DESIGN OF EFFICIENT POWER CONVERTERS FOR ELECTRIC VEHICLE CHARGING AND VEHICLE-TO-GRID APPLICATIONS

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Presentation Outline

- Introduction & Background
- Scope of V2G
- Comparison of Charging Topologies
- Conventional and Proposed Designs
- Modes of Operation
- Flow and Block Charts
- Results
- Analysis
- Challenges and Future Research

Introduction & Background

- Electric vehicles (EVs) have emerged as invaluable tools in the pursuit of carbon neutrality.
- Growing number of EVs poses a challenge to current power grids by introducing additional load.
- One solution to manage this increased demand is integrating EV batteries into the power grid.
- Vehicle-to-grid technologies utilize EV battery storage capabilities to balance the grid, supply power when necessary and prevent the inefficient and complex grid upgrade/gas peaker plant operations.

Introduction & Background

- Different types of charging and discharging systems, such as integrated/non-integrated and on/off board, etc., which have been used for electric vehicle applications.
- Common uses such as Tesla Powerwall or Ford Charge Station Pro etc. are only beneficial on an individual level.
- The conventional on-board EV charger configuration involves the use of two converters.

Introduction & Background

- The proposed topology leverages EV batteries as dynamic energy storage units.

- EV charger can accept and deliver energy to and from the grid in a bidirectional manner.

- Bidirectional onboard chargers can be used to charge other vehicle batteries in Vehicle-to-Vehicle (V2V) or V2H applications as well.

Importance Of Clean Energy

- Transitioning to clean energy sources is of paramount importance in Canada as it plays a vital role in reducing carbon emissions and combating climate change.

- By shifting away from fossil fuels and embracing renewable energy technologies, Canada can contribute to global efforts aimed at achieving sustainable development and meeting international climate targets.

- Investing in clean energy not only helps protect the environment but also presents opportunities for job creation, economic growth, and the development of a resilient and sustainable energy sector in Canada.

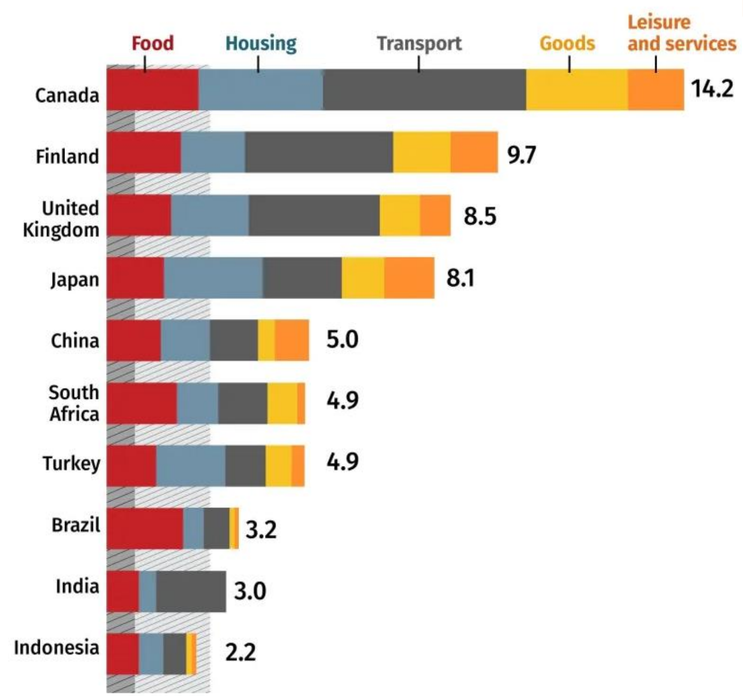


Figure: CO_2 Footprint(tonnes) /capita /year

The Scope of V2G and NL

It's important to note that while the energy consumption of EVs will increase, the overall environmental impact depends on the emissions associated with electricity generation. By transitioning to cleaner energy sources, such as renewable and low-carbon sources, the environmental benefits of widespread EV adoption can be maximized, leading to reduced carbon emissions and improved air quality.

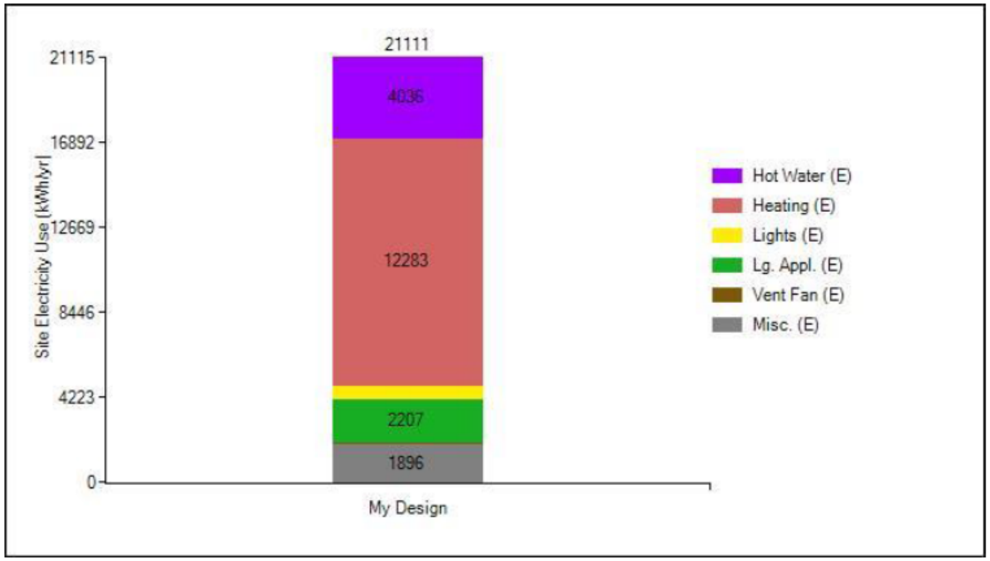


Figure: Average household energy use per year, NL

Comparison of Different Charging Topologies

	Charging Efficiency	EV/Battery Degradation	Flexibility/Comfort	Cost
Level 1-2 Charging	Low	Very Low	Low	Low
DC Fast Charging	Very High	Low	Medium	High
Inductive Charging	Very Low	Medium	Medium	High
Battery Exchange	-	-	Very High	-
Bidirectional V2G (Proposed Method)	Very High	Medium*	High	Very Low – Low*

Block diagram

The isolated bidirectional DC-DC converter block diagram shown in Figure 1 is referred to as a single-stage topology [41].

These topologies consist of a minimum number of converter stages. The number of required elements is lower compared to other multi-stage topologies.

Nevertheless, operating across a wide input and output voltage variation range can lead to inefficient use of transformers and switch elements.

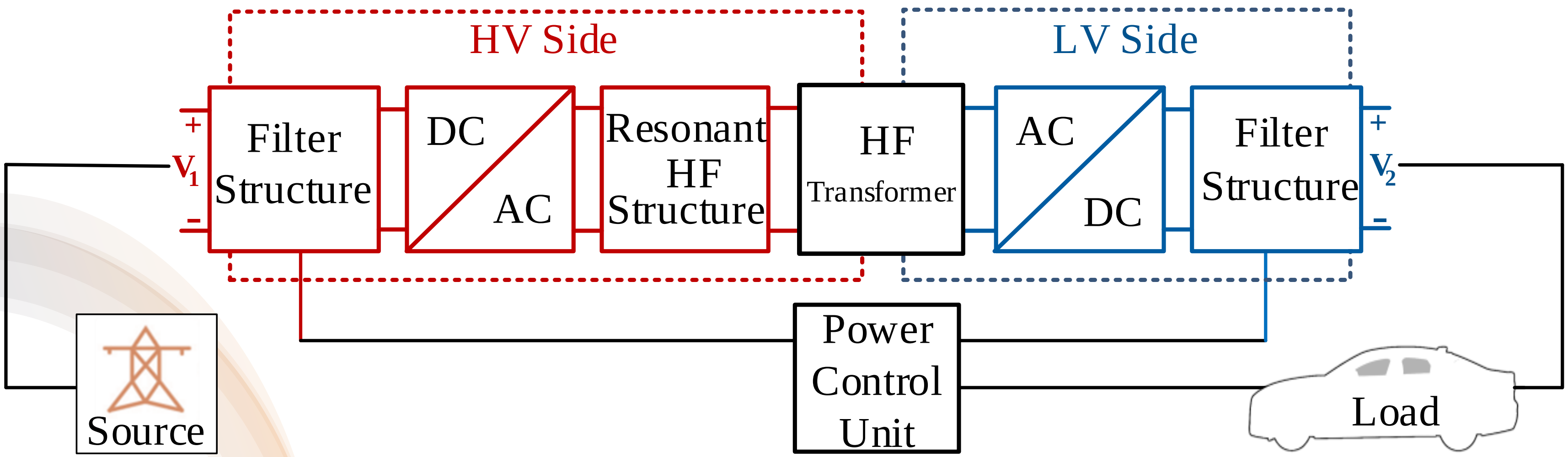
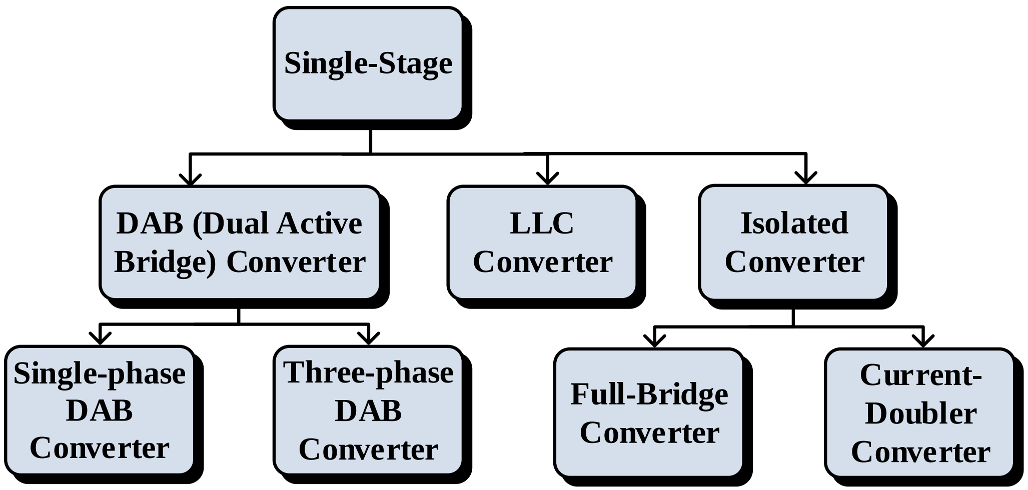
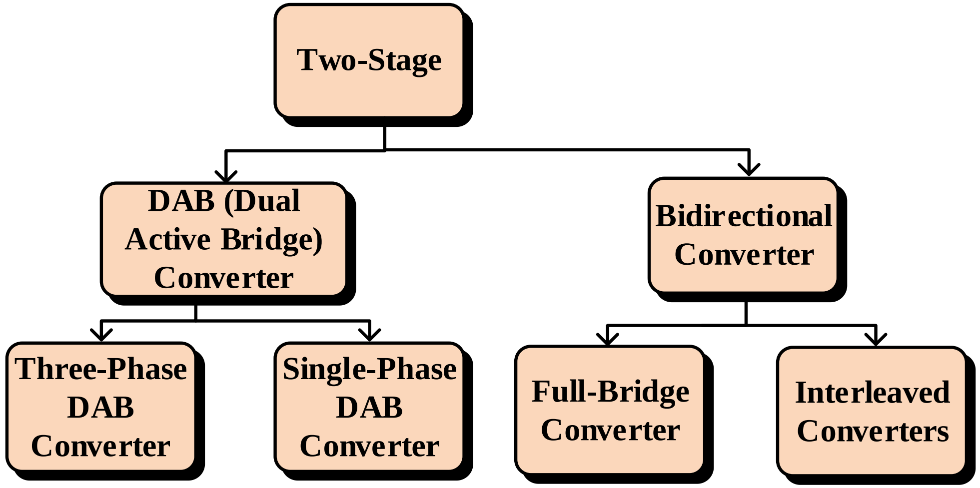


