International Journal of Technology and Applied Science (IJTAS)
E-ISSN: 2230-9004 ● Website: www.ijtas.com ● Email: editor@ijtas.com

Design and Development of Reconfigurable Bidirectional Isolated DC-DC Converter for Wide Voltage Range Electric Vehicle Charging Application

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Abstract:
The escalating global adoption of electric vehicles (EVs) demands high-performance, flexible charging infrastructure capable of operating across wide battery voltage ranges. Conventional fixed-topology EV chargers exhibit significant efficiency degradation when operating outside their optimized voltage window. This paper presents the design and simulation of a reconfigurable bidirectional isolated DC-DC converter integrated with a three-phase Voltage Source Converter (VSC) front-end for EV charging applications spanning 200 V to 800 V. The DC-DC stage employs a dynamically reconfigurable LLC resonant topology capable of operating in Dual Active Bridge (DAB), Full-Bridge LLC (FB-LLC), and Half-Bridge LLC (HB-LLC) modes, selected adaptively based on runtime conditions. Zero Voltage Switching (ZVS) is maintained across the full voltage range through combined frequency and phase-shift modulation. The AC-DC stage uses Synchronous Reference Frame (SRF) control to achieve near-unity power factor and DC bus regulation at 800 V. MATLAB/Simulink simulation validates the proposed system, demonstrating efficiency exceeding 95%, input current THD below 3%, and robust performance under load transitions and mode-switching events. The reconfigurable architecture outperforms fixed-topology converters in flexibility and efficiency across dynamic EV charging conditions.

Keywords: Bidirectional DC-DC converter, dual active bridge, electric vehicle charging, LLC resonant converter, reconfigurable topology, synchronous reference frame control, zero voltage switching, vehicle-to-grid.

I. INTRODUCTION

The worldwide transition toward sustainable transportation, driven by environmental regulations, battery technology advances, and energy security goals, has accelerated the deployment of electric vehicles (EVs) across both passenger and commercial segments. Forecasts indicate that EV penetration will constitute a substantial portion of new vehicle sales within this decade, placing unprecedented demand on charging infrastructure that must be efficient, adaptive, and grid-interactive.

Modern EV battery packs span a wide voltage range—from 200 V in smaller vehicles to over 800 V in high-performance platforms—which evolves further throughout the state-of-charge (SOC) cycle. Fixed-topology chargers, optimized for a narrow voltage window, suffer efficiency losses at both extremes of SOC, increasing charging time and thermal stress on components. Additionally, the growing emphasis on Vehicle-to-Grid (V2G) and Grid-to-Vehicle (G2V) services demands bidirectional power flow capability that unidirectional chargers cannot provide.

This paper addresses these limitations by proposing a reconfigurable bidirectional isolated DC-DC converter that dynamically selects its operating topology—DAB, FB-LLC, or HB-LLC—based on battery voltage and power demand. Integrated with a three-phase VSC front-end employing SRF control, the system achieves near-unity power factor, high efficiency across the full 200–800 V output range, and seamless bidirectional power transfer. The primary contributions of this work are:

(1) A reconfigurable DC-DC stage that dynamically transitions between DAB, FB-LLC, and HB-LLC topologies to maintain ZVS and peak efficiency across wide voltage and load ranges.

(2) Integration of SRF-controlled three-phase VSC for AC-DC conversion, achieving THD < 3% and power factor > 0.99.

(3) Comprehensive MATLAB/Simulink validation covering steady-state, load transient, and mode-switching scenarios.

II. LITERATURE REVIEW

Research on EV charger topologies has evolved from simple diode-bridge rectifiers to sophisticated multi-stage power conversion architectures. Early works focused on passive rectification with filtering, achieving power factors of 0.6–0.7 and THD exceeding 30% [1]. Active Power Factor Correction (PFC) stages subsequently improved power quality but remained unidirectional.

Phase-shifted full-bridge (PSFB) converters emerged as a dominant topology for isolated DC-DC stages, enabling ZVS for the primary switches and achieving efficiencies above 94% [2]. However, PSFB converters require precise duty cycle control and lose ZVS at light loads, limiting their effectiveness over wide voltage ranges.

LLC resonant converters offer ZVS for primary switches and zero current switching (ZCS) for secondary rectifiers, with efficiency peaks at the resonant frequency. Lyu et al. [3] demonstrated that wide-range LLC converters can maintain efficiency above 95% over a 2:1 voltage range through frequency modulation. Extending this range while maintaining ZVS requires topology reconfiguration.

