Project Report
Power Electronic Systems for Electric Vehicles (EE-665 Jan-May 2025)

Submitted by

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January-May 2024

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Contribution

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- Documentation and report writing
- Experimental result analysis

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- System architecture design
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1 Introduction

1.1 Context and Motivation

The development of high-voltage battery packs and effective charger topologies are critical to the advancement of electric vehicles (EVs). Large battery stacks are usually formed by connecting battery cells in series and parallel to meet the voltage and power needs of EV propulsion systems. However, these series-connected cells experience charge imbalance due to slight variations in manufacture, operating circumstances, and cell ageing. This imbalance can shorten the battery pack's lifespan, affect system performance, and drastically lower the total amount of energy it can produce. For battery stacks to continue operating at their best, charge equalisation is consequently crucial. Furthermore, as EVs are increasingly included into future smart grids, there is an increasing demand for chargers that offer reactive power control and bidirectional power flow in addition to managing battery health. These features make EVs active players in contemporary power networks by facilitating grid-to-vehicle (G2V) and vehicle-to-grid (V2G) operations. The necessity to overcome these technical obstacles by creating a charger system that incorporates charge equalisation, bidirectional operation, and sophisticated control techniques to enhance battery longevity, system dependability, and grid compatibility serves as the driving force behind this effort.

1.2 Objectives

The primary objective of this project is to study and understand the topology of a bidirectional battery charger with modular integrated charge equalization, as proposed in the referenced research paper. The aim is to analyze the working principles, control strategies, and performance characteristics of the system through detailed simulation. By modeling the charger and charge equalization circuit in a simulation environment, we seek to observe system responses under various operating modes, such as G2V and V2G, and to evaluate the effectiveness of the integrated control approach. This simulation-based approach allows us to investigate key aspects like charge balancing, current ripple, and system flexibility, ultimately deepening our understanding of advanced EV charger designs and preparing us for future work in power electronics and battery management systems

2 Charger and System Architecture

2.1 System Overview

The system is designed to manage the charging and discharging of batteries in electric vehicles in a flexible and efficient way. It uses a two-stage approach: first, an AC-DC converter connects the system to the electric grid and manages the flow of power, and second, a DC-DC converter connects to a battery pack that is built from several modules joined together. This setup allows the system to work in both directions-it can charge the batteries from the grid (grid-to-vehicle mode) or send energy from the batteries back to the grid (vehicle-to-grid mode). To make sure all the battery modules stay balanced and healthy, a charge equalization circuit is included.