Figure: Block diagram of the basic structures in an isolated bidirectional DC/DC converter

Single & Two-Stage Converter Topologies





Conventional Design

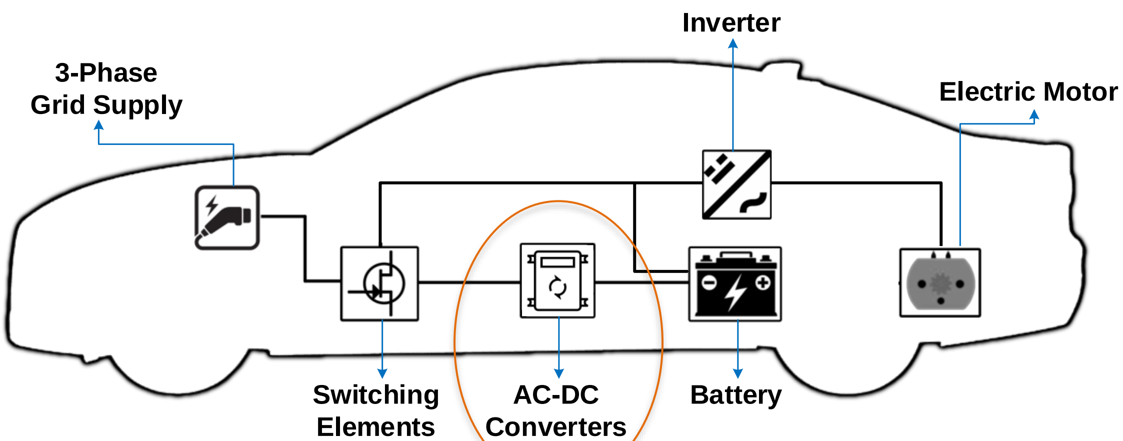


Figure: Conventional AC-DC On-Board Charger Design

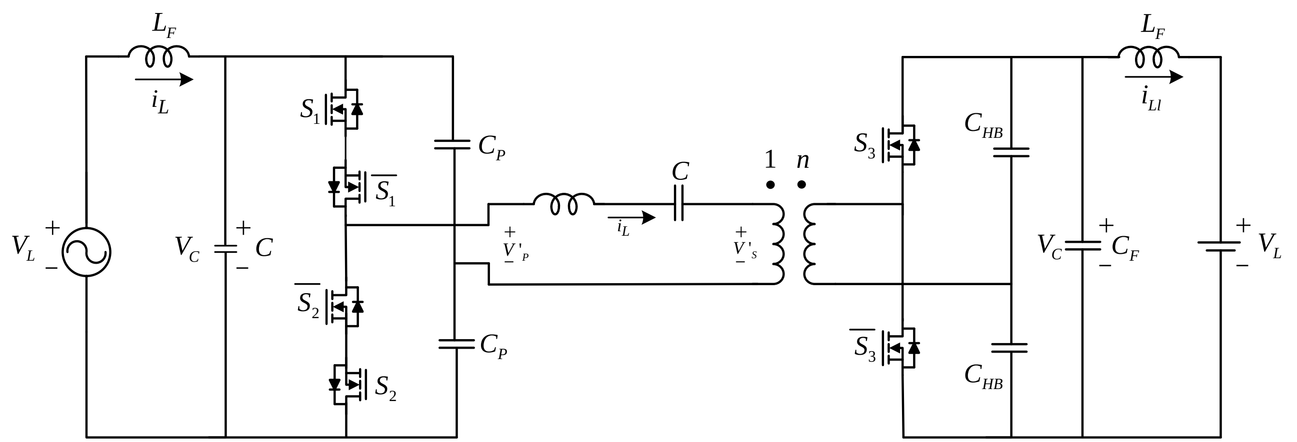


Figure: AC-DC Bidirectional Single Stage Converter with V2G Capability

Potential Implementations

- Bidirectional chargers offer higher charging efficiency, minimizing energy losses during conversion and transmission. This leads to faster charging, improved energy utilization, reduced charging time, and better energy economy.

- Although bidirectional chargers may have higher upfront costs, they offer long-term cost savings. EV owners can possibly even generate revenue by providing grid services and participating in energy markets, offsetting installation costs. Additionally, the utilization of EV batteries for both transportation and grid support reduces the need for additional stationary energy storage systems, optimizing overall costs.

Proposed Topology

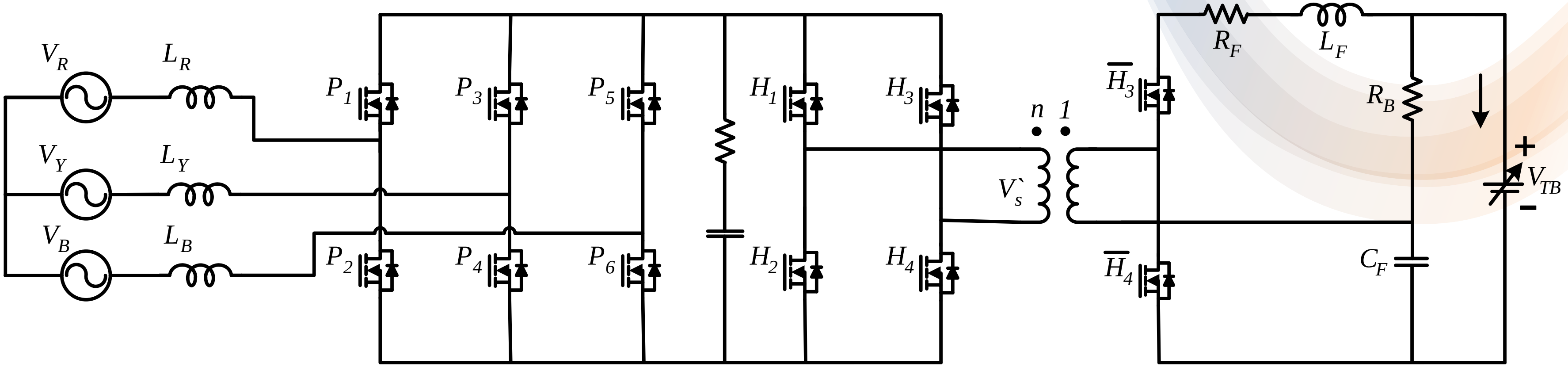


Figure. AC-DC-DC Bidirectional Two-Stage Converter with V2G Capability

- Enhanced Efficiency through **Soft Switching**
- **High-Frequency DC-Link** with Advanced Monitoring
- Optimized for **High Power and Efficiency**
- **Phase-Locked-Loop** Control Methodology

