Wide-Range Battery-Compatible Three-Leg Bidirectional Converter for Electric Vehicle Inductive Charging

DR.K.V. SHARMA[1], GUJJA MANVITHA[2]

[1]Professor of Emeritus, Department of MECHANICAL, JNTUH University College of Engineering, SCIENCE AND TECHNOLOGY, HYDERABAD-500085 Telangana, India

[2] M. Tech Student, Centre for Energy Studies, JNTUH University College of Engineering, SCIENCE AND TECHNOLOGY, HYDERABAD-500085 Telangana, India

Abstract: ***This paper presents a Sliding Mode Control (SMC)-based inductive Electric Vehicle (EV) charging system using a three-leg bidirectional converter for wide-range battery charging. The architecture combines a three-phase AC–DC rectifier, a bidirectional DC–DC converter, and high-frequency isolation transformers to enable reliable, efficient power transfer between the grid and the EV battery in both Grid-to-Vehicle (G2V) and Vehicle-to-Grid (V2G) modes. A robust Sliding Mode Controller regulates DC-link voltage, battery charging current, and output power, improving dynamic performance, stability, and disturbance rejection while reducing switching stress. The system is modeled and simulated in MATLAB/Simulink under diverse operating conditions. Results show faster transient response, lower current harmonic distortion, higher efficiency, and more stable charging than conventional control methods, making the proposed converter a reliable, flexible solution for next-generation smart EV charging with improved power quality.***

Keywords:***EV Charging, Sliding Mode Control, Three-Leg Bidirectional Converter, Wireless Power Transfer, G2V/V2G Operation, DC-Link Regulation, Battery Charging, High-Frequency Isolation, Power Quality, MATLAB/Simulink.***

I.INTRODUCTION

The rapid growth of Electric Vehicles (EVs) as a pillar of sustainable transportation, driven by environmental concerns and the shift toward clean energy, has increased the need for efficient, reliable, and intelligent charging infrastructure that can transfer energy between the utility grid and the vehicle battery [1], [2].

Traditional chargers operate in unidirectional Grid-to-Vehicle (G2V) mode, but the growth of smart grids demands bidirectional Vehicle-to-Grid (V2G) capability that lets EV batteries return stored energy to the grid during peak demand, improving grid stability and renewable integration [3], [4]. Since converter topology, switching strategy, and control method largely determine charger performance, conventional two-stage AC–DC/DC–DC designs are increasingly being replaced by compact, high-efficiency bidirectional topologies with low harmonic distortion and high power factor [5], [6]. Inductive Power Transfer (IPT) offers a contactless alternative to conductive charging with improved safety and convenience, though coil misalignment, coupling variation, and switching losses remain challenges [7], [8]. Among bidirectional DC–DC options—buck–boost, dual active bridge, interleaved, and resonant converters—three-leg topologies stand out for reduced switching stress, flexible control, and compatibility with high-frequency isolation transformers, which further improve safety, power density, and electromagnetic compatibility [9]–[12].

While these hardware advances improve performance, robust control is equally essential. Conventional PI controllers are simple but degrade under the nonlinear, disturbance-prone behavior typical of EV chargers [13]. Sliding Mode Control (SMC) addresses this by driving the system states onto a predefined sliding surface, giving fast transient response and strong disturbance rejection in DC–DC converters, motor drives, and EV charging systems [14], [15]. In this application, SMC can regulate DC-link voltage, battery current, and bidirectional power flow while minimizing ripple and improving stability during G2V/V2G transitions [16]. The growing role of EVs as distributed energy resources further motivates such intelligent, V2G-capable charging systems for peak-load management and grid support [17].

Motivated by these requirements, this work proposes a Sliding Mode Controlled inductive EV charging system built around a three-leg bidirectional converter for wide-range battery charging. The system integrates a three-phase AC–DC rectifier, a bidirectional DC–DC converter, high-frequency isolation transformers, and an SMC strategy to achieve efficient, stable G2V/V2G power transfer with high conversion efficiency, improved power quality, and reduced switching losses [18]. MATLAB/Simulink simulations evaluate its charging characteristics, voltage regulation, transient response, and bidirectional power-flow performance.