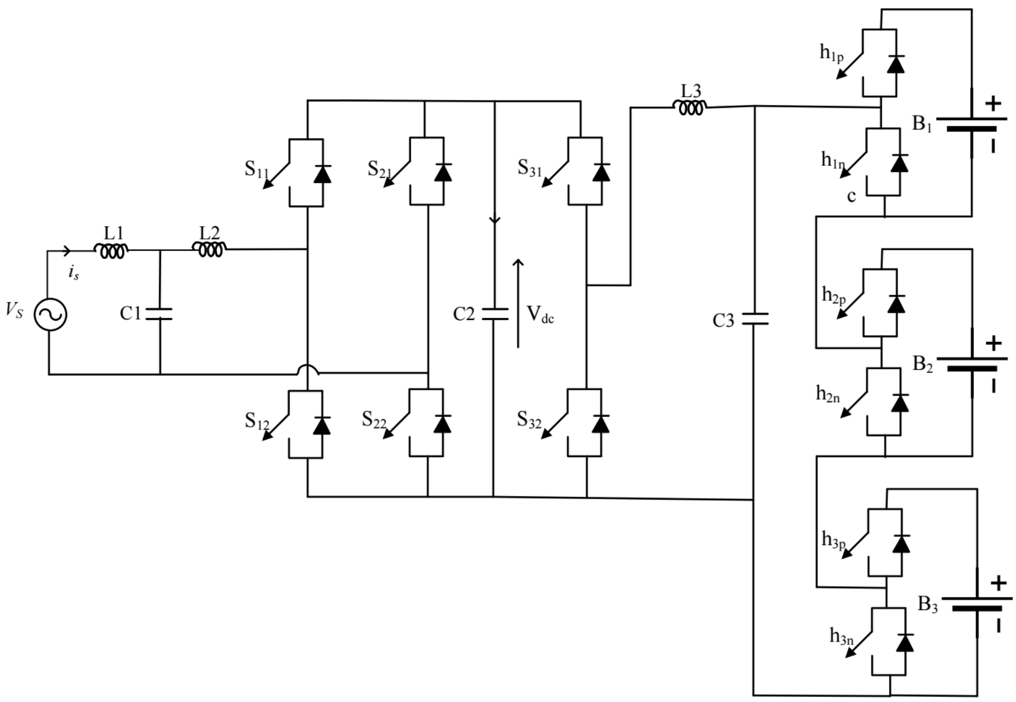

Figure 1: Main system circuit diagram of the bidirectional battery charger with modular integrated charge equalization.

This circuit helps distribute energy evenly among the modules, which improves the overall life and performance of the battery pack. The modular design also means that if one battery module has a problem, it can be bypassed without affecting the rest of the system, making the whole setup more reliable and easier to maintain. The system's operation and control strategies can be studied and tested using simulation tools, which helps in understanding its performance under different scenarios.

2.2 Operation Modes

Electric vehicle battery charging systems with bidirectional capability are designed to operate in two main modes: grid-to-vehicle (G2V) and vehicle-to-grid (V2G). These modes allow energy to flow in both directions-either from the power grid to the vehicle for charging, or from the vehicle's battery back to the grid to support energy needs elsewhere. This dual functionality not only helps in efficient battery management but also enables electric vehicles to play an active role in modern energy systems.

2.2.1 G2V Converter Operation

In grid-to-vehicle (G2V) mode, the charger draws AC power from the grid and converts it to DC to charge the battery pack. This operation ensures sinusoidal input current, low harmonic distortion, and precise control of battery charging current and voltage.

H-Bridge Converter Operation In Grid-to-Vehicle (G2V) mode, the H-bridge converter operates as a boost rectifier to convert AC grid voltage (V_S) to regulated DC-link voltage (V_{dc}) while maintaining low harmonic distortion. The switching strategy employs single-switch transitions per half-cycle to minimize losses.

For positive grid voltage ($V_S > 0$), switch S_{12} (IGBT) activates during the charging phase. The inductor L_2 charges through the path $V_S \to S_{12} \to L_2 \to$ body diode of S_{22}, with inductor voltage:

$$V_{L,\text{on}} = V_S - V_{\text{sw}} - V_{\text{fd}} - I_S(r_s + r_d + r_L) \tag{1}$$

where V_{sw} and V_{fd} represent switch and diode voltage drops, while r_s, r_d, and r_L denote switch, diode, and inductor resistances respectively.

During the discharge phase (S_{12} OFF), energy transfers through the path $V_S \to$ diode of $S_{11} \to L_2 \to C_2 \to$ diode of S_{22}, with:

$$V_{L,\text{off}} = V_S - V_{dc} - 2V_{\text{fd}} - I_S(2r_d + r_L) \tag{2}$$

Applying volt-second balance over a switching period T_s:

$$V_{L,\text{on}} \cdot D \cdot T_s + V_{L,\text{off}} \cdot (1 - D) \cdot T_s = 0 \tag{3}$$

Substituting equations (1) and (2) into (3) and solving for V_{dc}:

$$V_{dc} = \frac{V_S - 2(1 - D)V_{\text{fd}} + D(V_{\text{sw}} + V_{\text{fd}})}{1 - D + \frac{r_L}{1-D} + (1 - D)2r_d + \frac{D^2(r_s+r_d)}{1-D}} \tag{4}$$

For negative grid voltage ($V_S < 0$), the operation mirrors with S_{22} as the active switch and current paths through S_{21} and S_{12} diodes.

