. Unlike standard resistive loads, a battery pack's terminal voltage varies significantly depending on its specific chemistry, internal temperature, and State of Charge (SOC).

To ensure longevity and safety, lithium-ion and other advanced battery chemistries mandate a strict Constant Current / Constant Voltage (CC-CV) charging profile. During the deeply discharged state, the charger must provide a heavily regulated constant current (CC), allowing the voltage to gradually rise. Once a predefined threshold is reached, the system must seamlessly transition to a constant voltage (CV) mode, allowing the current to taper off to zero **[2]**. To interface these variable-voltage storage units safely with fixed DC buses or active power factor correction (PFC) front-ends, DC-DC converters must offer dynamic voltage scaling, high bidirectional efficiency, and minimal current ripple to prevent thermal degradation of the cells.

While early charging systems relied on simple phase-controlled rectifiers or linear regulators, modern high-power demands strictly necessitate switched-mode power supplies (SMPS). This paper presents a comprehensive comparative analysis of thirteen distinct SMPS topologies. It divides them into non-isolated configurations—suitable for low-to-medium power onboard charging—and isolated configurations mandated for high-power, off-board fast charging. Additionally, the critical dynamic control requirements, specifically the mitigation of the Right-Half-Plane (RHP) zero using Type II and Type III compensation networks, are mathematically detailed to provide a complete system-level overview.

II. Non-Isolated Topologies for Battery Charging

Non-isolated topologies are predominantly preferred for onboard EV chargers and localized low-voltage applications due to their drastically reduced component count, cost-effectiveness, and superior volumetric power density.

A. Fundamental Architectures

1. Buck Converter: The buck converter operates strictly as a step-down topology. Assuming ideal components in Continuous Conduction Mode (CCM), its voltage gain is directly proportional to the duty cycle (D):

$$V_{out} = D \cdot V_{in} \tag{1}$$

Its primary advantage in battery charging is the inherently continuous output current, which is heavily filtered by the series output inductor (Fig. 1). This makes it exceptionally suited for the Constant Current (CC) charging phase, minimizing thermal stress on the battery cells. However, its inability to charge a battery pack if the source voltage drops below the terminal voltage severely limits its versatility.

2. Boost Converter: Conversely, the boost converter steps up the input voltage, governed by the ideal CCM gain equation:

$$V_{out} = \frac{V_{in}}{1 - D} \tag{2}$$

While it draws a continuous input current—making it an excellent candidate for grid-side active Power Factor Correction (PFC)—its output current is inherently discontinuous

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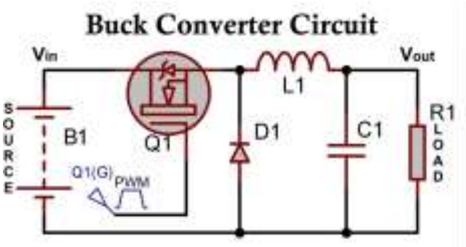

Fig. 1. Standard Buck Converter topology for step-down CC charging.

(Fig. 2). Pumping highly pulsed current directly into a battery accelerates internal chemical degradation; therefore, the boost topology necessitates substantial output capacitive filtering **[3]**.

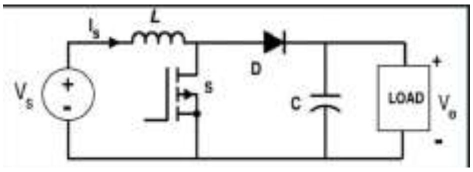

Fig. 2. Standard Boost Converter topology.

3. Traditional Buck-Boost Converter: This topology offers versatile step-up and step-down capabilities by inverting the output polarity. Its CCM gain is given by:

$$V_{out} = -\frac{D}{1-D}V_{in} \tag{3}$$

While highly flexible (Fig. 3), the traditional single-inductor buck-boost suffers from discontinuous currents at both terminals. More critically, the active switch must withstand a peak voltage stress equal to the sum of the input and output voltages ($V_{in} + V_{out}$), making it unsuitable for high-power EV applications without significant over-rating of semiconductor devices **[4]**.

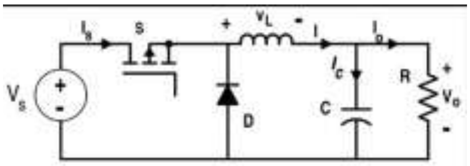

Fig. 3. Traditional Bidirectional Buck-Boost Converter.

B. Advanced Buck-Boost Derivatives

4. Cascaded Buck-Boost: To mitigate the extreme component stress of the traditional architecture, the cascaded topology decouples the buck and boost stages using a shared central inductor and four active switches (Fig. 4). By operating only the necessary switches for step-up or step-down modes, RMS current stress is drastically reduced. Furthermore, the inductor current ripple (ΔI_L) is decreased by a factor of $(1 - D)$ during step-down operation, enabling a significant reduction in magnetic core volume **[5]**.