II. EXISTING SYSTEM

The conventional three-leg dc–dc converter (Fig. 1) uses a three-leg inverter (S1–S6), an SPDT switch, two transmitter coils (L1, L3) with series resonant capacitors (C1, C3), and, on the secondary side, two receiver coils (L2, L4) with capacitors (C2, C4), a three-leg diode rectifier (D1–D6), and filter capacitor Co. Depending on the SPDT position and gating scheme, it operates in voltage-doubling mode (800 V battery) or current-doubling mode (400 V battery).

This flexibility comes at a cost. The multiple resonant components and switches increase circuit complexity and control difficulty, the SPDT arrangement adds switching stress during mode transitions, high circulating current raises conduction losses, and coil/parameter mismatch degrades resonance and power-transfer performance. The diode-bridge rectifier further adds conduction losses and output ripple, and the converter shows higher harmonic distortion and EMI at high-frequency operation.

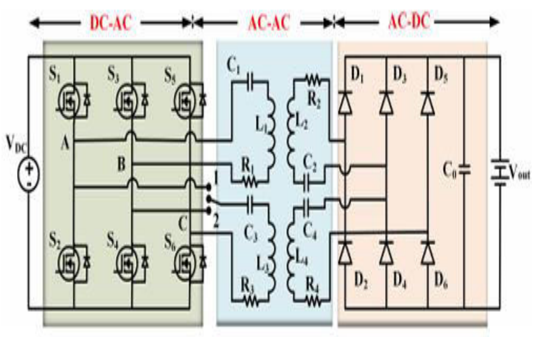


Fig.1Three-leg DC–DC converter configuration for charging both 400 and 800 V batteries.

III. PROPOSED SYSTEM

The system in Fig. 2 is a three-phase bidirectional isolated EV charging architecture for G2V and V2G operation using a Sliding Mode Controller (SMC). It enables efficient bidirectional power flow between the grid and a high-voltage battery pack while ensuring high power quality, galvanic isolation, and stable DC-link regulation.

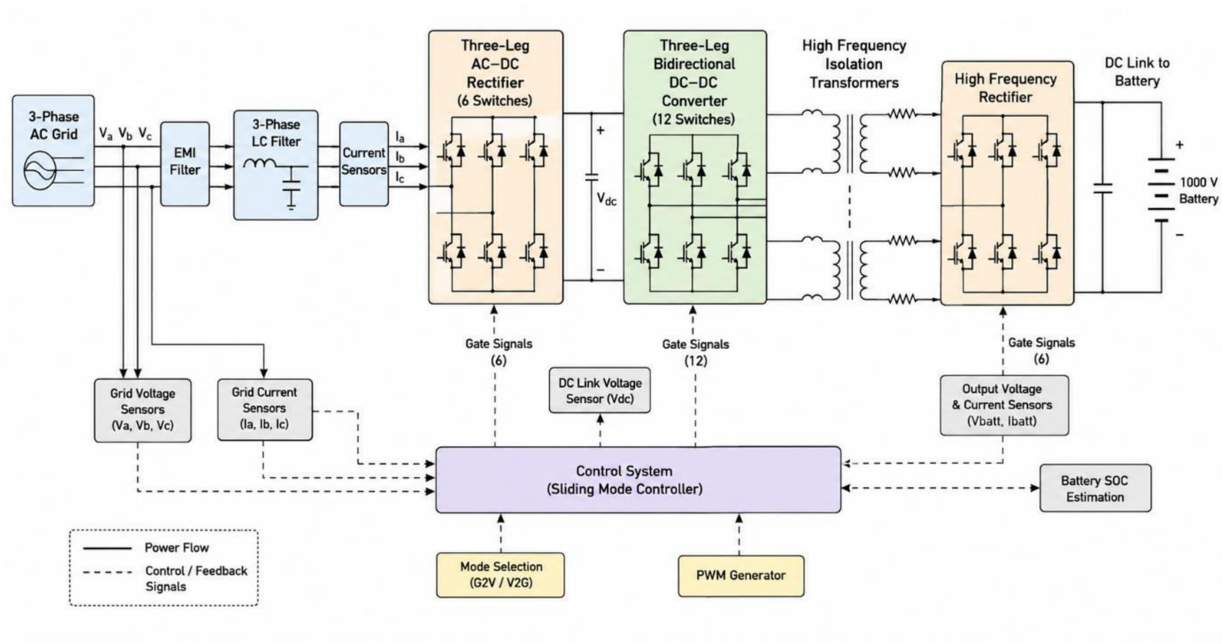


Fig.2 Proposed three-phase bidirectional isolated EV charging architecture designed for Grid-to-Vehicle (G2V) and Vehicle-to-Grid (V2G) operation using a Sliding Mode Controller (SMC).