Modes of Operation

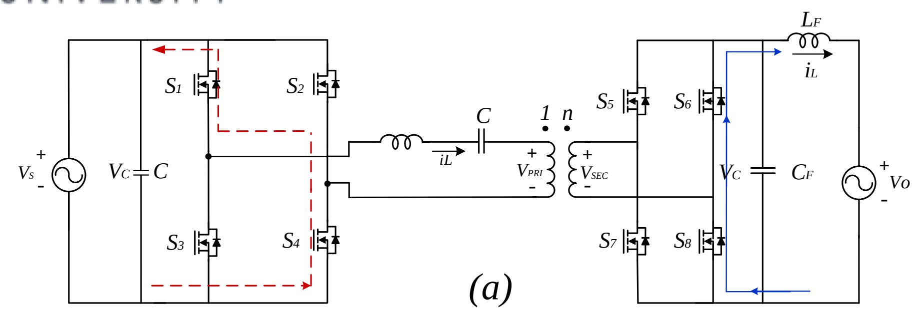


Figure a. Idle/Control Mode of Operation

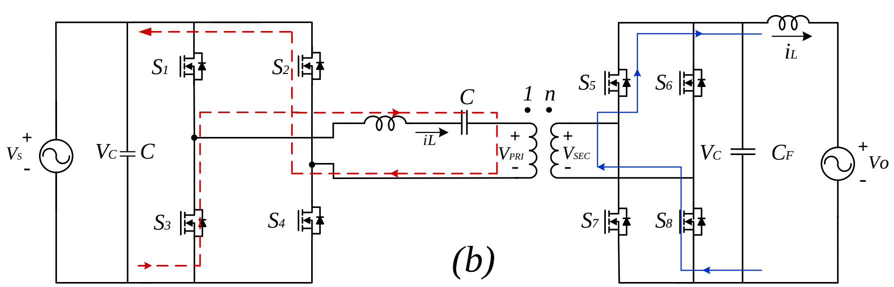


Figure b. CC Charging Mode of Operation

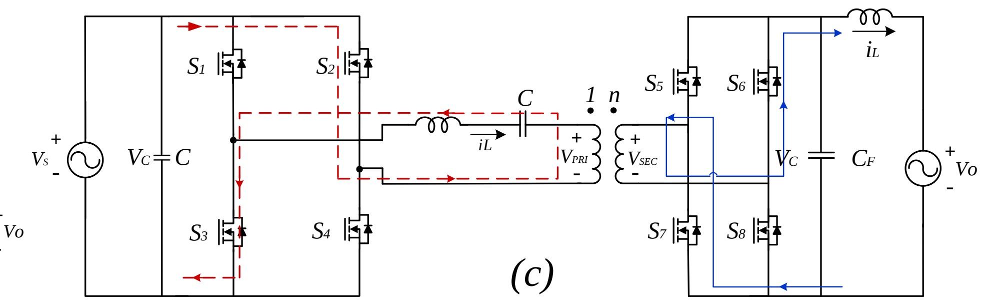


Figure c. CV Charging Mode of Operation

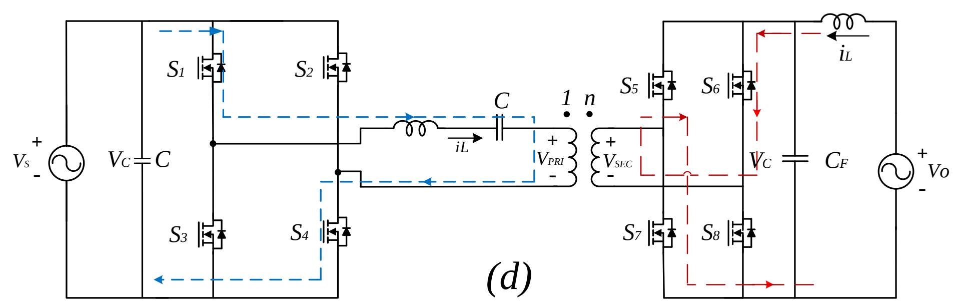


Figure d. V2G/Reverse Charging Mode of Operation

Modes of Operation

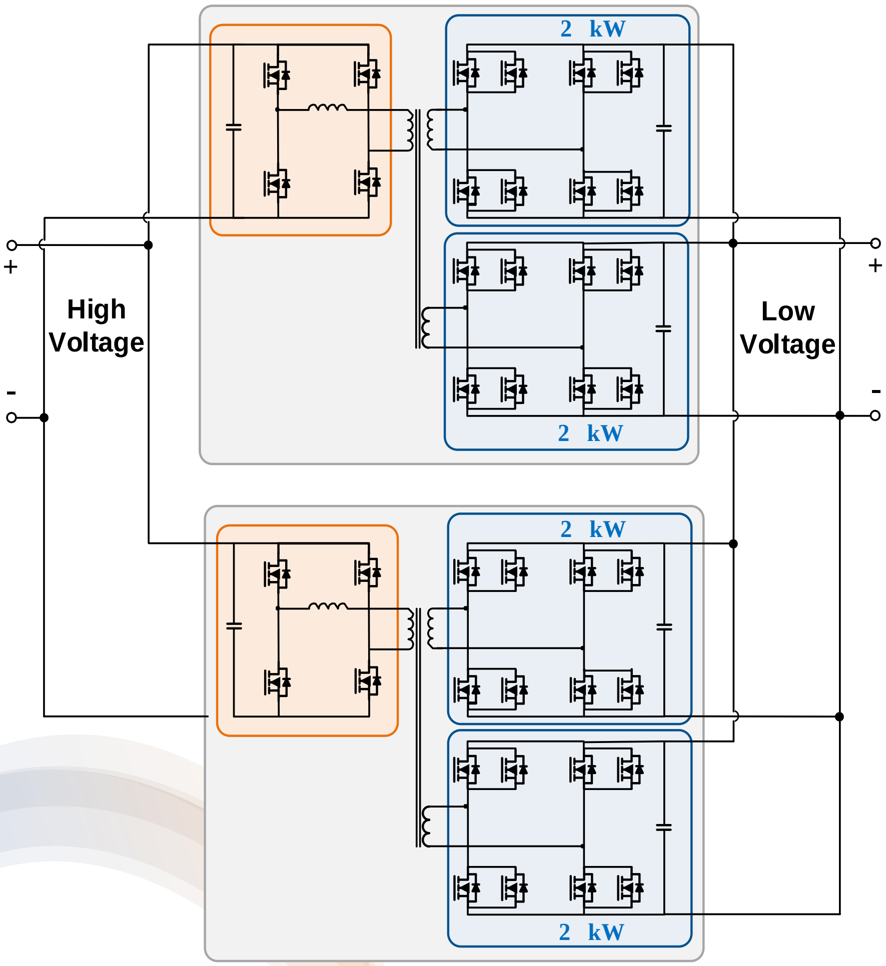


Figure. Connection-2 for the 4 kW Converter

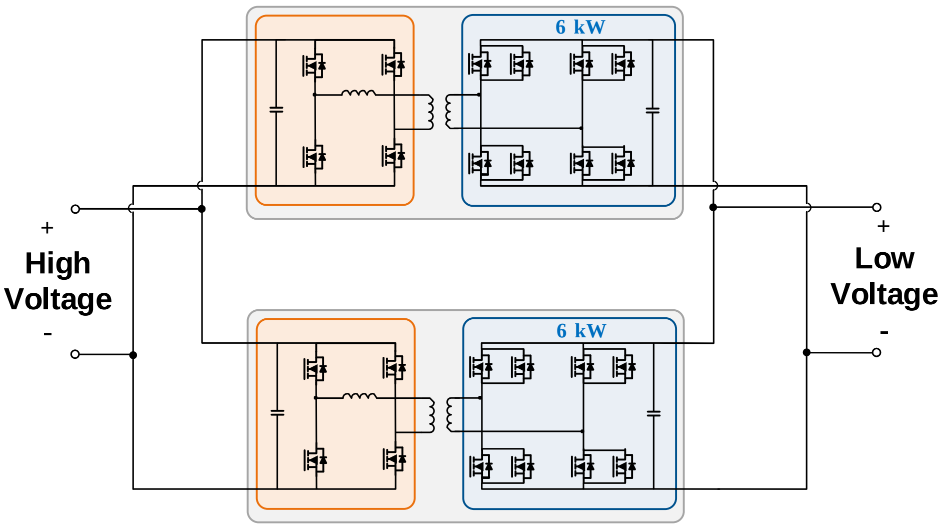


Figure. Connection for the 11.5 kW Converter

Modes of Operation

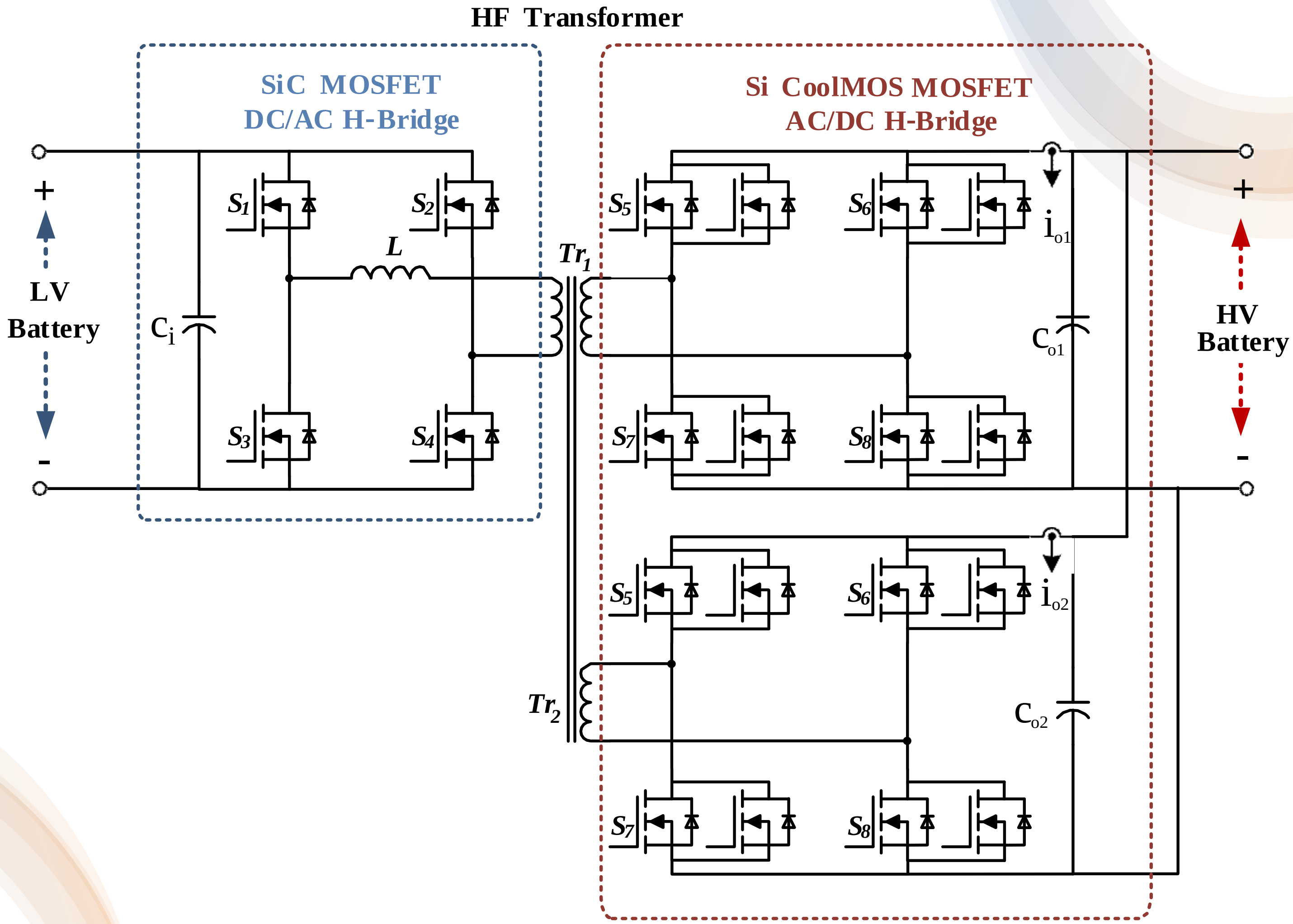


Figure. Main circuit diagram of the 5.6 kW DAB converter.