5. Interleaved Multiphase Buck-Boost: For ultra-high-power fast charging, multiple buck-boost phases are paralleled and operated with a phase shift of $360^{\circ}/N$, where N is the number of active phases (Fig. 5). This topological advancement achieves active ripple cancellation at both the input and output nodes. The resulting near-zero ripple current maximizes battery lifespan and significantly reduces the volumetric footprint of passive filtering components **[6]**.

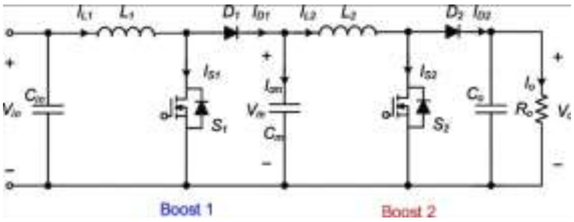

Fig. 4. Cascaded Buck-Boost Converter featuring decoupled hardware stages.

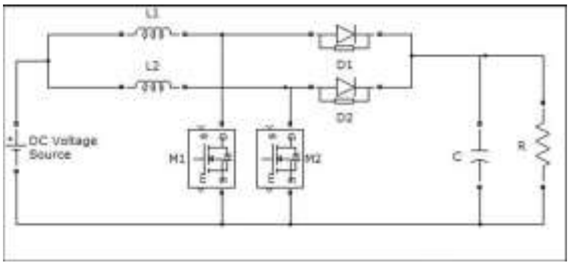

Fig. 5. Multiphase Interleaved Buck-Boost Converter for active ripple cancellation.

C. High-Order Topologies

High-order topologies utilize multiple inductors and intermediate transfer capacitors to improve waveform quality, ensuring continuous energy flow.

6. SEPIC Converter: The Single-Ended Primary-Inductor Converter utilizes an intermediate coupling capacitor to provide non-inverted buck-boost functionality (Fig. 6). Its continuous input current minimizes electromagnetic interference (EMI), making it a preferred topology for solar Maximum Power Point Tracking (MPPT) chargers. However, the coupling capacitor must withstand high RMS currents, posing a thermal design challenge at elevated power levels **[7]**.

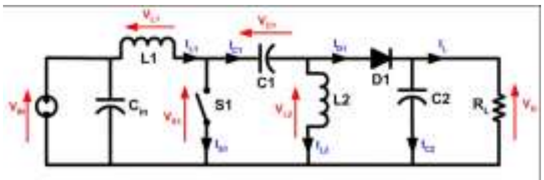

Fig. 6. SEPIC Converter topology with intermediate coupling capacitor.

7. Cuk Converter: Operating similarly to the SEPIC but yielding an inverted output, the Cuk converter is distinguished by its continuous current at both the input and output terminals (Fig. 7). This dual-continuous nature provides near-zero ripple charging, which is optimal for extending battery cycle life, albeit at the cost of a higher component count and complex control dynamics **[8]**.

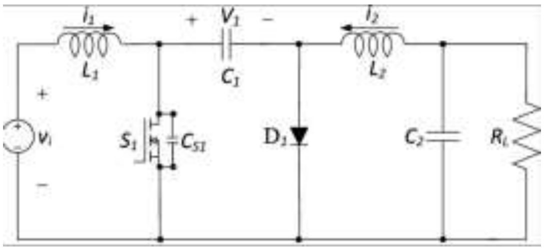

Fig. 7. Cuk Converter topology for dual-continuous current.

8. Zeta Converter: The Zeta converter is a high-order topology that delivers a non-inverted output (Fig. 8). Because its output current is continuous, it behaves similarly to a buck converter but retains bidirectional voltage scaling capabilities. This makes it highly effective for the precise Constant Voltage (CV) finishing phase of battery charging.

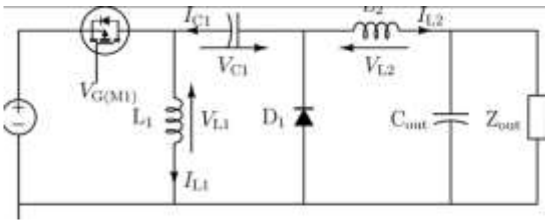

Fig. 8. Zeta Converter topology for continuous output current.

III. Isolated Topologies for Battery Charging

Galvanic isolation, achieved via high-frequency magnetic transformers, is a strict safety mandate for off-board fast chargers and Vehicle-to-Grid (V2G) systems to protect users and isolate grid-side faults from the vehicle chassis.