DC-DC Buck Converter Operation The DC-DC converter regulates battery charging current using pulse-width modulation (PWM) of switch S_{31} in buck configuration. During the ON state:

$$V_{L3,\text{on}} = V_{dc} - V_{\text{sw}} - I_{\text{batt}}(r_s + r_L) \tag{5}$$

During OFF state:

$$V_{L3,\text{off}} = -V_{\text{fd}} - I_{\text{batt}}(r_d + r_L) \tag{6}$$

Applying volt-second balance:

$$(V_{dc} - V_{\text{sw}} - I_{\text{batt}}r_s - I_{\text{batt}}r_L)D + (-V_{\text{fd}} - I_{\text{batt}}r_d - I_{\text{batt}}r_L)(1 - D) = 0 \tag{7}$$

Solving for battery voltage V_{batt}:

$$V_{\text{batt}} = \frac{DV_{dc} - DV_{\text{sw}} + (1 - D)V_{\text{fd}}}{1 + D^2 r_s + (1 - D)^2 r_d + r_L} \tag{8}$$

This configuration maintains battery current ripple below 2% through L_3-C_3 filtering, extending battery lifespan while enabling constant-current constant-voltage (CC-CV) charging strategies.

2.2.2 V2G Converter Operation

In Vehicle-to-Grid (V2G) mode, the system inverts energy flow to supply power back to the grid. This requires coordinated operation between the DC-DC boost converter and H-bridge inverter, with integrated control of both voltage conversion and charge equalization.

DC-DC Boost Converter Operation The boost converter elevates battery voltage (V_{batt}) to the DC-link level (V_{dc}) using PWM control of switch S_{32}. During the ON state ($0 < t < DT_s$):

$$V_{L,\text{on}} = V_{\text{batt}} - I_{\text{batt}}(r_s + r_L) - V_{\text{sw}} \tag{9}$$

During OFF state ($DT_s < t < T_s$):

$$V_{L,\text{off}} = V_{\text{batt}} - V_{\text{dc}} - I_{\text{batt}}(r_d + r_L) - V_{\text{fd}} \tag{10}$$

Applying volt-second balance:

$$[V_{\text{batt}} - I_{\text{batt}}(r_s + r_L) - V_{\text{sw}}]D + [V_{\text{batt}} - V_{\text{dc}} - I_{\text{batt}}(r_d + r_L) - V_{\text{fd}}](1 - D) = 0 \tag{11}$$

Solving for V_{dc}:

$$V_{\text{dc}} = \frac{V_{\text{batt}} - (1-D)V_{\text{fd}} - DV_{\text{sw}}}{1 - D + \frac{D^2 r_s + (1-D)^2 r_d + r_L}{1-D}} \tag{12}$$

DC-AC Inverter Operation The H-bridge inverter converts DC-link voltage to grid-compatible AC using simplified PWM. For positive half-cycles ($V_s > 0$), switches S_{11}/S_{22} are controlled, while S_{12}/S_{21} handle negative half-cycles.

Considering switch/diode non-idealities, the output voltage derivation uses volt-second balance:

$$V_{s,\text{on}} = D \cdot V_{\text{dc}} - 2D \cdot V_{\text{sw}} \quad \text{(ON state)} \tag{13}$$

$$V_{s,\text{off}} = -(1-D)(V_{\text{fd}} + V_{\text{sw}}) \quad \text{(OFF state)} \tag{14}$$

Averaging over a switching period:

$$V_s = D \cdot V_{\text{dc}} - 2D \cdot V_{\text{sw}} - (1-D)(V_{\text{fd}} + V_{\text{sw}}) \tag{15}$$

Including resistive losses in switches (r_s) and inductor (r_L):

$$V_s = \frac{D \cdot V_{\text{dc}} - 2D \cdot V_{\text{sw}} - (1-D)(V_{\text{fd}} + V_{\text{sw}})}{1 + r_L + 2D^2 r_s + (1-D)^2 (r_s + r_d)} \tag{16}$$

The LCL filter (L_1, C_1, L_2) attenuates harmonics to achieve THD ¡ 5%, while the dual-loop PI controller maintains grid synchronization and reactive power control.

