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# Advanced Bipolar DC-Bus Voltage Balancing with Integrated DC-DC Conversion for Electric Vehicle Fast Charging Infrastructure

Pavan Mishra[1], Devendra Sharma[2],

Pavanmishra521@gmail.com[1], devendrasharma798@gmail.com

[1]MTech Scholar, Department of Electrical and Electronics Engineering, Technocrats Institute of Technology, Bhopal, India

[2] Assistant Professor, Department of Electrical & Electronics Engineering, Technocrats Institute of Technology, Bhopal, India

## Abstract

The rapid proliferation of electric vehicles (EVs) necessitates the development of high-power charging infrastructure with enhanced efficiency and reliability. Bipolar DC-bus-fed charging stations offer significant advantages over conventional AC-bus-fed systems, including reduced conversion stages and easier integration with distributed generation. However, voltage imbalance between the positive and negative DC buses remains a critical challenge. This paper reviews a novel high-efficiency voltage balancer (VB) with integrated DC-DC converter functionality proposed by Kim et al., which addresses the fundamental limitations of conventional three-level (TL) converter-based balancing systems. Unlike traditional approaches where voltage balancing capability depends on output load power, the proposed topology enables independent voltage balancing control regardless of load conditions, achieving 96.39% peak efficiency while maintaining bidirectional power transfer capability. This review examines the operating principles, comparative advantages, experimental validation, and future research directions for this emerging technology.

**Keywords:** Bipolar DC-bus, electric vehicle charging station, voltage balancer, DC-DC converter, voltage balancing control, high conversion ratio

## 1. Introduction

The global transition toward electric mobility has intensified research efforts in high-power EV charging infrastructure. DC microgrids have emerged as preferred platforms for charging stations due to their higher conversion efficiency, better power density, and absence of reactive power flow compared to AC microgrids [1]. Among DC microgrid configurations, bipolar DC-bus systems provide two voltage levels, enabling easier interfacing with loads of different power ratings, enhanced reliability through redundant bus structures, and reduced voltage-to-ground stress [2].

Despite these advantages, bipolar DC-bus systems inherently suffer from voltage imbalance caused by asymmetrical power distribution between the positive and negative buses. This imbalance degrades power quality, increases neutral line losses, and may cause premature switching device failure [3]. Consequently, voltage balancing control (VBC) mechanisms are indispensable. Traditional solutions employ dedicated voltage balancers or three-level DC-DC converters that serve dual purposes of charging and balancing. However, TL-converter-based systems exhibit fundamental limitations: balancing capability is proportional to output power, becomes impossible under no-load conditions, and fails when unbalanced power exceeds output power [4].

The innovative voltage balancer proposed by Kim et al. [5] addresses these limitations through a modified series-capacitor high-conversion-ratio DC-DC converter topology, enabling independent VBC with integrated charging functionality. This review critically examines this breakthrough technology.

## 2. Literature Review

### 2.1 Conventional Voltage Balancer Topologies

Early voltage balancer implementations focused on buck-boost type converters due to their simple structure and easy controllability [6]. For high-voltage applications, three-level voltage balancers employing diode-clamped switch legs reduce device voltage stress [7]. Dual-buck voltage balancers eliminate shoot-through risks and reduce diode reverse recovery losses [8]. However, these dedicated VBs cannot serve as DC-DC converters, requiring additional power stages for EV charging.

### 2.2 Interleaved Voltage Balancers

To address current stress and ripple issues, interleaved voltage balancers were developed from conventional interleaved buck-boost converters [1]. While these reduce switch current stress and improve dynamic performance, they remain incapable of providing output load power.

### 2.3 Three-Level Converter-Based Balancing

TL DC-DC converters have been integrated into bipolar EV charging stations to simultaneously provide fast charging and VBC [9]. This approach eliminates separate balancing circuits. However, as demonstrated in [4], the neutral current depends on output load current, creating intrinsic balancing limitations.

### 2.4 Modified Three-Level Voltage Balancer

The MTL-VB, derived by adding an inductor to the neutral line, achieves both VB and DC-DC functions [10]. Nevertheless, discontinuous inductor current imposes higher voltage and current stresses on switches, making it unsuitable for high-power EV charging applications.

## 3. Proposed Topology and Operating Principles

The proposed voltage balancer, shown in Fig. 3 of the base paper, connects a modified series-capacitor high-conversion-ratio DC-DC converter directly in parallel with the bipolar DC-bus. The topology comprises four switches ($S_1$–$S_4$), two inductors ($L_1$, $L_2$), two input capacitors ($C_1$, $C_2$), and one output capacitor ($C_0$).

