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A Comprehensive Review of Closed-Loop DC–DC Converter Topologies and Advanced Control Techniques for Electric Vehicle Charging Applications

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Abstract*– *The increasing adoption of electric vehicles (EVs), renewable energy systems, and smart power infrastructures has significantly accelerated the development of high-performance DC–DC power converters. Among non-isolated converter topologies, Boost, Cuk, and SEPIC converters are extensively utilized due to their efficient voltage conversion capability, adaptability, and compatibility with battery-powered systems. Recent research trends emphasize the importance of closed-loop control, intelligent control techniques, improved transient response, reduced ripple, and high-efficiency operation for EV charging systems. This review paper presents a comprehensive comparative analysis of major DC–DC converter topologies and advanced control techniques for EV charging applications. The paper critically evaluates converter operating principles, mathematical modelling methods, dynamic response characteristics, efficiency trends, ripple performance, and disturbance rejection capability. Furthermore, modern control approaches including PI control, fuzzy logic control, model predictive control, sliding mode control, and AI-based control techniques are reviewed. The study also investigates EV charging architectures, bidirectional charging systems, harmonic reduction strategies, and wide-bandgap semiconductor technologies. A detailed comparison of existing literature reveals major research gaps related to real-time implementation, EV-oriented dynamic analysis, power quality assessment, and advanced digital control integration. Finally, future research directions for intelligent, high-efficiency, and grid-interactive EV charging systems are presented.

Keywords:* *DC–DC Converters, Boost Converter, Cuk Converter, SEPIC Converter, Electric Vehicle Charging, Closed-Loop Control, Power Electronics, Digital Control, EV Powertrain, Renewable Energy Systems.

I. INTRODUCTION

Electric vehicles (EVs) are rapidly transforming the global transportation industry because of their environmental benefits, reduced carbon emissions, and improved energy efficiency. Modern EV systems require advanced power electronic converters for efficient battery charging, voltage regulation, power distribution, and energy management. DC–DC converters play a fundamental role in EV charging systems by converting and regulating voltage levels between the grid, battery, and auxiliary systems.

The rapid increase in EV deployment has created new challenges for converter systems, including:

- High efficiency requirements
- Fast charging capability
- Reduced switching losses
- Low harmonic distortion
- Improved dynamic response
- Grid compatibility

Among non-isolated converter topologies, Boost, Cuk, and SEPIC converters have received significant research attention due to their ability to provide flexible voltage conversion with relatively simple implementation. The Boost converter is widely preferred for high voltage gain applications, while the Cuk converter offers superior ripple reduction because of continuous current conduction. The SEPIC converter provides stable operation under wide input voltage variations, making it suitable for EV battery charging systems.

Recent developments in closed-loop control strategies and intelligent control algorithms have significantly improved converter stability, transient response, and disturbance rejection capability. Conventional PI controllers are commonly employed because of their simplicity and low computational complexity. However, advanced control methods such as fuzzy logic control (FLC), model predictive control (MPC), sliding mode control (SMC), and AI-based controllers are increasingly being investigated for high-performance EV charging applications.

This review paper presents a comprehensive study of DC–DC converter topologies and advanced control techniques for EV charging systems.

The paper critically reviews:

- Converter operating principles
- Closed-loop performance characteristics
- Dynamic response analysis
- Advanced digital control methods
- EV charging architectures
- Power quality improvement techniques
- Research gaps and future trends

II. CLASSIFICATION OF DC–DC CONVERTERS

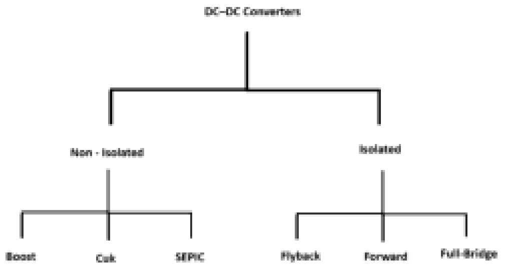

Fig. 1. Classification of DC–DC converter topologies used in modern power electronic systems.

A. Non-Isolated DC–DC Converters

Non-isolated converters are widely used in EV systems due to:

- High efficiency
- Compact structure
- Low implementation cost

Major Non-Isolated Topologies:

1. Boost Converter
2. Buck Converter
3. Buck–Boost Converter
4. Cuk Converter
5. SEPIC Converter
6. Zeta Converter
7. Luo Converter

B. Isolated DC–DC Converters

Isolated converters provide electrical isolation between input and output using transformers.