Operating Phases

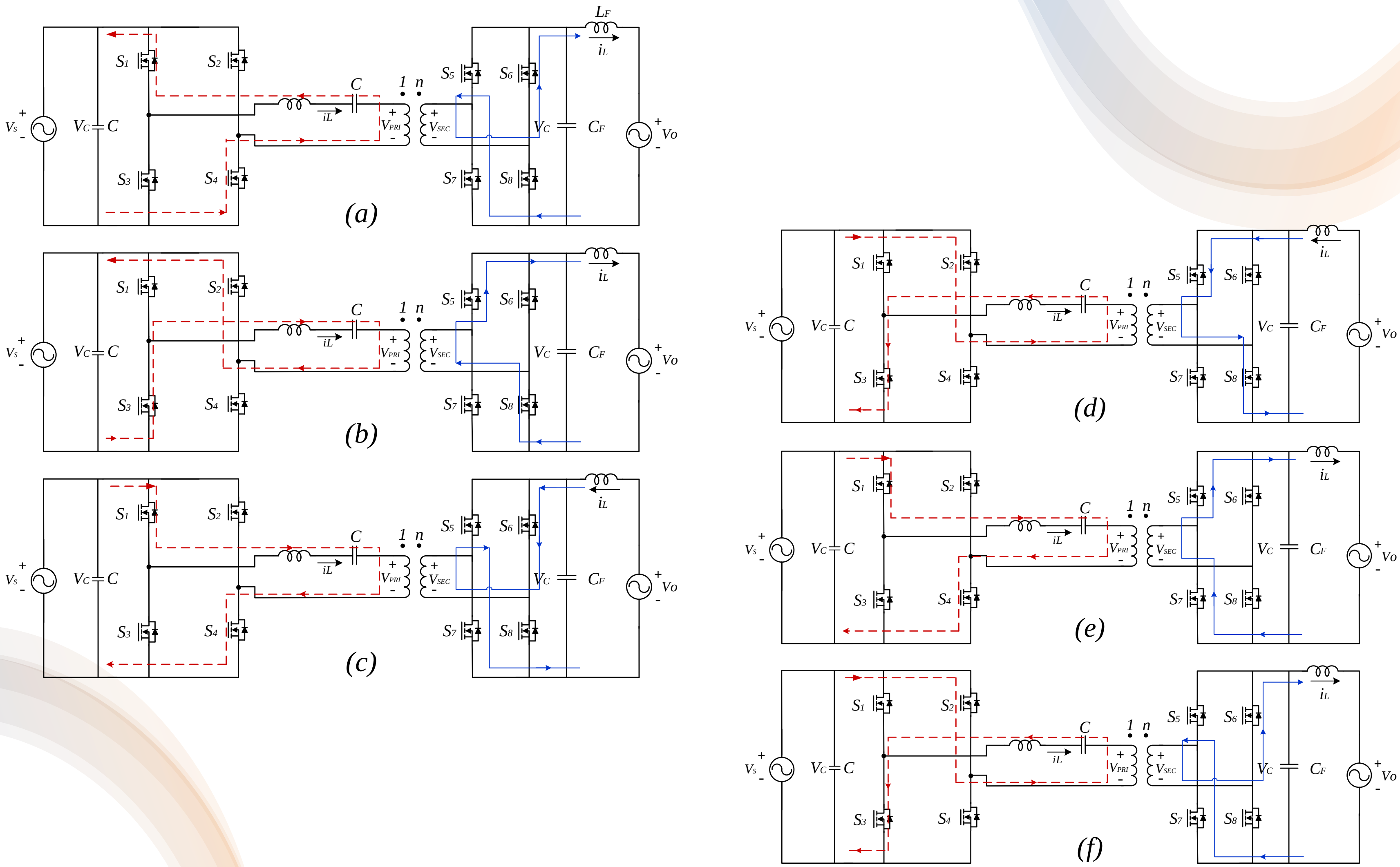


Figure. Operating phases of the DAB converter - Phases 1-6 (a-f)

Controller and Battery Block Chart

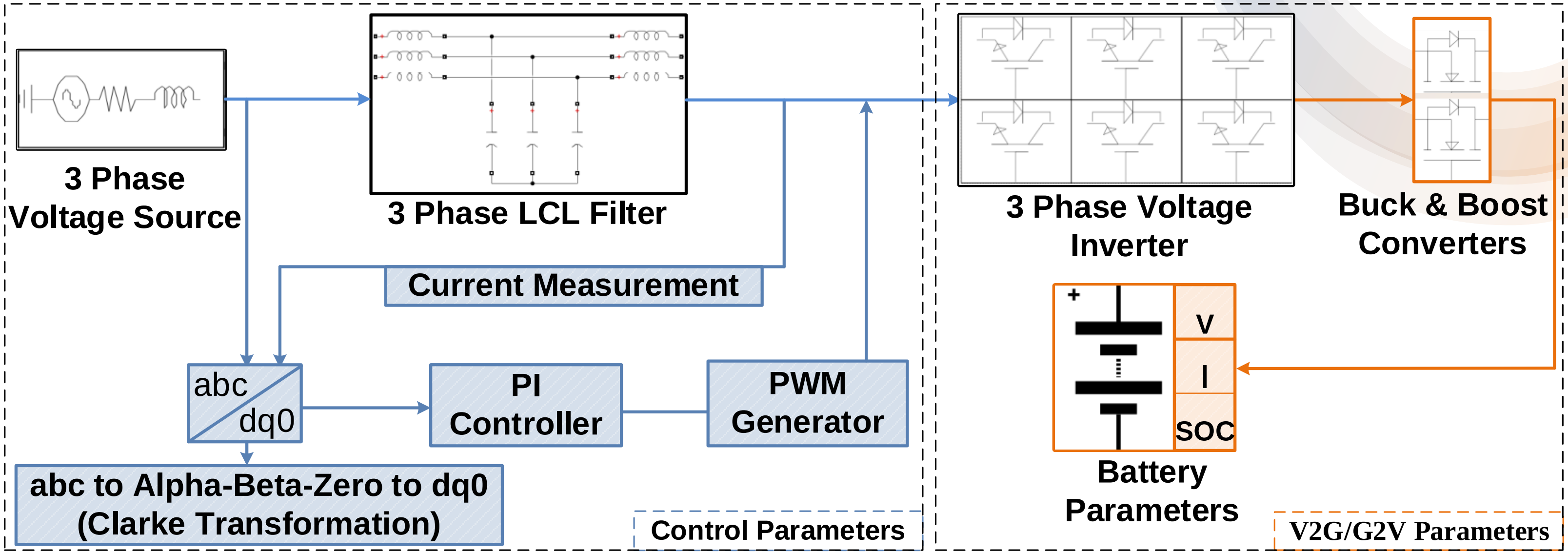
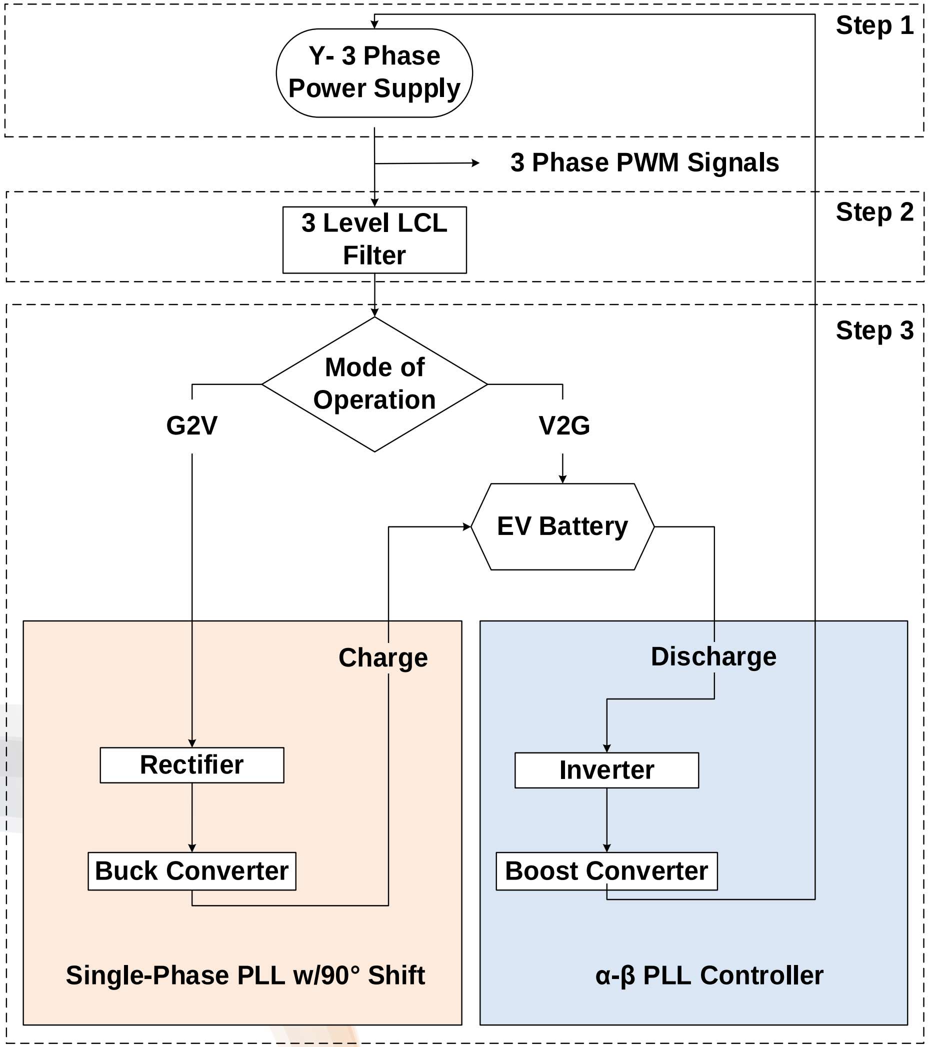


Figure. Block Chart for Control Methodology

- PWM signal used for the CC/CV charging is generated through the square wave carrier with a constant signal.
- This duty cycle signal is dynamically adjusted.

❖ **Zero Current/Voltage Switching (ZCS/ZVS)**

G2V/V2G PLL Flow Chart



- The operational mode, is determined by an input that tailors the PWM pulse signals for the switches accordingly.
- In V2G mode, there is a synchronization between voltage & current signals.