2.2.3 Modular Battery Stack Configuration

The modular battery stack is composed of several battery modules connected in series, each equipped with high-side (*hip*) and low-side (*hin*) switches. This arrangement allows individual modules to be either included in the series stack or bypassed as needed. By controlling the state of these switches, the system can dynamically reconfigure the stack: to connect a module, its high-side switch is turned ON and low-side switch is OFF; to bypass a module, the low-side switch is turned ON and the high-side switch is OFF. This enables the charger to maintain operation even if a module is faulty, as the affected module can be isolated from the stack without interrupting the overall function.

3 CEC Algorithm and Design

The Charge Equalization Circuit (CEC) is designed to ensure that all modules within a modular battery stack are charged and discharged as uniformly as possible. Each module, equipped with its own switching elements, can be individually connected or bypassed, allowing for flexible configuration and improved system reliability. Central to the operation of the CEC is the monitoring and estimation of the State of Charge (SOC) for each module, which represents the available capacity relative to its maximum. By continuously tracking SOC, the CEC can dynamically manage the flow of energy among modules, preventing overcharging or over-discharging and thereby extending battery life. In this work, the CEC's behavior and effectiveness are analyzed through detailed circuit simulations under both charging and discharging scenarios.

3.1 CEC Architecture

The modular Charge Equalization Circuit (CEC) comprises series-connected battery modules, each equipped with high-side (`hip`) and low-side (`hin`) switches. This configuration requires only $2n$ switches for n modules, enabling three operational states:

- **Connected**: `hip=ON`, `hin=OFF` (module participates in charging/discharging)
- **Bypassed**: `hip=OFF`, `hin=ON` (module excluded from stack)
- **Fault State**: Permanent bypass via `hin` for failed modules

3.2 Operation Principles

3.2.1 Grid-to-Vehicle (G2V) Mode

SOC estimation combines Coulomb counting and OCV calibration:

$$\mathrm{SOC}_i(t) = \mathrm{SOC}_i(0) + \frac{1}{C_{\mathrm{rated}}} \int_0^t I_{\mathrm{batt}}(\tau)d\tau \tag{17}$$

The CEC sequentially charges modules starting with the lowest SOC. When $|\mathrm{SOC}_i - \mathrm{SOC}_{\mathrm{avg}}| \leq 2\%$, the next module is activated. Fully charged modules ($\mathrm{SOC} = 100\%$) are bypassed to prevent overcharging.

3.2.2 Vehicle-to-Grid (V2G) Mode

Modules discharge starting with the module with highest SOC. Discharge continues until $|\mathrm{SOC}_i - \mathrm{SOC}_{\mathrm{min}}| \leq 5\%$. Modules below $\mathrm{SOC} = 30\%$ are bypassed to prevent damage.

3.3 Features

The proposed modular CEC structure offers several important advantages for electric vehicle battery management. By enabling active and reactive power control in both G2V and V2G operation, the system supports advanced grid interaction and flexibility. The integrated charge equalization capability during both charging and discharging ensures that battery modules are balanced, which extends battery life and maintains consistent performance. Low-ripple charging and discharging currents, achieved through precise CC-CV control and optimized filter design, further contribute to improved battery longevity. The modular configuration enhances system reliability, as faulty modules can be bypassed without interrupting operation, and overall efficiency is increased through the use of a simplified PWM strategy that reduces switching losses. Simulation results confirm that the proposed structure achieves high efficiency, low harmonic distortion, and robust charge equalization, validating its suitability for modern electric vehicle applications.