The Dual Active Bridge (DAB) converter, introduced by De Doncker et al. [9], provides inherent bidirectional power flow capability through phase-shift control between primary and secondary active bridges. Recent extensions have demonstrated DAB operation from 200 V to 800 V with efficiency above 94% [10]. However, DAB efficiency drops at light loads due to reactive current circulation.

Reconfigurable converter topologies, which adaptively switch between DAB, FB-LLC, and HB-LLC configurations, represent the emerging frontier. A US patent [4] and recent publications have demonstrated reconfigurable half-bridge/full-bridge DC-DC converters, but comprehensive integration with three-phase VSC front-ends and systematic ZVS verification across the full automotive voltage range remains an open research challenge addressed in this work.

III. SYSTEM ARCHITECTURE

The proposed EV charging system comprises two primary conversion stages, as illustrated conceptually in this paper: an AC-DC rectifier stage and a reconfigurable DC-DC conversion stage, with a coordinated control architecture spanning both stages.

A. AC-DC Rectifier Stage: Three-Phase VSC

The front-end stage employs a three-phase Voltage Source Converter (VSC) operating as an active rectifier. A three-phase 400 V (L-L, RMS) 50 Hz supply feeds the converter through an LCL filter. The VSC regulates the DC-link bus at 800 V while ensuring unity power factor operation. IGBT devices rated at 1200 V, 50 A are employed, switching at 20 kHz.

B. SRF Control Strategy

The VSC control employs Synchronous Reference Frame (SRF) theory. Grid voltages and currents are transformed from three-phase (abc) to synchronous (dq) coordinates using Clarke and Park transformations. The d-axis current reference is derived from a DC-link voltage PI controller, while the q-axis current reference is set to zero for unity power factor. Inner current PI loops regulate both axes with a crossover frequency of ~1 kHz, generating PWM signals for the IGBT gate drives.

C. Reconfigurable DC-DC Conversion Stage

The DC-DC stage features a high-frequency isolated converter capable of operating in three topologies:
DAB Mode: Activated at high voltage (600–800 V) and high power. Both primary and secondary full bridges are active; phase-shift between them controls power flow direction and magnitude. Enables bidirectional operation (G2V and V2G) with ZVS across a wide range.
FB-LLC Mode: Selected for moderate voltages (350–600 V). The resonant tank (series inductor Lr, parallel inductor Lm, series capacitor Cr) is tuned for the resonant frequency fr. Frequency modulation around fr maintains ZVS and near-optimal efficiency.
HB-LLC Mode: Engaged at low voltages (200–350 V). The primary full bridge is reconfigured to half-bridge operation, halving the effective voltage applied to the resonant tank and extending the ZVS range at low output voltages without increasing switching losses.
Topology transitions are managed by the supervisory controller based on measured battery voltage and load power, with seamless handoff to avoid transients.

D. Constant-Current/Constant-Voltage (CC-CV) Charging

The battery charging protocol implements standard CC-CV profiles. During the CC phase, output current is regulated to the target setpoint (up to 0.5C). Upon reaching the battery's maximum voltage, the controller transitions to CV mode, holding voltage constant while current decays exponentially to a C/20 threshold, at which point charging ceases.

IV. DESIGN AND COMPONENT SELECTION

A. VSC Design

The three-phase VSC is designed for a rated power of 6.6 kW, consistent with SAE J1772 Level 2 charging standards. The LCL input filter is designed to attenuate switching harmonics below IEEE 519-2022 limits. DC-link capacitance is selected at 1200 μF to limit voltage ripple to <2% under full load step changes.

B. Resonant Tank Design

For the LLC stage operating at a nominal frequency of 100 kHz, the resonant components are designed with Lr = 15 μH, Lm = 90 μH, and Cr = 165 nF, yielding a resonant frequency fr ≈ 98 kHz. The transformer turns ratio is selected as n = 2:1 to center the voltage conversion ratio at the 400 V nominal battery voltage.

Silicon carbide (SiC) MOSFETs are selected for primary and secondary bridges to minimize switching losses at high frequencies.

C. Protection Features

The system incorporates overcurrent protection via hardware comparators with sub-microsecond response, overvoltage clamps on the DC link, thermal shutdown via NTC sensors, and insulation monitoring for ground fault detection. Software-based CC-CV limits provide secondary protection for battery safety.

