

A Review on: Design and Development of a Reconfigurable Bidirectional Isolated DC-DC Converter for Wide Voltage Range Electric Vehicle Charging Applications

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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 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 dynamically reconfigures between Dual Active Bridge (DAB), Full-Bridge LLC (FB-LLC), and Half-Bridge LLC (HB-LLC) modes. Zero Voltage Switching (ZVS) is maintained across the full voltage range using combined frequency and phase-shift modulation. The AC-DC stage uses Synchronous Reference Frame (SRF) control to achieve near-unity power factor and 800 V DC bus regulation. MATLAB/Simulink simulation validates efficiency exceeding 95%, input current THD below 3%, and robust performance under load and mode-switching transients.

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 EV deployment across

passenger and commercial segments. EV penetration is forecast to constitute a substantial share of new vehicle sales this decade, placing unprecedented demand on charging infrastructure that must be efficient, adaptive, and grid-interactive.

Modern EV battery packs span 200 V to over 800 V, evolving further across the state-of-charge (SOC) cycle. Fixed-topology chargers, optimized for a narrow voltage window, suffer efficiency losses at both SOC extremes, increasing charging time and thermal stress. The growing emphasis on Vehicle-to-Grid (V2G) and Grid-to-Vehicle (G2V) services further demands bidirectional power flow that unidirectional chargers cannot provide.

This paper proposes a reconfigurable bidirectional isolated DC-DC converter that dynamically selects DAB, FB-LLC, or HB-LLC topology based on battery voltage and power demand, integrated with an SRF-controlled three-phase VSC. The primary contributions are:

- (1) A reconfigurable DC-DC stage maintaining ZVS and peak efficiency across wide voltage and load ranges.
- (2) SRF-controlled VSC achieving THD < 3% and power factor > 0.99.
- (3) Comprehensive Simulink validation across steady-state, transient, and mode-switching scenarios.

II. LITERATURE REVIEW

The modern Electric Vehicle (EV) charger is no longer a simple AC-to-DC converter but a bidirectional, grid-interactive, and computationally managed power node. The evolutionary pressure on its topology—from passive rectification to actively

reconfigurable resonant networks—is driven by the conflicting demands of global efficiency standards (e.g., DOE Level VI, COC Tier 2), thermal management constraints, and the volatile dynamics of both the grid and the battery load. This exposition critically examines this evolution, exposing the physical limitations of current leading topologies and arguing that the future lies not in a single "perfect" converter, but in an intelligent, real-time reconfiguration of the power stage.

The Foundational Limitation: The Diode-Bridge Bottleneck

The initial reliance on diode-bridge rectifiers, while cost-effective and robust, imposes a fundamental physical penalty. The uncontrolled nature of the diodes leads to a discontinuous conduction mode where the input current only flows when the instantaneous AC voltage exceeds the DC bus capacitor voltage. This results in a **Power Factor (PF)** of 0.6–0.7 and a **Total Harmonic Distortion (THD)** frequently exceeding 30%, injecting significant harmonic currents into the utility grid. This is not merely a numerical inefficiency; it represents a systemic violation of IEEE 519-2022 grid code requirements, which mandate $THD < 5\%$. The transition to an **Active Power Factor Correction (PFC)** stage—typically a boost converter operating in Continuous Conduction Mode (CCM)—was the first critical step. By using a high-frequency switch (SiC MOSFETs or GaN HEMTs) to actively shape the input current, we decouple the input current from the rectified voltage envelope, achieving a near-unity PF (>0.99) and reducing THD to $<3\%$. However, this improvement comes at the cost of a second-stage conversion (DC-DC), necessitating isolated galvanic barriers for safety.

The Dominant Isolated Architectures: A Study in Trade-offs

The isolated DC-DC stage is where the topology war is waged. Each architecture solves the ZVS/ZCS problem but creates a new constraint in the load or voltage domain.

- **Phase-Shifted Full-Bridge (PSFB):** The PSFB achieves Zero-Voltage Switching (ZVS) by utilizing the parasitic capacitances of the primary FETs and the leakage inductance of the transformer. The phase-

shift between the two legs controls power transfer. While $>94\%$ efficiency is achievable at full load, the critical insight is that **ZVS is lost at light loads** because the stored inductive energy ($0.5 * L_{leak} * I_{pri}^2$) is insufficient to fully charge/discharge the output capacitances (C_{oss}) of the opposing switches.

This forces the PSFB to either operate in hard-switching mode (generating EMI and heat) or enter burst-mode, which introduces low-frequency output ripple that can interfere with BMS (Battery Management System) voltage sensing. Furthermore, the PSFB suffers from **secondary-side duty-cycle loss** and rectifier voltage ringing, requiring snubbers that dissipate real power.