4 Control Strategies

Effective control strategies are essential for managing power flow, ensuring battery safety, and maximizing efficiency in a bidirectional charger with modular charge equalization. This section describes the coordinated control of the AC-DC and DC-DC converters, the integration of the charge equalization circuit (CEC) with the main power stages, and the implementation of constant-current constant-voltage (CC-CV) charging and power flow control. Special attention is given to the role of state of charge (SOC) estimation for each battery module, which enables dynamic reconfiguration and balanced operation during both charging and discharging modes. All strategies are analyzed and validated through detailed circuit simulation.

4.1 AC-DC and DC-DC Converter Control

The bidirectional charger utilizes a hierarchical control structure to achieve precise and efficient power conversion in both grid-to-vehicle (G2V) and vehicle-to-grid (V2G) modes. For the AC-DC H-bridge converter, a dual-loop PI controller is implemented. The outer voltage loop regulates the DC-link voltage (V_{dc}) to a reference value, typically set at 400 V, by adjusting the reference active power (P_{ref}) according to the deviation between the measured and desired DC-link voltages:

$$P_{ref} = k_{p,v}(V_{cref} - V_{dc}) + k_{i,v} \int (V_{cref} - V_{dc}) dt \tag{18}$$

where $k_{p,v}$ and $k_{i,v}$ are the proportional and integral gains, respectively. The inner current loop ensures that the grid current is sinusoidal and synchronized with the grid voltage, minimizing total harmonic distortion (THD) to below 5%. This is achieved by generating a reference current (i_{ref}) that is tracked by the converter. The system employs a simplified PWM strategy, where only one switch (either S_{12} or S_{22}) operates at high frequency in each half-cycle, reducing switching losses by up to 75% compared to conventional methods. The use of an LCL filter, with typical values such as $L_1 = 12.7$ mH and $C_1 = 150$ nF, further attenuates grid-side harmonics.

For the DC-DC converter, the control strategy adapts to the operational mode. In G2V mode, the converter operates as a buck converter, with the switch S_{31} modulated to control the battery charging current. The duty cycle for the buck operation is determined by the ratio of the battery voltage to the DC-link voltage, accounting for non-idealities such as switch and diode voltage drops and resistances:

$$D_{buck} = \frac{V_{batt} + V_{fd} + I_{batt}(r_d + r_L)}{V_{dc} - V_{sw}} \tag{19}$$

In V2G mode, the converter functions as a boost converter, where S_{32} is modulated and S_{31} acts as a diode. The duty cycle for the boost operation is given by:

$$D_{boost} = 1 - \frac{V_{batt} - V_{sw}}{V_{dc} + V_{fd}} \tag{20}$$

This control ensures that the battery current and DC-link voltage remain within safe and efficient operating ranges during both charging and discharging.

4.2 Integration with CEC

The Charge Equalization Circuit (CEC) is seamlessly integrated with the converter control through dynamic reconfiguration based on the state of charge (SOC) of each battery module. SOC estimation is performed using a hybrid approach that combines Coulomb counting and periodic open-circuit voltage (OCV) calibration:

$$SOC(t) = SOC_0 + \frac{1}{C_{rated}} \int_0^t I_{batt}(\tau) d\tau \tag{21}$$

where C_{rated} is the rated capacity of the module. OCV measurements are taken during brief rest periods to correct for drift in the Coulomb counting method, ensuring accurate SOC tracking. During G2V operation, modules with the lowest SOC are connected first by enabling their high-side switches, while fully charged modules are bypassed to prevent overcharging. In V2G mode, the system prioritizes discharging modules with the highest SOC, maintaining uniform energy extraction and preventing over-discharge. Faulty modules are permanently bypassed, allowing the system to continue operating without interruption. This modular and dynamic approach to module management enhances both the reliability and the efficiency of the overall battery system.