Software Simulation

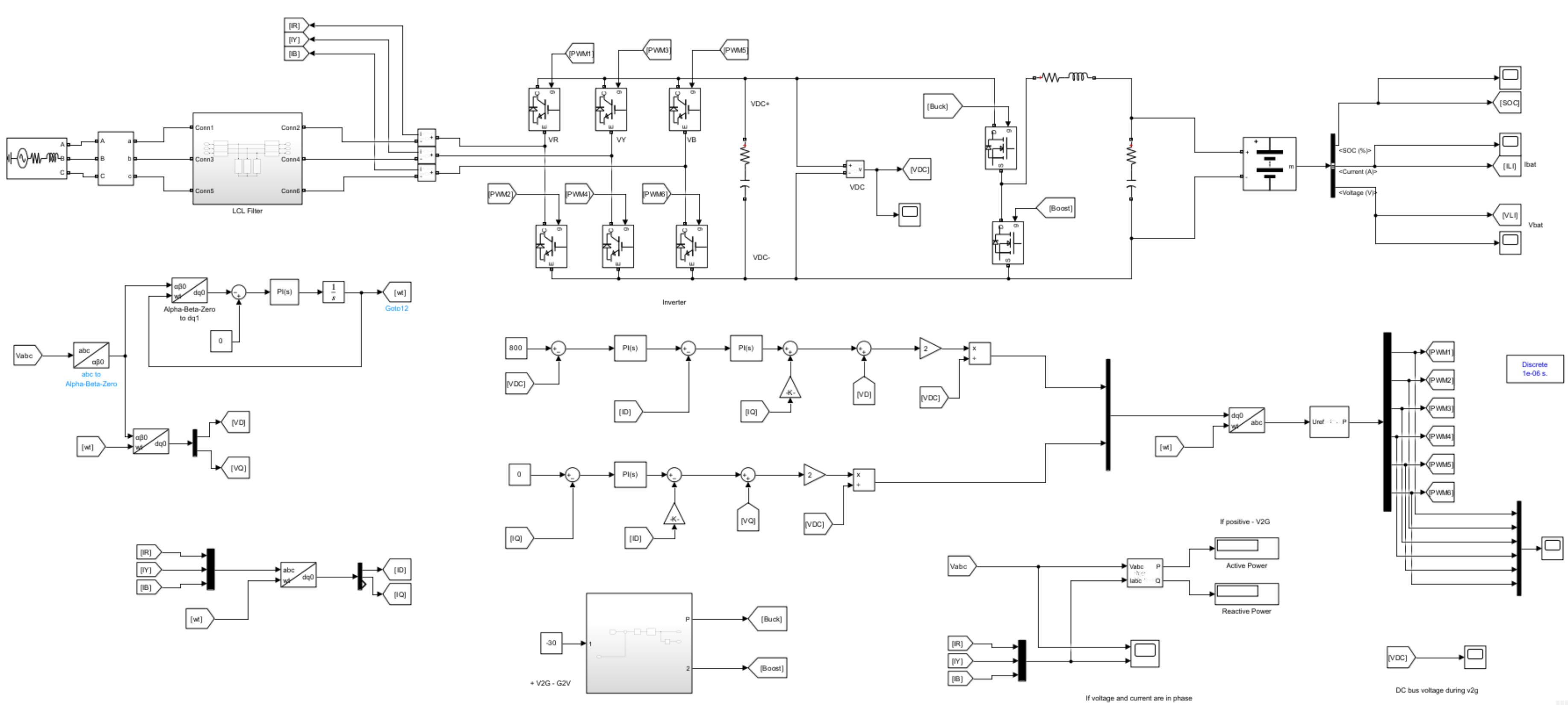


Figure: MATLAB Simulink Simulation

Software Simulation

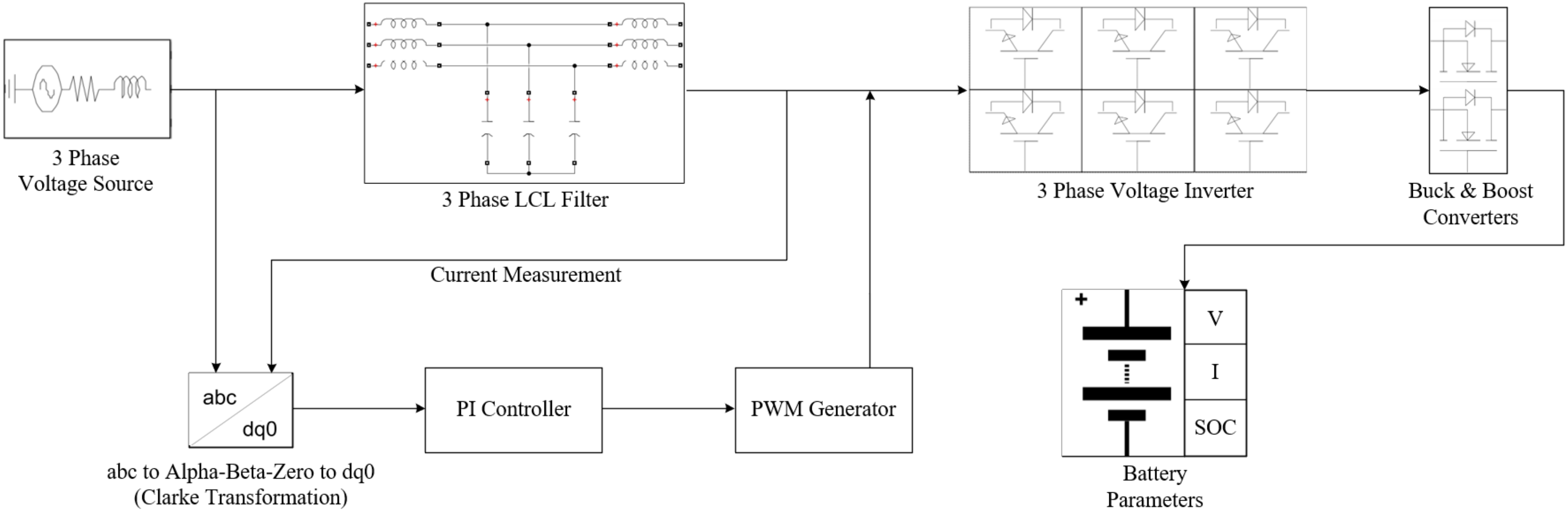
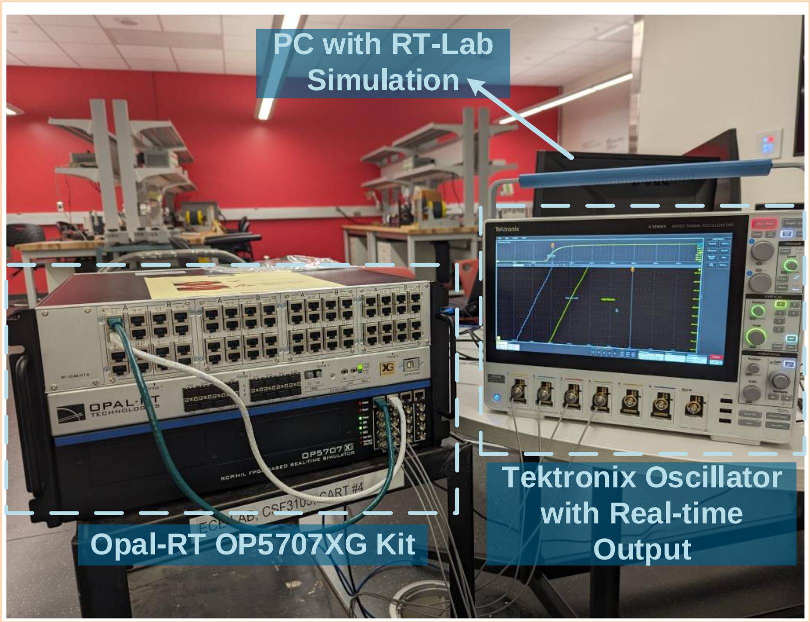
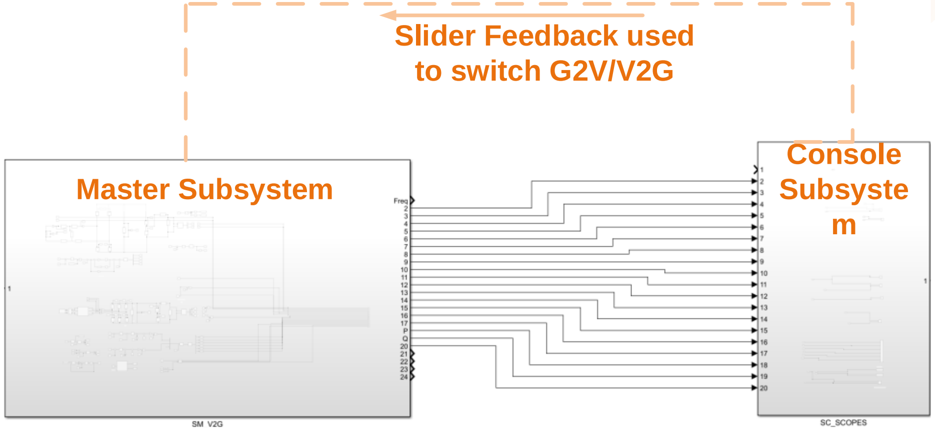


Figure: Flow Chart Representation of the Simulation

Results and Analysis





- The OP5707XG RT-Laboratory from OPAL-RT, real-time simulator, was employed for this study. The real-time (RT) laboratory setup includes two PCs: one serving as the host and the other as the target, connected via TCP/IP protocol.

Hardware Validation

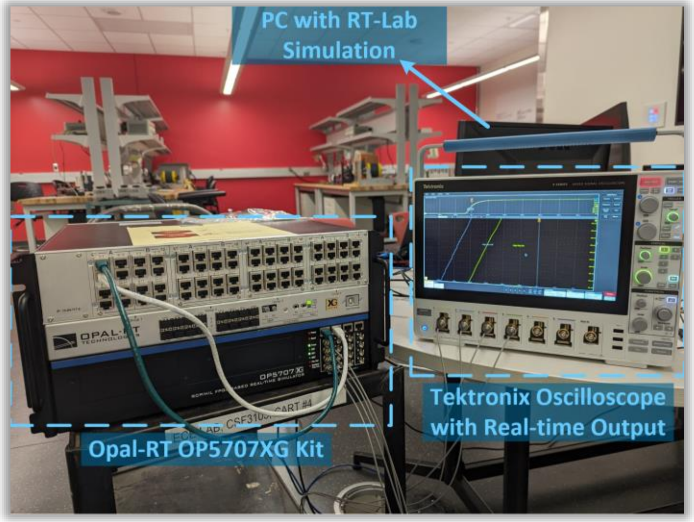
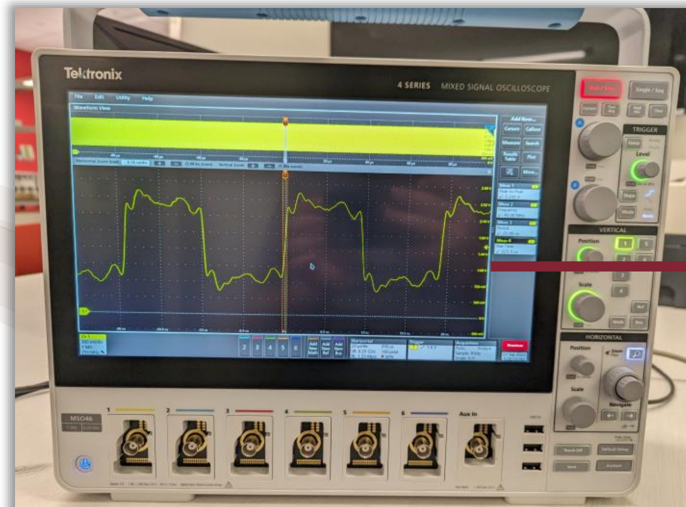


Figure: Hardware Validation Lab Setup

To validate the proposed approach's efficiency, numerous simulation experiments were conducted using practical electric vehicle (EV) data and a range of potential real-world situations. These outcomes were then compared against a standard charging method. The model simulations were executed utilizing MATLAB and RT-Lab.