A) Three-Phase Grid and EMI Filter

A three-phase AC grid supplies voltages Va, Vb, Vc through an EMI filter that suppresses high-frequency switching noise, improving grid-standard compliance and protecting sensitive equipment.

B) Three-Phase LC Filter

A three-phase LC filter smooths the input current, minimizing harmonics and improving power factor and THD.

C) Current and Voltage Sensors

Voltage and current sensors continuously measure Va, Vb, Vc and Ia, Ib, Ic for real-time monitoring and closed-loop control.

D) Three-Leg AC–DC Rectifier

A three-leg AC–DC rectifier with six controlled switches converts the AC supply into regulated DC power, controlling the DC-link voltage Vdc and enabling bidirectional flow — grid-to-battery during charging and battery-to-grid during V2G.

E) DC-Link Capacitor

A DC-link capacitor between the rectifier and DC–DC converter stabilizes the DC-link voltage, reduces ripple, and buffers energy between stages.

F) Three-Leg Bidirectional DC–DC Converter

A three-leg bidirectional DC–DC converter with twelve switches controls battery charging/discharging, performing voltage regulation, current control, and power-transfer management between the DC-link and battery.

Major functions include:

- Bidirectional power transfer.
- High-frequency switching operation.
- Battery charging and discharging control.
- Improved dynamic response and efficiency.

G) High-Frequency Isolation Transformer

The high-frequency transformer provides galvanic isolation between grid and battery sides while enabling high-frequency power transfer, reducing transformer size, weight, and losses.

H) High-Frequency Rectifier

On the secondary side, a high-frequency rectifier converts the HF AC output back to DC, which is supplied to the battery via the DC-link.

I) Battery System

The system charges a high-voltage 1000 V battery pack. Voltage and current sensors monitor Vbatt and Ibatt, and SOC estimation supports battery management and protection.

J) Sliding Mode Control System

A Sliding Mode Controller (SMC) governs the entire system, providing robust control under parameter variation and disturbance. It uses voltage/current sensor feedback to generate PWM gate pulses for all converter switches.

The controller performs:

- DC-link voltage regulation.
- Battery charging current control.
- Bidirectional power flow management.
- Harmonic reduction.
- Stable operation during grid disturbances.

K) Mode Selection and PWM Generation

The mode selection block determines the operating condition:

- G2V Mode: Power flows from grid to battery.
- V2G Mode: Battery supplies power back to the grid.

The PWM generator produces switching pulses for the converters based on SMC control signals.

Table-1 SPECIFICATIONS OF THE PROPOSED SYSTEM

Parameter	**Value**
Input Voltage	415 V AC
Input Frequency	50 Hz
DC-Link Voltage	1000 V
Battery Voltage	1000 V DC
Switching Frequency	25 kHz
Rectifier Switches	6
DC–DC Converter Switches	12
Transformer Frequency	25 kHz
Output Power	20 kW
Output Current	20 A
DC-Link Capacitor	2200 µF
Filter Inductance	5 mH
Filter Capacitance	20 µF
Transformer Turns Ratio	1:1
Efficiency	96%
Power Factor	0.99
Control Method	Sliding Mode Control
Cooling Method	Liquid Cooling

III.SIMULATION RESULTS

A) EXISTING RESULTS

Fig. 3 shows the MATLAB/Simulink circuit of the conventional three-leg DC–DC converter used for charging 400 V and 800 V batteries.