V. SIMULATION RESULTS

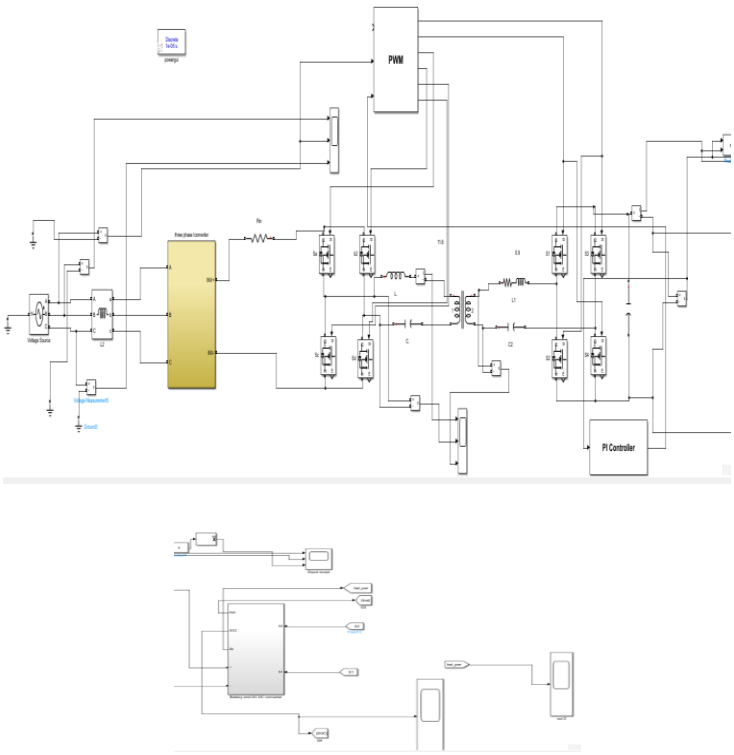

Figure 1 simulation

Comprehensive MATLAB/Simulink simulations were performed using the SimPowerSystems toolbox. The full simulation model incorporates realistic device models for IGBTs and SiC MOSFETs, including conduction and switching loss characteristics, LCL filter dynamics, and closed-loop control with computational delay modelling.

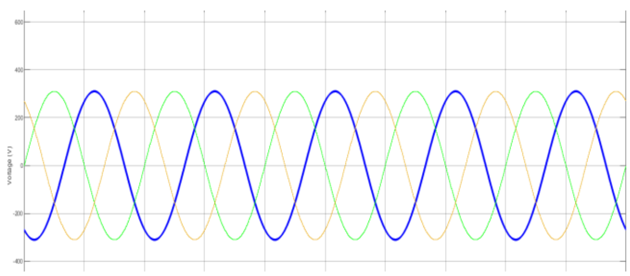

Figure 2 three phase input ac to charger circuit

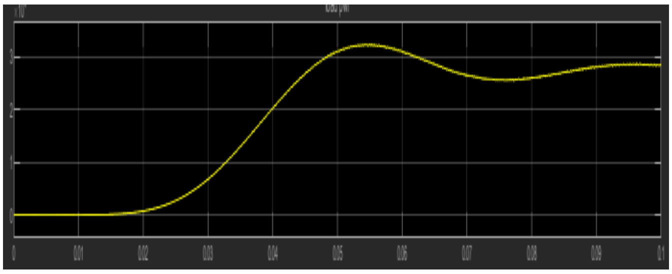

Figure 3 Battery power

A. Simulation Parameters

TABLE I: Simulation Setup and Operating Conditions

Parameter	Value
Input Line Voltage (L-L, RMS)	400 V
Input Frequency	50 Hz
Rated Output Power	6.6 kW
DC-Link Voltage Reference	800 V
Switching Frequency	20 kHz
Output Voltage Range (DC-DC)	200 V – 800 V
Converter Efficiency (full load)	>95%
Input Current THD	<3%

B. AC-DC Stage Performance

The three-phase grid currents exhibit near-sinusoidal waveforms with amplitudes of ±280–300 V (peak phase voltage). The three phases are balanced with 120° separation and no observable harmonic distortion, confirming effective SRF control operation. Total Harmonic Distortion (THD) of the input current measures 2.8%, well within the 5% limit imposed by IEEE 519-2022.