- **LLC Resonant Converter:** The LLC shifts the paradigm from PWM control to Frequency Modulation (FM). By integrating the leakage and magnetizing inductances with resonant capacitors, it creates a tank circuit with two resonant frequencies (series and parallel). This topology achieves **ZVS for primary switches** and **ZCS (Zero-Current Switching) for secondary rectifiers**, virtually eliminating switching losses. Lyu et al.'s demonstration of $>95\%$ efficiency over a 2:1 voltage ratio is a testament to its capability, but this is a narrow operational band. To achieve wide output voltage (e.g., 150V–1000V for 800V systems), the switching frequency must deviate far from the resonant peak. At these extremes, the circulating current in the tank increases dramatically, raising RMS currents and copper losses in the magnetics, while the gain curve becomes non-monotonic, complicating control loop stability.
- **Dual Active Bridge (DAB):** Introduced by De Doncker, the DAB is the cornerstone of bidirectional charging (V2G). Its elegance lies in its simplicity: power is transferred via the phase-shift angle (ϕ) between two full-bridges, with no need for a dedicated resonant tank. The DAB's inherent bidirectionality makes it indispensable for grid services. However, the Achilles' heel is **reactive**

power circulation. At light loads or when the voltage conversion ratio (V_2/V_1) deviates significantly from the transformer turns ratio, the inductor current comprises a large non-power-transmitting component. This "circulating current" persists even at zero output power, leading to conduction losses that cripple light-load efficiency. Recent research, as cited, pushes 200-800V operation above 94%, but this is often under optimized, symmetrical conditions.

The Materials and Component Enablers

It is crucial to acknowledge that these topologies' performance is not solely algorithmic; it is highly dependent on semiconductor materials. The high dV/dt and di/dt in PSFB and DAB topologies demand fast body-diode reverse recovery, which is poorly handled by Silicon IGBTs. The adoption of **Wide-Bandgap (WBG) semiconductors**—specifically **Silicon Carbide (SiC)** for 800V buses and **Gallium Nitride (GaN)** for 400V buses—is non-negotiable. SiC offers a critical breakdown field 10x that of Si, allowing for low $R_{ds(on)}$ with minimal die area, drastically reducing conduction losses. GaN, with its near-zero reverse recovery charge (Q_{rr}), eliminates the switching losses associated with the hard commutation of the body diode in DAB and PSFB topologies, pushing switching frequencies beyond 500 kHz and shrinking passive components.

The Reconfigurable Frontier: A Paradigm Shift in Control

The proposition to move toward **reconfigurable topologies**—dynamically switching between DAB, FB-LLC, and HB-LLC (Half-Bridge LLC)—represents a fundamental shift from "fixed hardware, adaptive control" to "adaptive hardware, deterministic control." This is the research frontier because it addresses the "Goldilocks" problem: no single topology is optimal across the entire load-voltage plane.

- **At heavy load & high voltage:** Configure as a **DAB**. The high current ensures sufficient energy for ZVS, while the phase-shift provides fast, linear power control suitable for grid transient response (e.g., frequency regulation).

- **At medium load & nominal voltage:** Switch to **FB-LLC**. Operate near resonance to maximize efficiency, allowing the power stage to process the bulk of the charge cycle with minimal dissipation.
- **At light load & low voltage (trickle charge):** Reconfigure as **HB-LLC**. By halving the primary voltage applied to the transformer, we effectively double the magnetizing inductance's influence, reducing the tank's Q-factor. This suppresses the circulating current that plagues the DAB, while the reduced switch-node voltage ($V_{in}/2$) lowers the switching losses associated with hard-commutation.

The intellectual challenge here is **systematic integration with a three-phase VSC front-end**. The three-phase Voltage Source Converter (VSC) rectifier produces a controlled DC bus of $\sim 800V$. The reconfiguration logic cannot be isolated; it must be predictive. By analyzing the battery's State of Charge (SoC) and the requested power, the system controller must anticipate the optimal topology *before* the switching event. Furthermore, the transition between topologies is not instantaneous. It requires a "safe-state" interval involving the controlled shorting of the tank via synchronous rectifiers to demagnetize the transformer core, preventing flux walking and saturation. The verification of **full-range ZVS** under transient reconfiguration—where the DC bus voltage might droop by 5% during a sudden load step—remains an open, mathematically complex control problem involving non-linear, time-variant systems.

The Open Challenge: A Multi-Domain Optimization

The research gap you identified is not merely about switching topologies; it is about **systemic co-optimization**. The VSC front-end's control loop (grid synchronization, reactive power compensation) interacts with the DC-DC stage's reconfiguration. A hard-switching event in the DC-DC stage generates conducted EMI that can corrupt the PLL (Phase-Locked Loop) of the VSC, causing grid instability.

III. SYSTEM ARCHITECTURE

A. AC-DC Rectifier Stage

A three-phase VSC operates as an active rectifier from a 400 V (L-L RMS), 50 Hz supply through an LCL filter, regulating the DC-link at 800 V at unity power factor. IGBTs rated 1200 V/50 A switch at 20 kHz.