### 3.1 Balancing Mechanism

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Unlike conventional VBs where balancing current must flow through the output load, the proposed VB enables a circulating current (i_L,cir) that flows independently of output load current. This circulating current compensates for unbalanced bus currents regardless of charging status. The relationship between circulating current and unbalanced current is derived as:

$$I_{L,cir} = I_{un}/(2d)$$

where d represents the duty ratio and Iun is the average unbalanced current.

### 3.2 Operational Modes

Three operational modes exist within one switching period for d < 0.5 operation. Mode 1 energizes inductors through the upper capacitor, Mode 2 provides a freewheeling path with zero inductor voltage, and Mode 3 utilizes the lower capacitor for energy transfer. This sequence enables bidirectional power flow while maintaining voltage balance.

### 3.3 Voltage Gain Characteristic

The voltage conversion ratio is given by $V_0$/V_pn = d/2, representing double step-down compared to conventional TL converters ($V_0$/V_pn = d). This characteristic reduces voltage stress on switching devices, enabling use of lower-rated, more efficient semiconductors.

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## 4. Advantages Over Conventional Approaches

### 4.1 Unlimited Voltage Balancing Range

The most significant advantage is complete decoupling of VBC from output load power. Unlike TL converters where $|P_{un}|$ must be less than $|P_o|$ for balancing, the proposed VB maintains balance even when $P_o = 0$ or $|P_{un}| > |P_o|$.

### 4.2 Reduced Component Stresses

Voltage stress on $S_1$, $S_3$, and $S_4$ equals $V_{pn}/2$ compared to $V_{pn}$ for MTL-VB switches. Current stress reduction is similarly achieved through the circulating current mechanism.

### 4.3 Superior Efficiency

Simulated efficiency comparison under identical conditions ($V_{pn}$ = 1500 V, $V_o$ = 300 V, $P_o$ = 10–70 kW) shows the proposed VB achieving 96.39% peak efficiency at 60 kW, compared to 94.92% for TL converters and 91.22% for MTL-VB.

### 4.4 Bidirectional Operation

Experimental validation confirms successful operation with positive (charging) and negative (discharging) output currents, enabling vehicle-to-grid applications.

## 5. Experimental Validation

A hardware prototype compensating for 1 kW unbalanced power was constructed with $V_{pn}$ = 400 V, $V_o$ = 50–70 V, and $f_s$ = 20 kHz. Experimental results demonstrate:

- Perfect voltage balance maintenance under extreme unbalanced loads ($R_1$ removed, $R_2$ = 40 Ω)
- Successful VBC with $P_o = 0$, confirming independent balancing capability

- Accurate tracking of output voltage reference under CV charging mode
- Bidirectional operation with negative load currents down to -2 A
- Waveform correspondence with theoretical analyses across all operational modes

## 6. Recent Challenges

Despite demonstrated advantages, several challenges require attention:

**6.1 Inductor Design Complexity** – Optimal inductor sizing requires consideration of both output and unbalanced currents, potentially leading to larger magnetic components than conventional designs.

**6.2 Control Loop Interaction** – The cascaded PI controllers for charging and balancing may exhibit dynamic interactions during rapid load transients, requiring careful compensation design.

**6.3 Component Count** – While switch count equals conventional topologies (four switches), the requirement for two balanced inductors adds complexity compared to single-inductor buck-boost balancers.

**6.4 High-Frequency Operation Limits** – Operating at $d < 0.5$ for efficiency benefits imposes upper bounds on conversion ratio, potentially limiting applicability in widely varying voltage environments.

## 7. Future Directions

**7.1 Integration with Renewable Sources** – Extending the topology to accept photovoltaic or wind power inputs while maintaining VBC functionality would enhance charging station sustainability.

**7.2 Multi-Port Architectures** – Developing multi-port versions capable of simultaneously balancing multiple bipolar buses or serving multiple EVs could reduce system-level component count.

**7.3 Advanced Control Strategies** – Implementing model predictive or sliding mode control could improve transient response and robustness against parameter variations.

**7.4 Gallium Nitride (GaN) Implementation** – Utilizing wide-bandgap devices could increase switching frequency, reducing passive component sizes while maintaining efficiency gains.

**7.5 Grid-Interactive Operation** – Further development of bidirectional capability for grid services (frequency regulation, peak shaving) would increase charging station value proposition.

## 8. Conclusion

This review has examined a high-efficiency voltage balancer with integrated DC-DC converter function for bipolar DC-bus-fed EV charging stations. The proposed topology fundamentally resolves the voltage balancing range limitations inherent in three-level converter-based systems by enabling circulating current independent of output load. Key findings include: (1) unlimited VBC range including no-load and extreme unbalanced conditions, (2) 96.39% peak efficiency superior to conventional approaches, (3) reduced voltage and current stresses enabling lower-rated semiconductors, and (4) successful bidirectional operation validated experimentally. As EV charging demands escalate toward megawatt levels, this topology presents a compelling solution for next-generation bipolar DC-bus charging infrastructure.

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