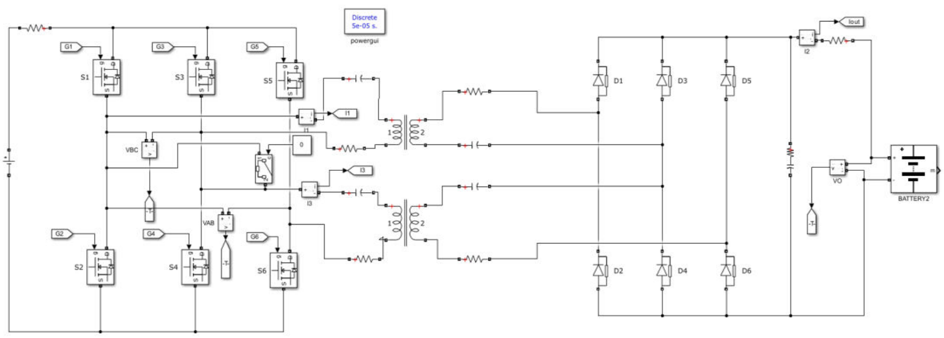
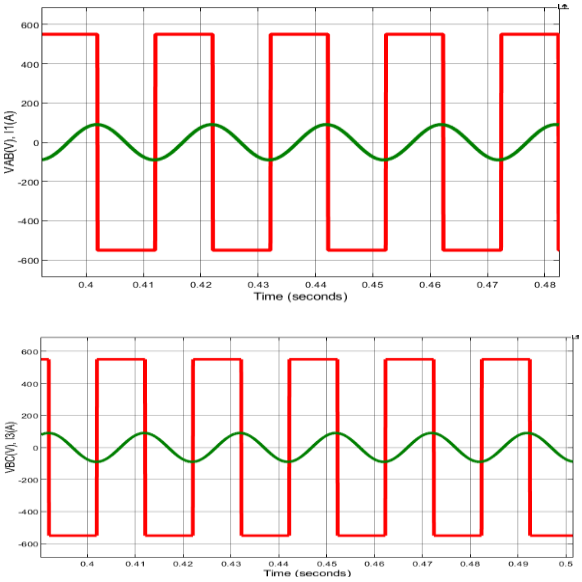


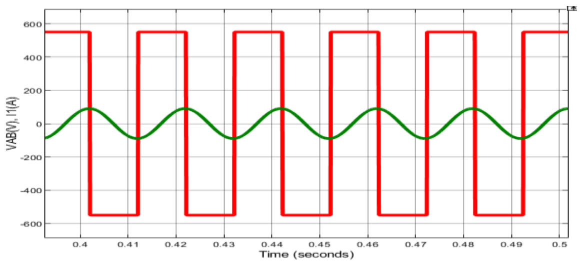
Fig.3 MATLAB/SIMULINK Circuit diagram of Three-leg DC–DC converter configuration for charging both 400 and 800 V batteries.

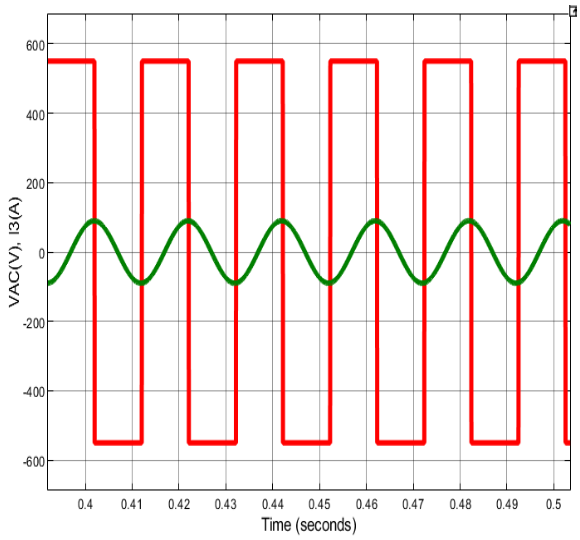
Fig. 4(a)–(b) show inverter voltage and transmitter coil current at 93 kHz in voltage-doubling and current-doubling modes, respectively, indicating stable switching and effective power transfer.

Fig. 5(a)–(b) show output voltage and current in voltage- and current-doubling modes; regulation is acceptable, though the conventional controller shows comparatively higher ripple and slower dynamic response.



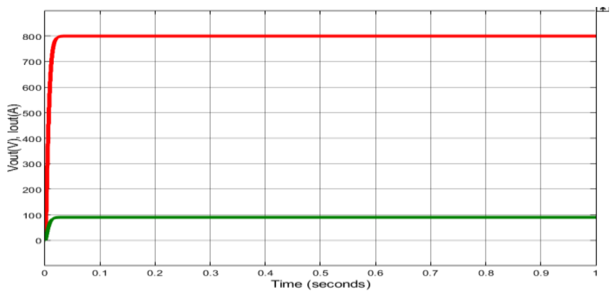
(a)