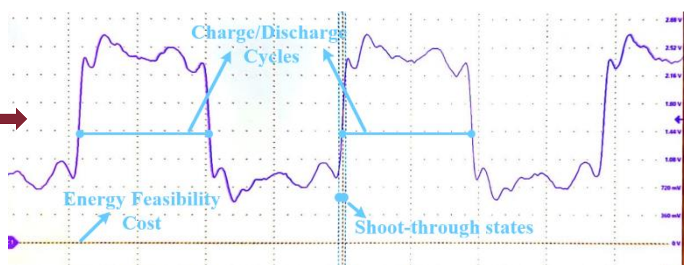


Figure: Oscilloscope Output for Energy Calculations

Results and Analysis

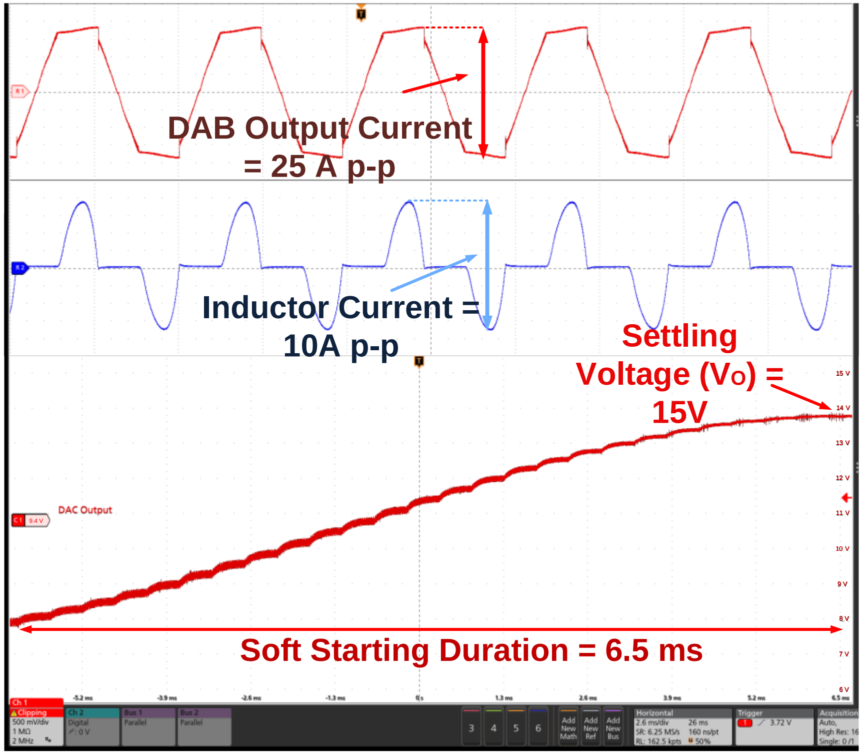


Figure. Converter voltage and the energy transfer inductor current

- ❑ Soft start control implemented for a light electric vehicle's 14 V battery is demonstrated.
- ❑ High-value capacitors are used to maintain the output voltage within a specified ripple range.

Results and Analysis

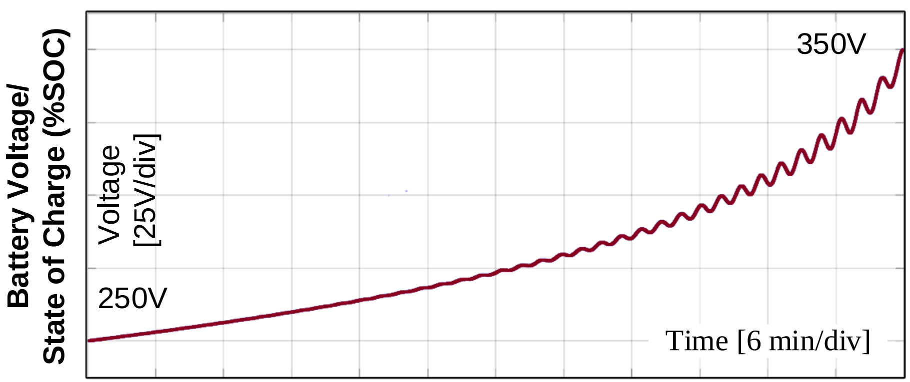


Figure. Simulink G2V Voltage Output

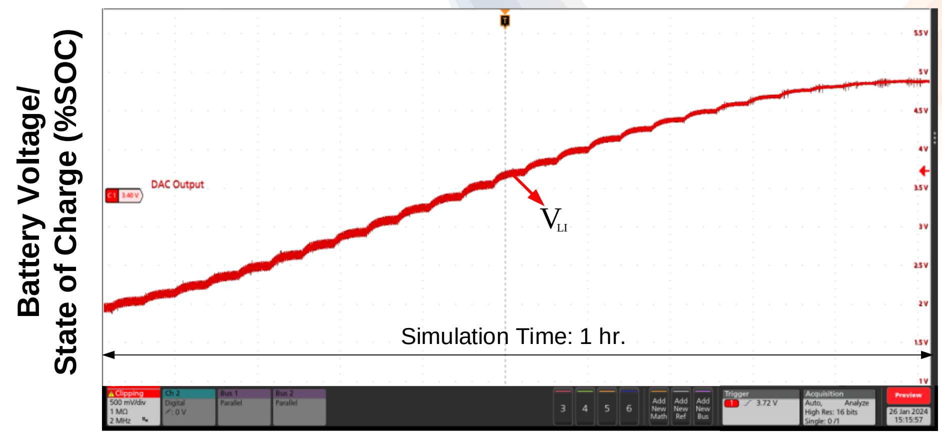


Figure. Real-Time G2V SOC% Outputs

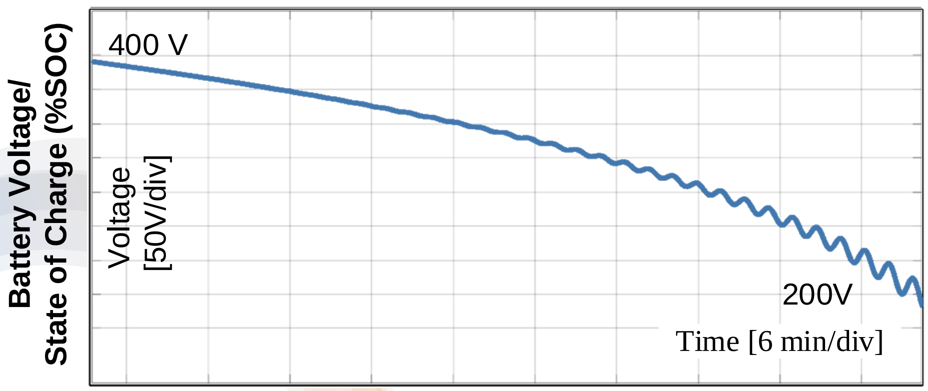


Figure. Simulink V2G Voltage Output

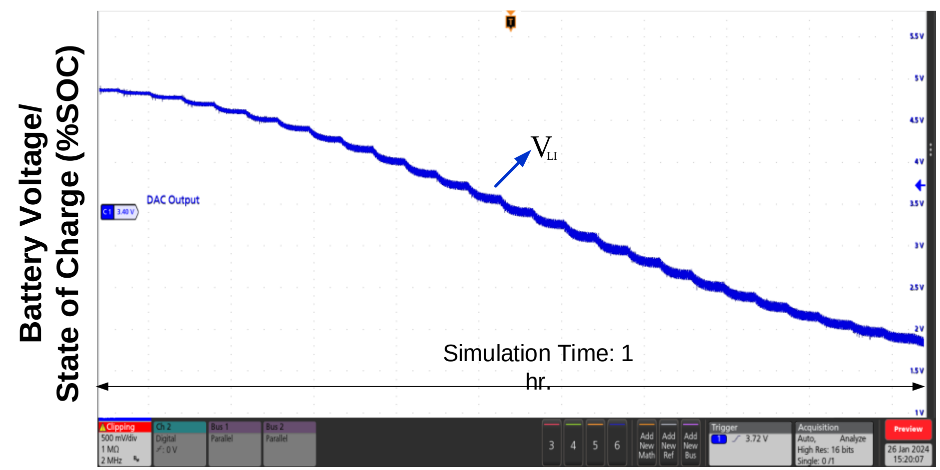


Figure. Real-Time V2G SOC% Outputs

Results and Analysis

DC-Link Active Bridge Values

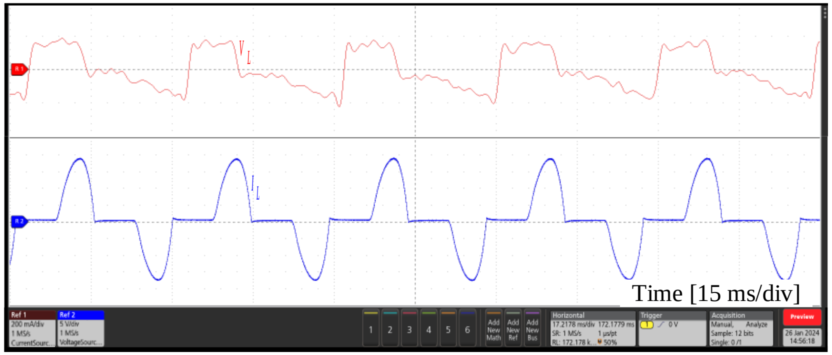


Figure. DC-Link Active Bridge Values

ZCS Zones during V2G

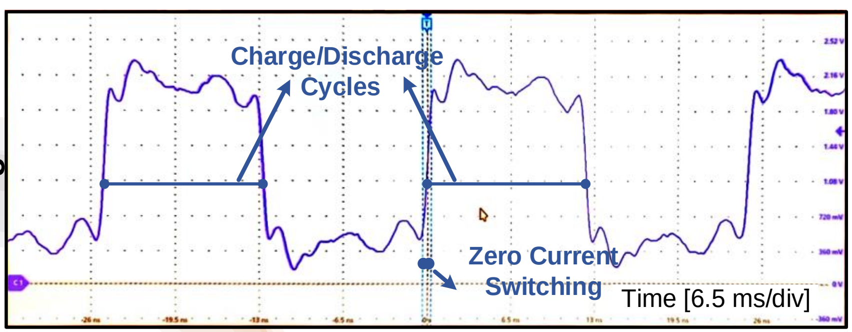


Figure. Zero Voltage Switching Signals

(Buck Mode)