4.3 CC-CV Charging and Power Flow Control

The battery charging process is governed by a constant-current constant-voltage (CC-CV) strategy to maximize battery life and performance. Initially, the battery is charged at a constant current (CC mode), typically set to 10 A in simulation, until the battery voltage approaches its nominal value. The system then transitions to constant-voltage (CV) mode, where the voltage is held steady and the current gradually tapers off as the battery reaches full charge. The transition between CC and CV modes is managed by a PI controller that adjusts the converter duty cycle to maintain the desired current or voltage:

$$D_{adj} = k_{p,c}(I_{ref} - I_{batt}) + k_{i,c} \int (I_{ref} - I_{batt}) dt \tag{22}$$

where $k_{p,c}$ and $k_{i,c}$ are the controller gains. This approach minimizes current ripple and avoids voltage overshoot, both of which are critical for battery health.

In V2G operation, the system also supports controlled power flow back to the grid, including the provision of reactive power. By adjusting the phase of the reference current relative to the grid voltage, the charger can inject or absorb reactive power as required, thereby supporting grid voltage stability and power factor correction. The reference current for active and reactive power is synthesized as:

$$i_{ref} = \frac{P_{ref}}{V_{dc}} \sin(\omega t) + \frac{Q_{ref}}{V_{dc}} \cos(\omega t) \tag{23}$$

where P_{ref} and Q_{ref} are the reference active and reactive power, respectively. This capability enables the charger to interact intelligently with smart grid commands and dynamic load conditions.

Overall, these control strategies ensure high efficiency, low harmonic distortion, and robust battery management, as confirmed by both simulation and experimental results in the referenced work.

5 System Design and Implementation

5.1 Key Design Parameters

The simulation is based on a single-phase bidirectional charger with modular charge equalization, as proposed in the referenced IEEE paper. The system is designed for a nominal power of 5 kW, suitable for residential grid integration. The AC grid voltage is set at 220 V (RMS), and the DC-link voltage is regulated to 400 V. Each battery module has a nominal voltage of 48 V, and three modules are connected in series to form a 144 V battery stack. The switching frequency for all converters is chosen as 20 kHz, balancing efficiency and current ripple. The battery capacity is set to 100 Ah for each module, and current ripple is maintained below 2% to ensure battery longevity and accurate charge equalization. The LCL filter is designed to limit grid current harmonics, with values for L_1 and C_1 taken from the paper.

Table 1: Key Simulation Parameters

Parameter	Value
AC Grid Voltage (V_s)	220 V (RMS)
DC-Link Voltage (V_{dc})	400 V
Battery Module Voltage	48 V
Number of Modules	3
Battery Stack Voltage	144 V
Battery Capacity	100 Ah
Switching Frequency (f_s)	20 kHz
LCL Filter Inductance (L_1)	2 mH
LCL Filter Capacitance (C_1)	150 μF
DC-Link Capacitance (C_2)	470 μF
Current Ripple (ΔI_{batt})	$<2\%$
SOC Balancing Threshold	$\pm 2\%$ (G2V), $\pm 5\%$ (V2G)

5.2 Simulation

The system is implemented and tested in MATLAB/Simulink using the above parameters. Each battery module is modeled using a Thevenin equivalent circuit with an open-circuit voltage (OCV) to SOC relationship, as described in the paper. The grid is represented as a 220 V, 50 Hz voltage source with a small series inductance to simulate realistic grid conditions. The LCL filter is included to ensure that the total harmonic distortion (THD) of the grid current remains below 5%, in compliance with IEEE-519 standards.

The simulation scenarios include both G2V (charging) and V2G (discharging) modes. In G2V mode, the AC-DC converter operates as a boost rectifier, while the DC-DC converter functions as a buck converter to regulate battery charging current. In V2G mode, the DC-DC converter operates as a boost converter, and the H-bridge inverter supplies power back to the grid. The charge equalization circuit (CEC) dynamically reconfigures the connection of battery modules based on their state of charge, ensuring balanced charging and discharging throughout the stack. SOC estimation is performed using Coulomb counting, with periodic OCV calibration for accuracy.

All simulations are performed with a fixed-step solver and a time step of 1 μs to accurately capture switching dynamics and transient behavior. The results are evaluated in terms of DC-link voltage regulation, grid current quality, battery SOC balancing, and overall system efficiency, and are compared with the performance benchmarks reported in the main paper.