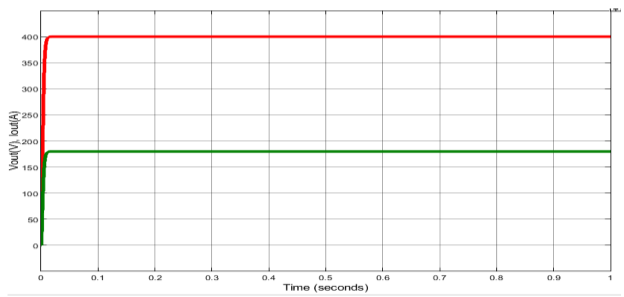


(b)

Fig. 4. Simulation waveforms of inverter voltage and the current flowing through the transmitter coils. Operation at 93 kHz and rated power. (a) Voltage doubling mode. (b) Current doubling mode.



(a)



(b)

Fig. 5. Simulation waveforms of the output voltage and current. (a) Voltage doubling mode. (b) Current doubling mode.

B) EXTENSION RESULTS

Fig. 6 shows the MATLAB/Simulink circuit of the proposed bidirectional three-leg DC–DC converter based on an SMC controller, charging a 1000 V battery and supporting both G2V and V2G operation.

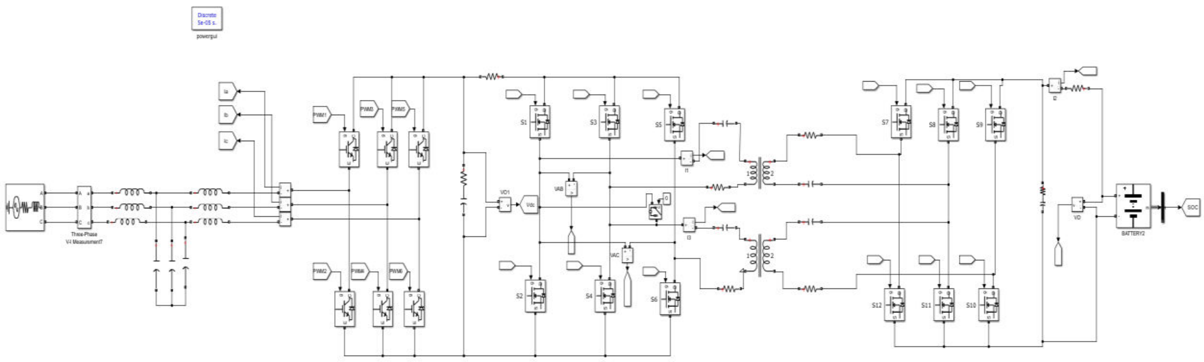


Fig.6 MATLAB/SIMULINK Circuit diagram of Proposed bidirectional Three-leg DC–DC converter configuration-based SMC controller for charging 1000V battery.

CASE-1 G2V

Fig. 7 shows grid voltage/current during G2V operation, confirming proper synchronization with the utility grid.

Fig. 8 shows inverter voltage and transmitter coil current; the SMC controller gives smooth switching with reduced oscillations.

Fig. 9 shows the battery SOC rising steadily, indicating efficient, reliable charging.

Fig. 10 shows output voltage/current during G2V operation, with the proposed controller significantly reducing ripple and improving regulation and dynamic response.