Common Isolated Topologies:

- Flyback converter
- Forward converter
- Push-pull converter
- Full-bridge converter

These converters are primarily used in:

- High-power EV charging stations
- Industrial power systems
- Fast-charging infrastructure

III. REVIEW OF BOOST, CUK, AND SEPIC CONVERTERS

A. Boost Converter

The Boost converter is a step-up converter capable of producing output voltage higher than the input voltage.

Advantages:

- High voltage gain
- Fast transient response
- Simple topology
- High efficiency

Limitations:

- Higher output ripple
- Increased switching stress
- Poor ripple performance

Applications:

- EV fast chargers
- Renewable energy systems
- Battery-powered devices

Several studies reported that the Boost converter achieves superior dynamic response and fast settling characteristics compared with other non-isolated topologies.

B. Cuk Converter

The Cuk converter transfers energy through capacitive coupling and provides continuous current characteristics at both input and output sides.

Advantages:

- Very low output ripple
- Excellent disturbance rejection
- Reduced electromagnetic interference

Limitations:

- Increased component count
- Complex controller design
- Higher implementation cost

Applications:

- Precision EV battery charging
- Low-noise power supplies
- Sensitive electronic systems

Research findings demonstrate that the Cuk converter offers superior ripple performance and better load disturbance rejection capability.

C. SEPIC Converter

The SEPIC converter provides output voltage regulation under wide input voltage conditions while maintaining non-inverted polarity.

Advantages:

- Wide input voltage adaptability
- Stable operation
- Moderate ripple characteristics

Limitations:

- Moderate efficiency
- Increased switching losses

Applications:

- EV battery management systems
- Variable voltage charging systems
- Renewable energy interfaces

Several studies indicate that SEPIC converters perform effectively in applications requiring stable operation under varying battery voltage conditions.

Literature Review Summary:-

Table I. Summary of major studies on DC–DC converter topologies and control methods.

Ref.	Converter	Control	Application	Key Finding
[1]	Cuk, SEPIC, Zeta	MPPT	PV Systems	Zeta highest efficiency
[2]	SEPIC, Luo, Zeta	Conventional	Power systems	Zeta improved ripple
[4]	Buck-Boost, Cuk	Fuzzy Logic	PV	FLC-Cuk best efficiency
[5]	Boost, SEPIC	PWM	Renewable energy	Voltage gain comparison
[11]	Multiple converters	MPC	EV Charging	Improved transient response
[12]	DC–DC converter	AI-based	Smart charging	Adaptive control

Comparative Evaluation under EV Charging Conditions

Parameter	Boost	Cuk	SEPIC
Fast Charging	Excellent	Moderate	Good
Ripple	High	Very Low	Medium
EV Stability	Moderate	Excellent	Good
Complexity	Low	High	Medium

IV. CLOSED-LOOP CONTROL TECHNIQUES

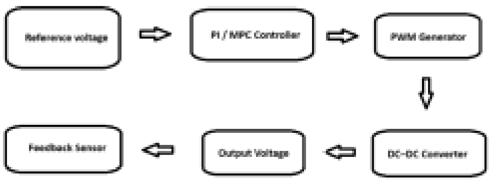

Fig. 2. General closed-loop control structure for DC–DC converter systems.

A. PI Control

PI controllers are widely used because of:

- Simple implementation
- Low computational cost
- Good steady-state performance

Limitations:

- Overshoot during transient conditions
- Reduced adaptability under nonlinear conditions

B. Fuzzy Logic Control (FLC)

Fuzzy Logic Controllers provide:

- Better nonlinear control
- Improved transient response
- Enhanced disturbance rejection

Challenges:

- Rule-base complexity
- Increased computational requirements

C. Sliding Mode Control (SMC)

SMC offers:

- Robust operation
- Fast dynamic response
- Reduced sensitivity to parameter variations

However:

- Chattering effect remains a major limitation

D. Model Predictive Control (MPC)

MPC is an advanced digital control strategy that predicts future system behavior and optimizes control action accordingly.

Advantages:

- Fast response
- Reduced overshoot
- Improved dynamic performance

Limitations:

- High computational complexity
- Expensive hardware implementation

MPC is considered one of the most promising control techniques for future EV charging systems.

E. AI-Based Control Techniques

Recent research focuses on:

- Neural networks
- Adaptive control
- Reinforcement learning
- Intelligent optimization algorithms

These techniques aim to achieve:

- Self-tuning capability
- Improved efficiency
- Real-time adaptive operation

Comparison of Control Techniques

Table II. Comparative analysis of advanced control techniques for DC–DC converters.