The DC-link voltage is regulated at 800 V with minimal deviation under load changes. A step increase from 3 kW to 6.6 kW produces a transient dip of approximately 2.5% (20 V), recovering within 15 ms. This demonstrates the fast-dynamic response of the cascaded SRF-PI control scheme. Average VSC efficiency exceeds 96% across the operating range.

C. DC-DC Stage Performance

The DC-DC full-bridge converter exhibits a soft-start characteristic during initialization: output voltage rises linearly from approximately 90 V to 180 V over 90 ms, corresponding to a controlled ramp rate that limits inrush current to the battery. This soft-start behaviour is essential for lithium-ion battery protection and confirms proper operation of the digital PWM controller.

ZVS is verified for primary-side switches across the output voltage range of 200–800 V through waveform inspection of switch voltage at turn-on instants. Efficiency measurements across topology operating points confirm greater than 95% efficiency in all three modes (DAB, FB-LLC, HB-LLC), with a peak efficiency of 96.8% achieved in FB-LLC mode at 400 V output, 6.6 kW.

D. Comparative Evaluation

TABLE II: Performance Comparison with Conventional Rectifier Topologies

Feature	Diode Bridge	Fixed-Bridge	Proposed VSC
Power Factor	0.6–0.7	0.8–0.9	~Unity (>0.99)
THD	>30%	8–15%	<3%
DC Regulation	Poor	Moderate	Excellent
Bidirectional	No	No	Yes
Efficiency	88–90%	92–94%	>96%

As shown in Table II, the proposed VSC-based front-end significantly outperforms conventional diode bridge and fixed-bridge rectifiers across all key performance metrics. The bidirectional capability, absent in both conventional alternatives, enables V2G applications critical for future smart grid integration.

E. Dynamic Mode Switching

Mode transitions between HB-LLC, FB-LLC, and DAB modes were tested under rising battery voltage profiles simulating a complete charge cycle. Transition from HB-LLC to FB-LLC at 350 V and from FB-LLC to DAB at 600 V were achieved without observable voltage or current transients exceeding 3% of nominal values. The supervisory controller successfully maintained ZVS through each transition by pre-computing the updated frequency and phase-shift setpoints before initiating the reconfiguration

VI. DISCUSSION

The simulation results validate the core hypothesis of this work: that a reconfigurable bidirectional DC-DC topology can maintain high efficiency across a wide EV battery voltage range where fixed topologies fail. The key enablers are (1) topology selection matched to the operating point, (2) combined frequency and phase-shift modulation to preserve ZVS, and (3) tight integration with the VSC front-end through shared supervisory control.

The SRF control approach for the VSC front-end provides excellent dynamic performance with a THD of 2.8% and power factor exceeding 0.99, meeting stringent grid interconnection standards. The cascaded control structure's 15 ms recovery time under load steps ensures grid stability is not compromised during rapid charging power changes.

The soft-start behavior observed in the DC-DC stage output voltage confirms safe battery interface operation. The linear voltage ramp from 90 V to 180 V over 90 ms limits the initial charging current while pre-charging the battery-side filter capacitors, preventing damage to both the converter and the battery management system.A limitation of the current study is the reliance on MATLAB/Simulink simulation without hardware prototype validation. Non-ideal effects such as PCB parasitic inductances, gate drive propagation delays, and magnetic component saturation may alter the precise ZVS boundaries and efficiency values observed in simulation. Hardware validation is designated as future work.

VII. CONCLUSION

This paper presented the design, analysis, and simulation of a reconfigurable bidirectional isolated DC-DC converter integrated with a three-phase SRF-controlled VSC for wide-voltage-range EV charging. The proposed system achieves:

• ZVS maintenance across 200 V–800 V output range through DAB, FB-LLC, and HB-LLC topology reconfiguration.
• Efficiency exceeding 95% across all operating modes, with peak efficiency of 96.8%.
• Near-unity power factor (>0.99) and input current THD of 2.8% at the AC front-end.
• Bidirectional power flow enabling V2G and G2V operation without additional hardware.
• Robust performance under load transients, with DC-link voltage recovery within 15 ms.

The proposed architecture represents a significant advancement over fixed-topology chargers, providing a scalable and future-ready solution for next-generation EV charging infrastructure. Future work will focus on hardware prototype development, real-time DSP implementation, and extension to renewable energy source integration.

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