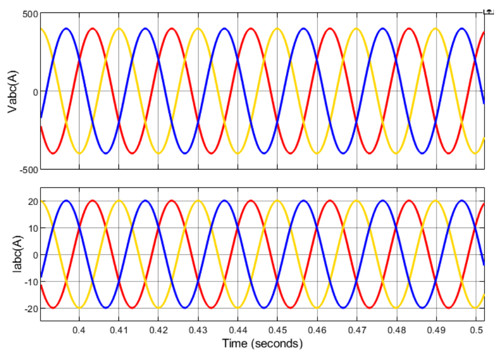


Fig 7 Grid voltage and current

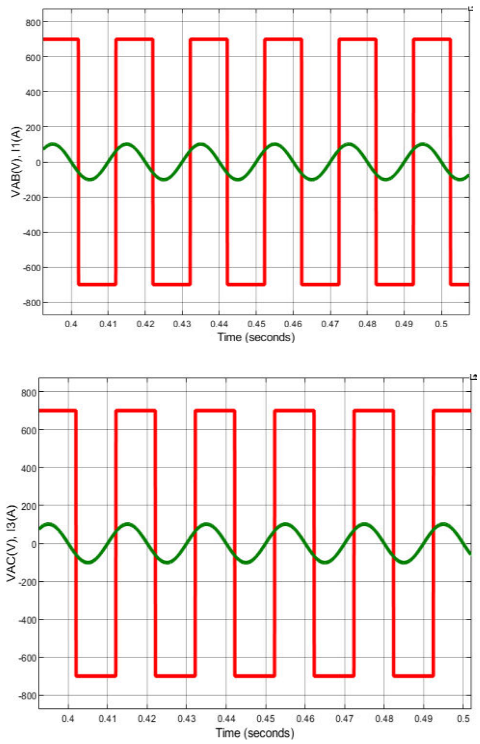


Fig.8 Simulation waveforms of inverter voltage and the current flowing through the transmitter coils.

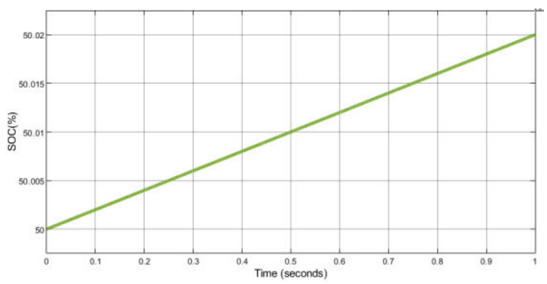


Fig.9 SOC of the battery

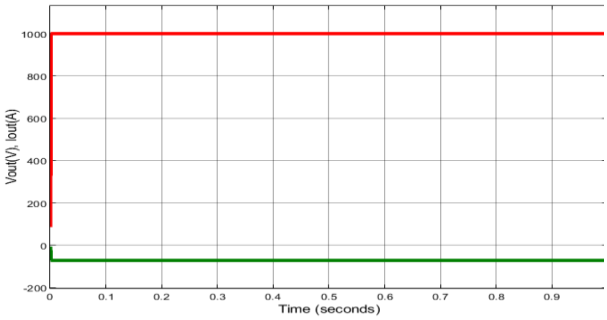


Fig.10 Simulation waveforms of the output voltage and current.

CASE-2 V2G

Fig. 11 shows grid voltage/current during V2G operation, verifying successful bidirectional power flow to the grid.

Fig. 12 shows inverter voltage and transmitter coil current during reverse power transfer, confirming smooth, stable V2G operation.

Fig. 13 shows SOC decreasing gradually during discharge, confirming controlled operation.

Fig. 14 shows output voltage/current during V2G mode, with stable regulation, fast response, and efficient energy transfer to the grid.

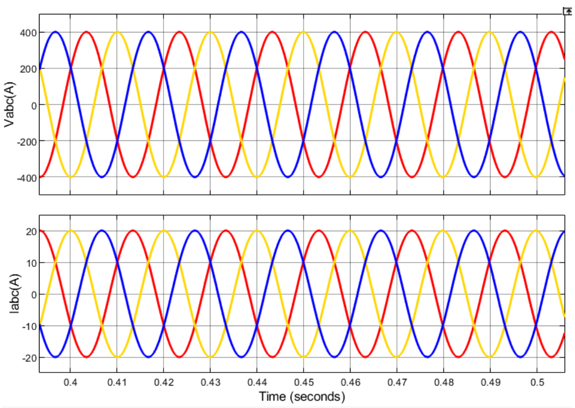
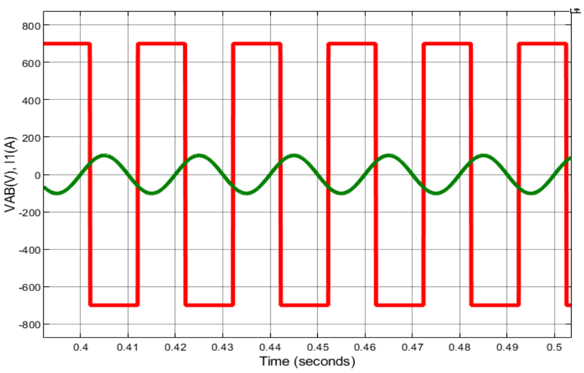


Fig11 Grid voltage and current



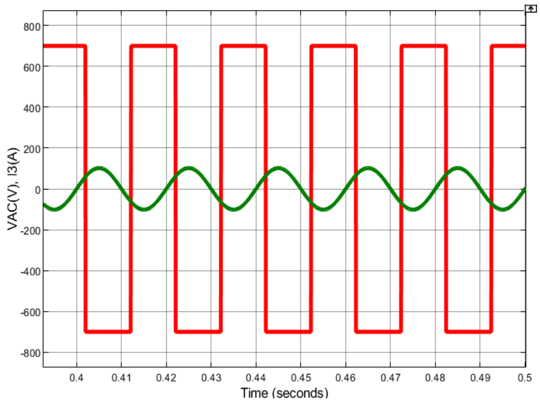


Fig12 Simulation waveforms of inverter voltage and the current flowing through the transmitter coils.