Control Technique	Advantages	Limitations	EV Suitability
PI Control	Simple, low cost	Overshoot, slower response	Moderate
Fuzzy Logic Control	Robust nonlinear control	Complex design	Good
Sliding Mode Control	Fast response	Chattering effect	Good
Model Predictive Control	Excellent transient response	High computation	Excellent
AI-Based Control	Adaptive operation	Complex implementation	Future systems

V. COMPARATIVE PERFORMANCE ANALYSIS

Parameter	Boost	Cuk	SEPIC
Voltage Gain	High	Moderate	Moderate
Ripple Performance	Poor	Excellent	Good
Dynamic Response	Fast	Stable	Balanced
Disturbance Rejection	Moderate	Excellent	Good
Efficiency	High	Moderate	Good
Complexity	Low	High	Medium
EV Charging Suitability	Fast charging	Low-noise charging	Variable battery charging

The comparative analysis indicates that no single converter is universally optimal. Converter selection depends on:

- Charging speed requirements
- Ripple constraints
- Efficiency requirements
- Battery operating conditions

VI. EV CHARGING ARCHITECTURE AND APPLICATIONS

A. EV Charging Architecture

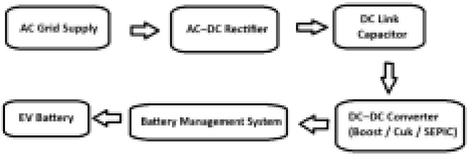

Fig. 3. Block diagram of a typical EV charging system employing DC–DC converter technology.

Converter Roles:

- Rectifier: AC–DC conversion
- DC–DC converter: voltage regulation and charging control
- Battery management system: charging protection and monitoring

B. Bidirectional Charging Systems

Modern EV systems increasingly support:

- Vehicle-to-Grid (V2G)
- Vehicle-to-Home (V2H)
- Regenerative energy transfer

Bidirectional DC–DC converters are essential for:

- Energy feedback
- Grid stabilization
- Smart charging systems

VII. POWER QUALITY AND HARMONIC ISSUES

EV charging systems may introduce:

- Harmonic distortion
- Reactive power issues
- Grid instability

Recent studies focus on:

- THD reduction
- Active filtering
- PWM-based harmonic control
- Grid-interactive converters

Power quality improvement remains a major research area in EV charging infrastructure.

VIII. WIDE-BANDGAP SEMICONDUCTOR TECHNOLOGIES

Modern EV charging systems increasingly employ:

- Silicon Carbide (SiC)
- Gallium Nitride (GaN)

Advantages:

- Higher switching frequency
- Reduced switching losses
- Improved thermal performance
- Increased efficiency

Wide-bandgap devices are expected to dominate next-generation EV charging systems.

IX. RESEARCH GAPS

Despite extensive research, several important challenges remain unresolved.

Existing Limitations:

- Limited EV-oriented dynamic analysis
- Lack of hardware validation
- Insufficient harmonic analysis
- Limited real-time adaptive control
- High computational complexity of advanced controllers
- Limited comparison under variable EV charging conditions

X. FUTURE RESEARCH DIRECTIONS

Research Gaps and Future Directions

Existing Limitation	Future Research Direction
Limited EV-oriented dynamic analysis	Real-time EV charging analysis
Lack of hardware validation	FPGA/DSP implementation
Limited harmonic analysis	THD reduction techniques
Conventional PI control dominance	AI/MPC-based intelligent control
Limited bidirectional charging studies	Vehicle-to-Grid (V2G) systems

Future research should focus on:

1. AI-based converter control
2. Model predictive control for EV charging
3. Real-time FPGA/DSP implementation
4. Bidirectional charging optimization
5. Ultra-fast EV charging systems
6. Wide-bandgap semiconductor integration
7. Grid-interactive smart charging systems
8. Hybrid renewable-EV charging infrastructure

XI. CONCLUSION

This review paper presented a comprehensive analysis of modern DC–DC converter topologies and advanced control techniques for EV charging applications. The review demonstrated that Boost converters provide superior dynamic response and high efficiency, Cuk converters offer excellent ripple reduction and disturbance rejection, while SEPIC converters provide stable performance under varying input voltage conditions. Closed-loop control significantly improves converter stability, voltage regulation, and dynamic response characteristics. Furthermore, advanced digital control techniques such as MPC, sliding mode control, and AI-based control show significant potential for future intelligent EV charging systems. The paper also identified major research gaps related to power quality analysis, hardware implementation, and adaptive control strategies. Future EV charging systems will require highly efficient, intelligent, and grid-interactive power electronic architectures capable of supporting sustainable transportation infrastructure.

XII. COMPARATIVE EVALUATION UNDER EV CHARGING CONDITIONS

Parameter	Boost	Cuk	SEPIC
Fast Charging	Excellent	Moderate	Good
Ripple	High	Very Low	Medium
EV Stability	Moderate	Excellent	Good
Complexity	Low	High	Medium

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