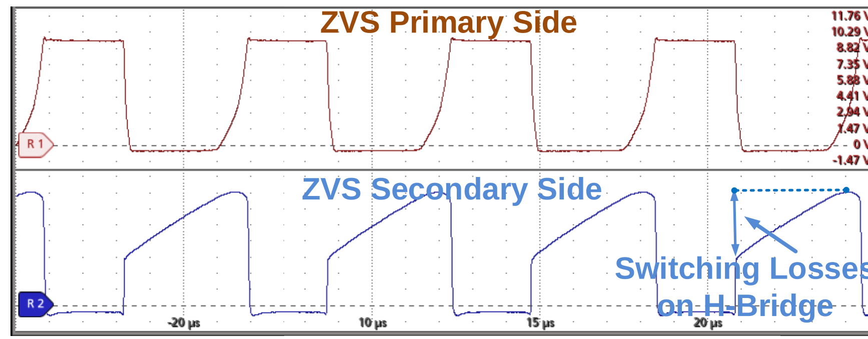
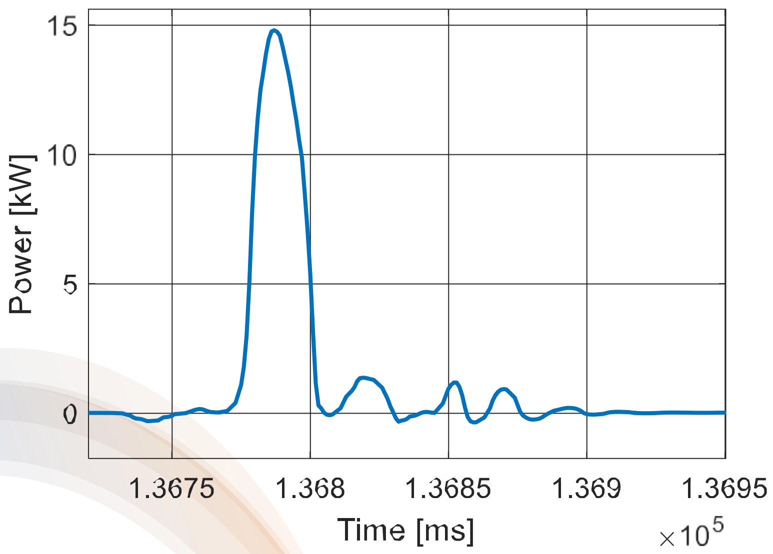


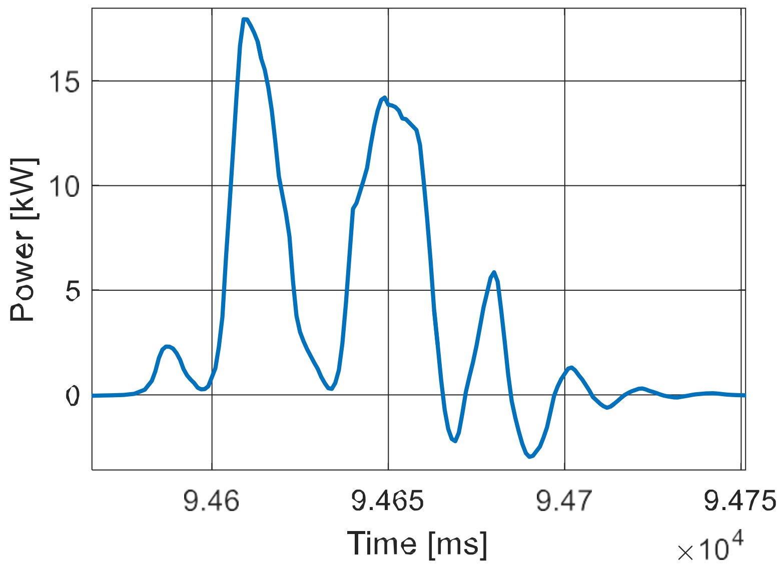
Figure. Waveforms for Buck Mode

Switching Losses

- The calculated switching losses for each switch during conduction and turn-off match the simulation results.
- Total loss for the switches on the input side of the converter is calculated as 72.8 W.
- The simulation results are shown in Figures, respectively:



Switching Loss During Conduction at H-Bridge Silicon Carbide Switches

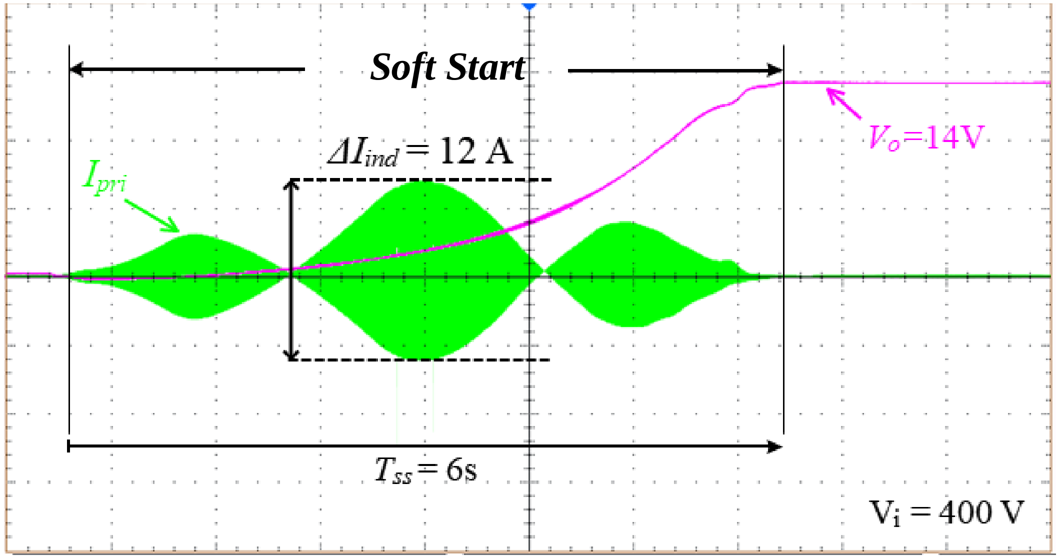


Switching Loss During Cut-Off at H-Bridge Silicon Carbide Switch

Switching Losses

- Converter output voltage and the current waveforms of the energy transfer inductor for the soft-start control applied.

- 14 V vehicle battery of a light electric vehicle are shown;

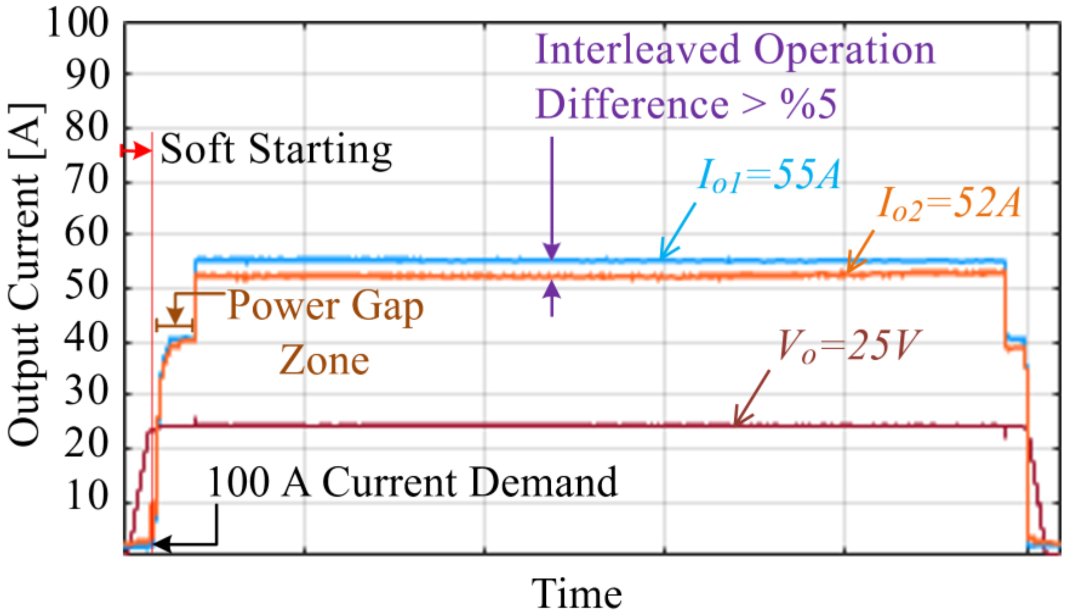


Primary Current of the Transformer and Converter Output Voltage During Soft Start

Voltage Switching

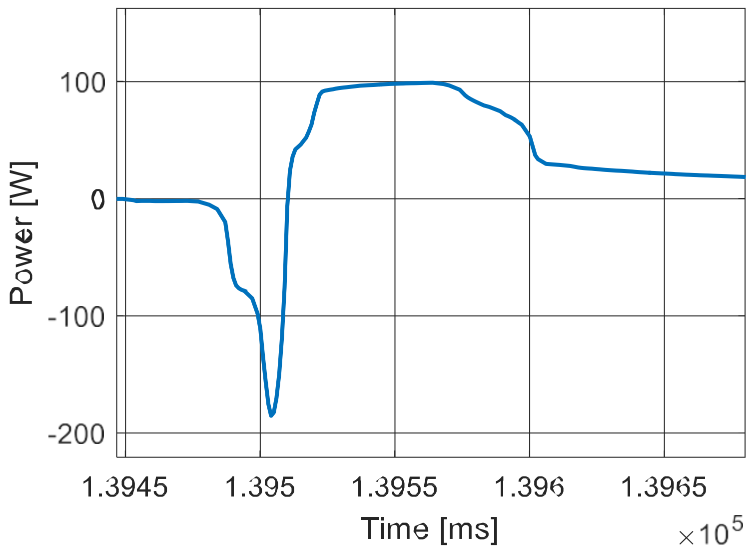
- Converter is operating in buck mode in the figure, and due to the current being positive in the regions marked in green

- Both the primary and secondary side switches are performing zero voltage switching