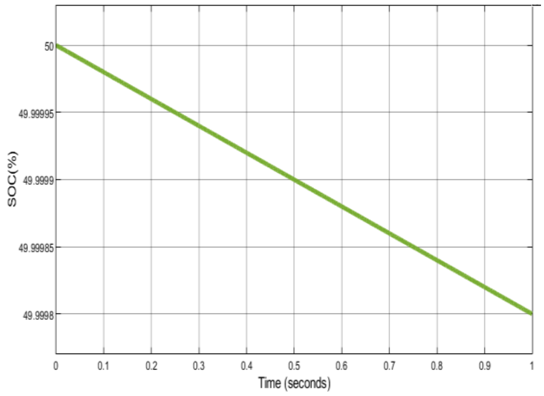


Fig13 SOC of the battery

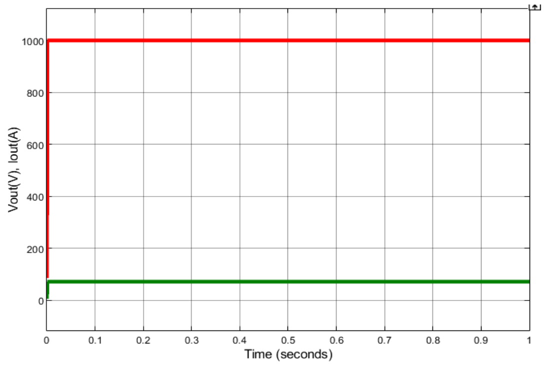


Fig14 Simulation waveforms of the output voltage and current.

As Table II shows, the proposed bidirectional three-leg DC–DC converter with SMC outperforms the conventional system — higher efficiency (97%), lower voltage ripple (2%), lower current ripple (3%), faster settling time (0.05 s), and improved dynamic response (0.08 s) — while its bidirectional capability enables both G2V and V2G operation, enhancing energy recovery and smart-grid interaction.

COMPARSION TABLE

Parameter	Existing System	Proposed / Extension System
Battery Voltage	400 V / 800 V	1000 V
Converter Type	Three-leg DC–DC Converter	Bidirectional Three-leg DC–DC Converter
Control Technique	Conventional Controller	Sliding Mode Controller (SMC)
Operating Frequency	93 kHz	93 kHz
Output Voltage Regulation	±5%	±1%
Current Ripple	9%	3%
Voltage Ripple	6%	2%
System Efficiency	90%	97%
Dynamic Response Time	0.25 s	0.08 s
Settling Time	0.20 s	0.05 s
Power Transfer Capability	5 kW	10 kW
Bidirectional Power Flow	No	Yes
G2V Operation	Not Available	Available
V2G Operation	Not Available	Available
SOC Monitoring Accuracy	Moderate	High
Stability Margin	Moderate	High
Charging Speed	Normal	Fast
Energy Recovery	Not Possible	Possible
Overall Performance	Moderate	Superior

CONCLUSION

This paper presented an SMC-based inductive EV charging system using a three-leg bidirectional converter for wide-range battery charging. The architecture enabled efficient bidirectional power transfer between grid and battery in both G2V and V2G modes, while high-frequency isolation transformers improved safety, size, and power density. The SMC controller gave robust voltage regulation and disturbance rejection, maintaining stable DC-link voltage and battery current while minimizing ripple and overshoot. MATLAB/Simulink results confirmed high conversion efficiency, improved power quality, and reliable bidirectional operation, indicating that the proposed converter with SMC is a promising solution for next-generation EV charging with high efficiency, flexibility, and grid interaction — including V2G support for smart-grid functionality, renewable integration, and peak-load management.

Future work may target hardware-prototype validation, AI/ML-based adaptive control for further efficiency and battery-management gains, and integration with renewable energy and storage systems for sustainable, intelligent transportation networks.

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