A. Basic Isolated Architectures

9. Flyback Converter: Derived from the traditional buck-boost, the isolated flyback converter replaces the standard inductor with a mutually coupled inductor (transformer). It is highly cost-effective and structurally simple (Fig. 9), making it ideal for low-power auxiliary charging (< 150W). However, uncoupled leakage inductance induces severe voltage spikes on the primary switch, necessitating dissipative snubber circuits that limit overall efficiency **[9]**.

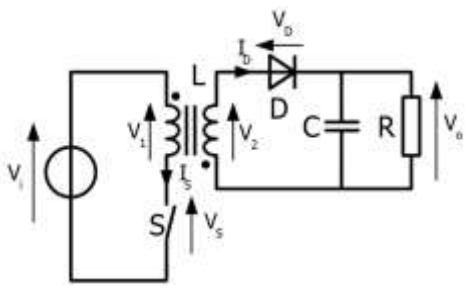

Fig. 9. Isolated Flyback Converter using a coupled inductor.

10. Forward Converter: Operating fundamentally as an isolated buck converter, the forward topology transfers energy to the secondary side while the primary switch is actively conducting (Fig. 10). It offers higher efficiency than the flyback at medium power levels. However, it requires a tertiary reset winding on the transformer to demagnetize the core during the OFF state, adding manufacturing complexity.

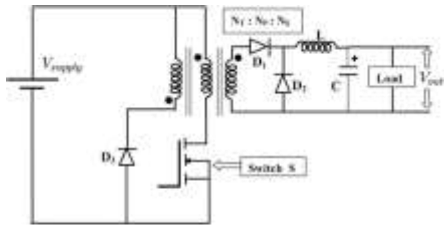

Fig. 10. Isolated Forward Converter with core reset mechanisms.

11. Push-Pull Converter: The push-pull topology utilizes a center-tapped transformer and two primary switches operating in antiphase (Fig. 11). It efficiently utilizes the entire $B-H$ magnetic curve of the transformer core, allowing for higher power density. Its primary vulnerability is "flux walking"; any asymmetry in the duty cycles of the two switches will cause the core to saturate, potentially leading to catastrophic switch failure.

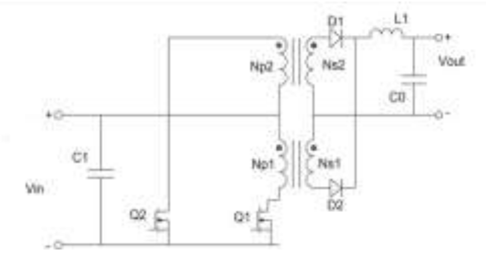

Fig. 11. Isolated Push-Pull Converter utilizing a center-tapped transformer.

B. High-Power Isolated Architectures

12. Dual Active Bridge (DAB): The DAB is the industry standard for high-power, bidirectional EV charging (Fig. 12). It utilizes two active H-bridges separated by a high-frequency isolation transformer. Power flow magnitude (P) and direction are regulated via phase-shift modulation (d) between the primary and secondary bridges, governed by:

$$P = \frac{n \cdot V_{in} \cdot V_{out}}{2 \cdot f_s \cdot L} d(1-d) \quad (4)$$

where n is the turns ratio, f_s is the switching frequency, and L is the leakage inductance. This topology inherently achieves Zero Voltage Switching (ZVS), practically eliminating turn-on switching losses **[10], [11]**.

13. LLC Resonant Converter: A documented limitation of the standard DAB is the loss of ZVS under light-load conditions (e.g., when the battery is nearing full charge). To resolve this, the LLC topology introduces a resonant tank consisting of an additional series inductor and capacitor (Fig. 13). This tank forces the currents and voltages to cross zero sinusoidally, guaranteeing both Zero Voltage Switching (ZVS)

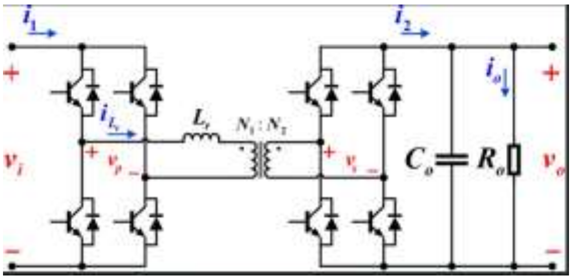

Fig. 12. Isolated Dual Active Bridge (DAB) Converter for bidirectional power flow.

and Zero Current Switching (ZCS) across a much wider load profile, thereby maximizing the system's thermal efficiency.