6 Results and Discussion

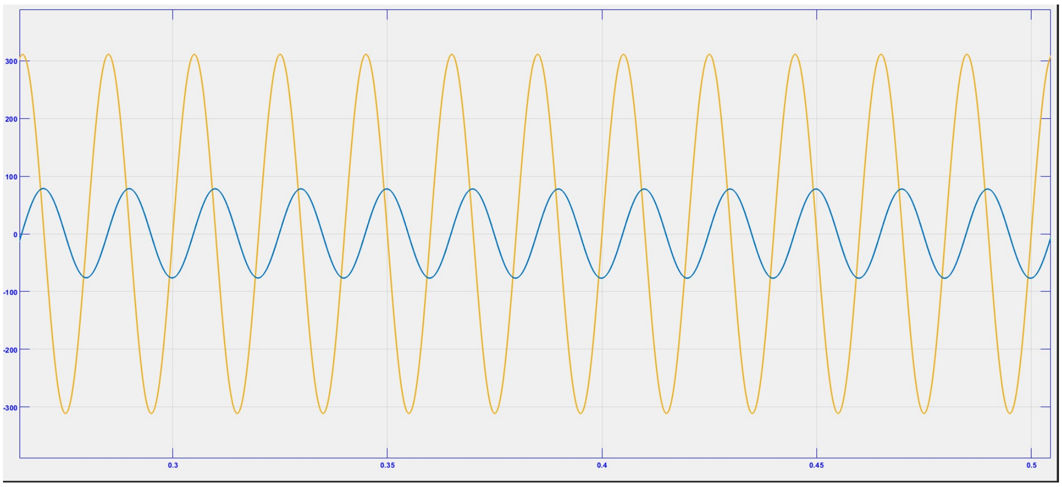

Figure 2: Input pf in main circuit

Since we were unable to perfectly tune the main circuit,we tried tuning it in a subsidiary H-bridge circuit where we got the pf correction. We got Kp=5 and Ki=50 while tuning this.