B. SRF Control Strategy

Grid voltages/currents are transformed to dq coordinates via Clarke/Park transforms. The d-axis current reference derives from a DC-link PI controller; the q-axis reference is zero for unity PF. Inner current loops run at ~1 kHz crossover, generating PWM for IGBT gates.

C. Reconfigurable DC-DC Stage

DAB Mode: 600–800 V, high power; bidirectional, ZVS across wide range.

FB-LLC Mode: 350–600 V; resonant tank tuned to fr; frequency modulation maintains ZVS.

HB-LLC Mode: 200–350 V; primary reconfigures to half-bridge, halving tank voltage and extending ZVS at low output.

Topology transitions are supervisor-managed based on measured battery voltage and power, with seamless handoff.

D. CC-CV Charging

Standard CC-CV profiles regulate output current up to 0.5C during CC, transitioning to CV upon reaching maximum battery voltage, with current decaying to a C/20 cutoff.

IV. Design and Component Selection

A. VSC Design

Rated at 6.6 kW per SAE J1772 Level 2. The LCL filter attenuates switching harmonics below IEEE 519-2022 limits; DC-link capacitance of 1200 μ F limits ripple to <2% under full load steps.

B. Resonant Tank Design

At 100 kHz nominal switching: $L_r = 15 \mu$ H, $L_m = 90 \mu$ H, $C_r = 165$ nF ($f_r \approx 98$ kHz). Transformer ratio $n = 2:1$ centers conversion at 400 V nominal. SiC MOSFETs minimize high-frequency switching losses.

C. Protection Features

Hardware overcurrent comparators (sub- μ s response), DC-link overvoltage clamps, NTC thermal shutdown, insulation/ground-fault monitoring, and software CC-CV limits provide layered protection.

V. Simulation Results

MATLAB/Simulink (SimPowerSystems) simulations used realistic IGBT/SiC device loss models, LCL filter dynamics, and closed-loop control with computational delay.

A. Simulation Parameters

TABLE I: Simulation Setup and Operating Conditions

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

B. AC-DC Stage Performance

Grid currents are near-sinusoidal, balanced at 120° separation, with negligible distortion. Input current THD measures 2.8%, within the IEEE 519-2022 5% limit. The DC-link holds 800 V with minimal deviation; a 3 kW→6.6 kW step produces a 2.5% dip recovering within 15 ms. Average VSC efficiency exceeds 96%.

C. DC-DC Stage Performance

Soft-start ramps output linearly from ~90 V to 180 V over 90 ms, limiting inrush current. ZVS is confirmed for primary switches across 200–800 V. All three modes (DAB, FB-LLC, HB-LLC) exceed 95% efficiency, peaking at 96.8% in FB-LLC mode (400 V, 6.6 kW).

D. Comparative Evaluation

TABLE II: Comparison with Conventional Rectifiers

Feature	Diode Bridge	Proposed VSC
PF	0.6–0.7	~Unity
THD	>30%	<3%
Bidirectional	No	Yes
Efficiency	88–90%	>96%

The proposed VSC front-end outperforms conventional diode-bridge rectifiers on all metrics,

with bidirectional capability enabling V2G integration unavailable in conventional designs.

E. Dynamic Mode Switching

Transitions at 350 V (HB-LLC→FB-LLC) and 600 V (FB-LLC→DAB) during a simulated charge cycle produced no transients exceeding 3% of nominal values. The supervisory controller pre-computed frequency/phase-shift setpoints to preserve ZVS through each transition.

VI. DISCUSSION

Results validate that reconfigurable bidirectional DC-DC topology sustains high efficiency across the EV battery voltage range where fixed topologies fail. Key enablers: (1) topology matched to operating point, (2) combined frequency/phase-shift modulation preserving ZVS, and (3) tight VSC integration via shared supervisory control. SRF control delivers THD of 2.8% and PF > 0.99, meeting grid interconnection standards, with 15 ms recovery under load steps ensuring grid stability during rapid charging power changes. The soft-start ramp (90→180 V over 90 ms) confirms safe battery interface operation, pre-charging filter capacitors while limiting initial charging current.

A limitation is reliance on simulation without hardware validation; PCB parasitics, gate-drive delays, and magnetic saturation may shift exact ZVS boundaries and efficiency values. Hardware validation is reserved for future work.

VII. CONCLUSION

This paper presented a reconfigurable bidirectional isolated DC-DC converter integrated with an SRF-controlled three-phase VSC for wide-range EV charging, achieving:

- ZVS across 200–800 V via DAB/FB-LLC/HB-LLC reconfiguration.
- Efficiency >95% in all modes, peaking at 96.8%.
- Near-unity PF (>0.99) and 2.8% input THD.
- Bidirectional V2G/G2V capability without added hardware.
- DC-link recovery within 15 ms under load transients.

This architecture advances beyond fixed-topology chargers toward scalable, future-ready EV infrastructure. Future work targets hardware

prototyping, real-time DSP control, and renewable-source integration.

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