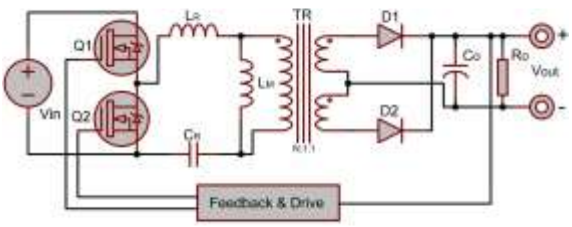

Fig. 13. LLC Resonant Converter featuring a soft-switching resonant tank.

IV. Control Dynamics and Compensation

Regulating battery charging voltage and current strictly requires closed-loop feedback. Several of the discussed topologies (Buck-Boost, SEPIC, Cuk, Flyback) operating in Continuous Conduction Mode (CCM) present severe dynamic stability challenges.

A. The Right-Half-Plane (RHP) Zero

In topologies where energy is stored in the inductor during the ON-state and delivered during the OFF-state, increasing the duty cycle temporarily starves the output. This causes a transient dip in output voltage, mathematically represented by a Right-Half-Plane (RHP) zero in the control-to-output transfer function **[3]**.

For a standard buck-boost, the RHP zero angular frequency is highly dependent on the duty cycle (D), load resistance (R_L), and inductance (L):

$$\omega_{rhpz} = \frac{R_L(1-D)^2}{D \cdot L} \tag{5}$$

This introduces a 90° phase lag while simultaneously increasing the high-frequency gain, destroying the phase margin and leading to severe system oscillation if left uncompensated.

B. Loop Compensation Techniques

To secure stability, an operational transconductance amplifier (OTA) or DSP-based error amplifier must be compensated using Type II or Type III networks. For average current-mode control, a **Type II Compensator** is heavily applied (Fig. 14).

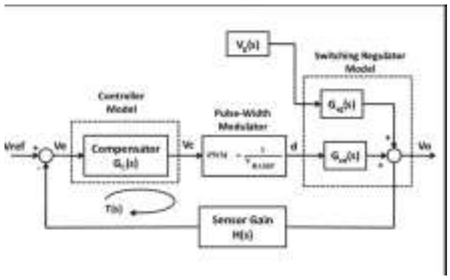

Fig. 14. Error amplifier utilizing a Type II compensation network.

The generalized transfer function of a Type II compensator is given by:

$$G_c(s) = \frac{K_c \left(1 + \frac{s}{\omega_z}\right)}{s \left(1 + \frac{s}{\omega_p}\right)} \tag{6}$$

The compensator introduces an origin pole for steady-state accuracy, a zero (ω_z) to boost phase, and a high-frequency pole (ω_p) to attenuate switching noise. To bypass the destabilizing effects of the RHP zero, the compensation parameters are mathematically tuned to force the open-loop crossover frequency (f_c) to be strictly less than one-fifth of the worst-case RHP zero frequency ($f_c < 0.2 f_{rhpz}$). This conservative bandwidth placement guarantees a phase margin safely between 45° and 60°, ensuring robust stability during grid transients and load shifting **[7], [13]**.

V. Comparative Analysis

Table I summarizes the critical tradeoffs between the primary non-isolated and isolated architectures discussed in this review.

TABLE I
Comparative Analysis of Battery Charger Topologies

Topology	Isolation	Current Ripple	Stress	Power Level
Buck	No	Low Output	Low	Low-Med
Boost	No	Low Input	Medium	Low-Med
Cascaded B-B	No	Low	Low	Medium-High
Cuk	No	Near-Zero	High	Medium
Flyback	Yes	High	Very High	Low
Push-Pull	Yes	Medium	Medium	Medium
DAB	Yes	Low	Low (ZVS)	Ultra-High

VI. Conclusion and Future Trends

The design of modern battery charging infrastructure demands a rigorous selection of power converter topologies based on power level, isolation safety requirements, and battery ripple constraints. This comprehensive review systematically analyzed thirteen distinct architectures. Non-isolated topologies, specifically the Cascaded Buck-Boost and Cuk converters, offer excellent ripple reduction for onboard charging integration. Conversely, for high-power off-board networks, the Dual Active Bridge (DAB) and LLC Resonant converters provide the high-efficiency, galvanically isolated framework necessary for rapid fast-charging and bidirectional V2G applications.

Regardless of topological choice, stabilizing systems with an inherent RHP zero mandates strict mathematical modeling and the precise application of Type II or Type III compensation networks. Looking forward, the integration of Wide-Bandgap (WBG) semiconductors, such as Silicon Carbide (SiC) and Gallium Nitride (GaN), will allow these topologies to operate at drastically higher switching frequencies (> 500 kHz). This will further reduce magnetic component sizing, pushing the boundaries of volumetric power density. Ultimately, the synthesis of these advanced power stages with robust control theory forms the indispensable foundation for reliable, high-density energy management systems in the electrified future.

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