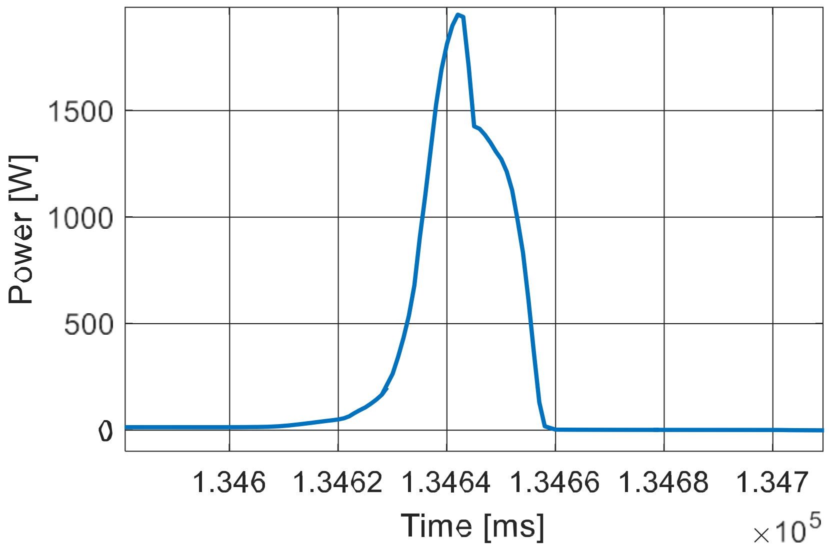


Voltage Switching Figure

Switching Losses

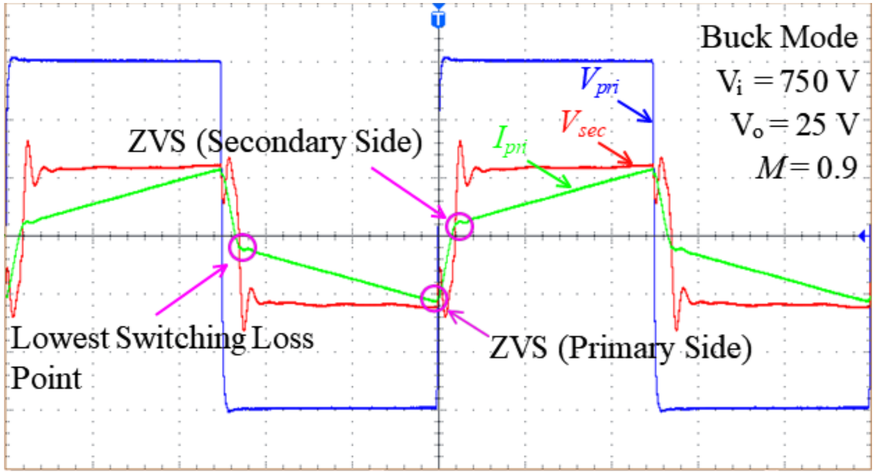


Simulation Result for Switching Loss During Conduction for the Output H-Bridge Silicon Switches.

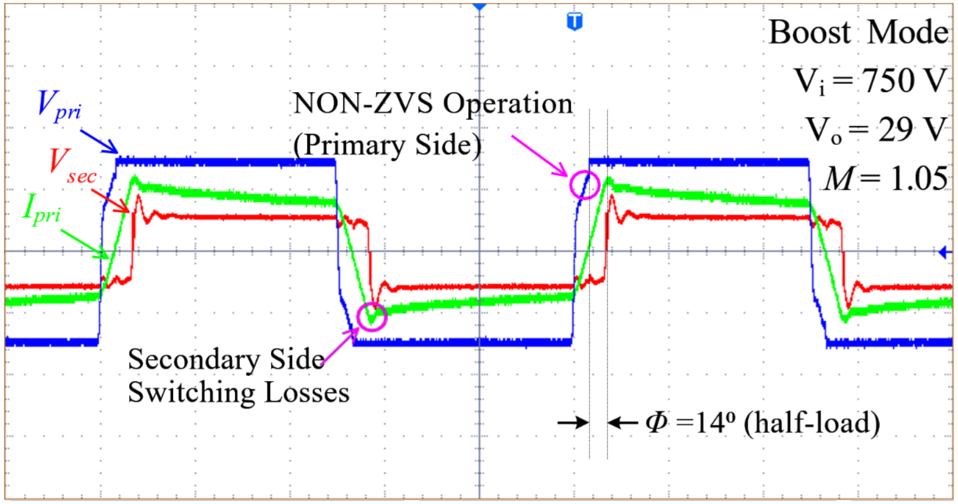


Simulation Result for Switching Loss During Turn-Off for the Output H-Bridge Silicon Switches.

Results and Analysis - LAB

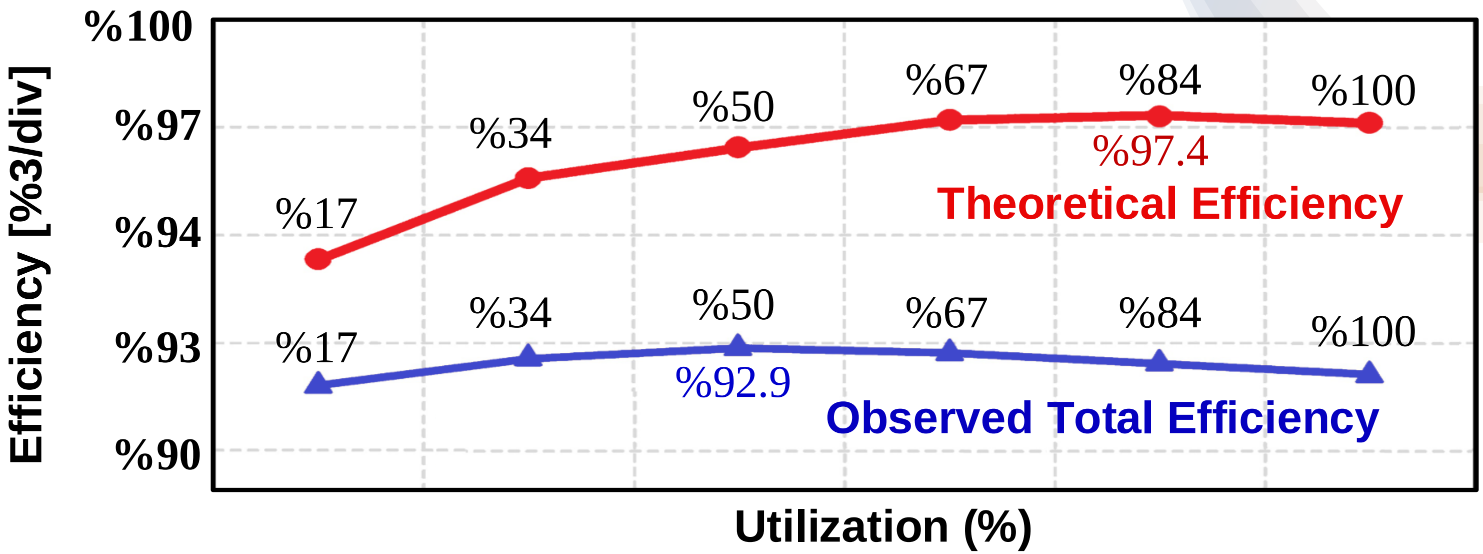


Transformer Primary Voltage, Current, and Inductor Current Waveform



Waveforms of the Converter Operation for Boost Mode

Conclusion



Efficiency-Utilization Graph

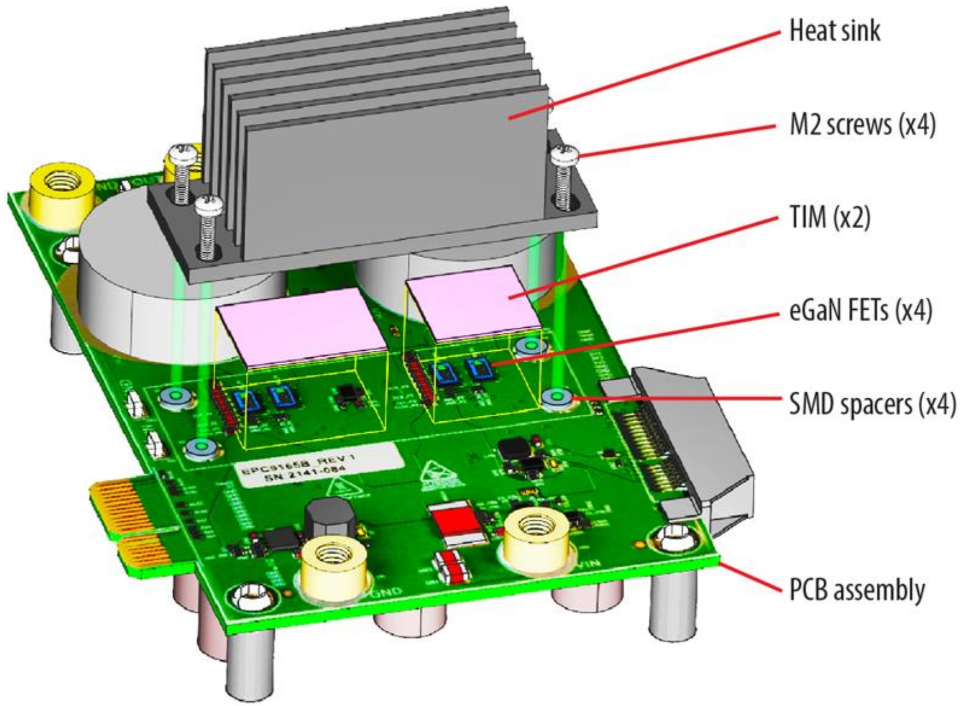
- ❑ As seen from the efficiency graph, the converter achieves its maximum efficiency of approximately 97% at half-load conditions.
- ❑ The DAB converter shows versatility by accommodating both heavy and light electric loads (11.5 kW & 4 kW outputs)

Challenges

Figure: Parked EV Being Charged From Top Floor

1. Limited Charging Infrastructure,
2. Parking Space Availability,
3. Time and Location Constraints,
4. Cost and Payment Complexity,
5. Tripping Hazards and Safety Concerns,
6. Unplugging by Unauthorized Users,
7. Parking Space Management,
8. Rural Charging Deserts.

Future Research



- ❑ Thermal Management
- ❑ Integration of GaN
- ❑ More sophisticated Control
- ❑ Renewable Energy Integration
- ❑ More Modular Design

GaN-Based Design of a 2 kW 48 V/12 V Bi-Directional Power Module for 48 V Mild Hybrid Electric Vehicles

Future Research

- Integrating EV models into the simulation, accounting for their charging and discharging behavior, and simulating various scenarios to assess the impact on grid stability, voltage regulation, and power quality.

- Analyzing the simulation results to understand the effects of widespread EV usage, optimizing grid operations, and informing decision-making regarding infrastructure upgrades, demand response strategies, and implementation of V2G technologies.

Thank You

Q & A