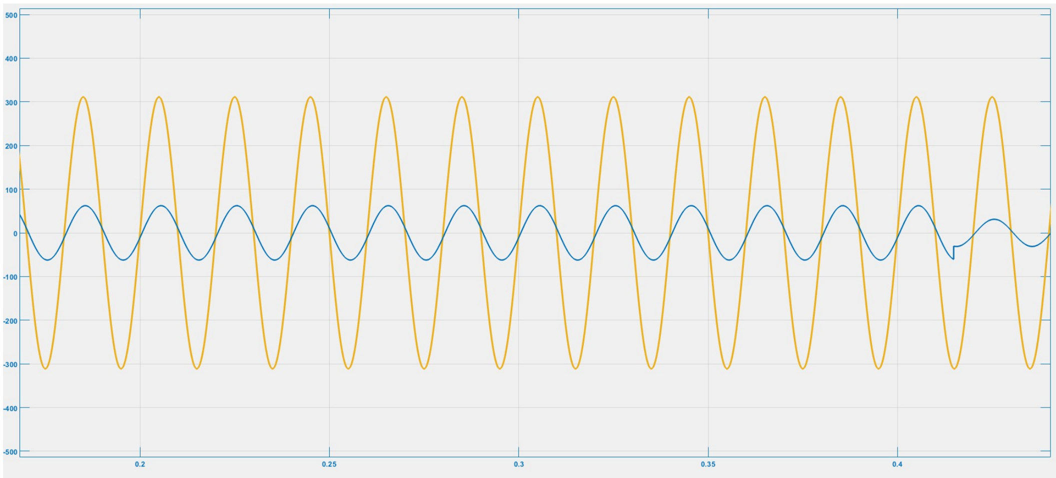

Figure 3: Input pf in a subsidiary circuit

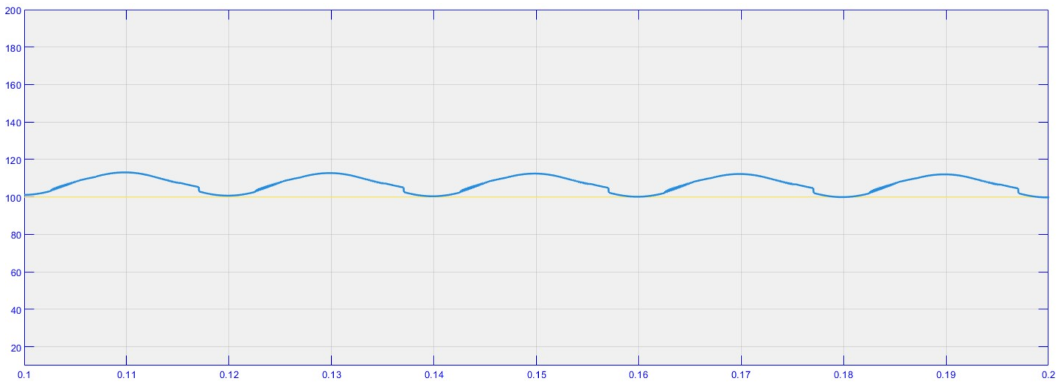

Figure 4: Output Voltage of H-Bridge in a subsidiary circuit

7 Strengths and Limitations

7.1 Strengths

The proposed bidirectional battery charger with modular integrated charge equalization circuit (CEC) offers several notable strengths. First, the system supports both active and reactive power control in grid-to-vehicle (G2V) and vehicle-to-grid (V2G) modes, enabling advanced grid interaction and compliance with future smart grid requirements [?]. The modular CEC provides effective charge equalization during both charging and discharging, which helps to maximize battery life, maintain accessible energy, and ensure consistent system performance even as individual modules age or degrade. The integrated control strategy allows seamless coordination between the charger and CEC, resulting in low-ripple battery current and improved overall efficiency. The modular design enhances system reliability and flexibility, as faulty modules can be bypassed without interrupting operation, and the system can be easily scaled or maintained. Simulation and experimental results in the paper confirm that the proposed structure achieves high efficiency, robust charge balancing, and reliable operation under various conditions.

7.2 Limitations and Trade-offs

Despite its advantages, the system also presents some limitations and trade-offs. The modular configuration, while improving reliability and flexibility, increases the number of required switches and associated control complexity compared to simpler, non-modular topologies. This can lead to higher initial cost and a more involved design process. The integrated CEC and its control require precise SOC estimation and fast switching logic, which may be challenging to implement in large-scale or real-time systems. Additionally, although the system achieves low current ripple and high efficiency in simulation and laboratory tests, practical deployment in high-power or harsh environments could reveal further challenges related to electromagnetic interference, thermal management, or long-term reliability. Finally, the focus on modularity and charge equalization may introduce additional losses or delays during module reconfiguration, especially as the number of modules increases. These trade-offs must be carefully considered when adapting the system for different applications or scaling to larger battery packs.

8 Conclusion

This report has presented the modeling and simulation of a bidirectional battery charger with modular integrated charge equalization, suitable for electric vehicle applications. The study covered the design of a modular battery stack, the integration of a charge equalization circuit (CEC), and the implementation of coordinated control strategies for both grid-to-vehicle (G2V) and vehicle-to-grid (V2G) operation. Emphasis was placed on the system's ability to provide active and reactive power control, maintain balanced state of charge across battery modules, and ensure reliable operation through a flexible modular configuration. All aspects of the system were analyzed and validated through detailed circuit-level simulations, providing a comprehensive understanding of the charger's operation and its potential benefits for advanced battery management in electric vehicles.

References

[1] N. Tashakor, E. Farjah, and T. Ghanbari, “A Bidirectional Battery Charger With Modular Integrated Charge Equalization Circuit,” *IEEE Transactions on Power Electronics*, vol. 32, no. 3, pp. 2133–2143, Mar. 2017.