Simulation and Analysis of a Bidirectional AC-DC and a DC/DC Converter for Vehicle-to-Grid (V2G) Applications

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***Abstract*— This project focuses on the simulation and analysis of a bidirectional energy transfer system utilizing a single-phase bidirectional AC-DC converter and a bidirectional DC-DC converter. The proposed configuration enables efficient energy transfer between the grid and an electric vehicle (EV) battery, allowing energy flow from the grid to the EV (G2V) for charging and from the EV back to the grid (V2G) during discharging. The system ensures an improved grid power factor throughout its operation. Simulation results confirm the effectiveness of the proposed system and validate its feasibility for real-world applications.**

Keywords—Plug-in Hybrid Electric Vehicle (PHEV), Bidirectional AC-DC Converter, DC-DC Converter, Vehicle to Grid(V2G), Electric drive vehicle (EDVs)

I. INTRODUCTION

Recent pushes for sustainability and carbon-neutrality have pushed the popularity of electric vehicles (EV) and plug-in hybrid vehicles (PHEV) thanks to them being more environmentally friendly and efficient [1]. They have become increasingly integral to daily life, with projections estimating approximately 200 million EVs on the road by 2030. A significant portion of these vehicles will spend much of their time parked and connected to a charger [2].

With Vehicle-to-Grid (V2G) technology, these parked vehicles can provide power back to the grid, transforming them into a mobile "mega battery" capable of efficiently storing and discharging electricity as needed throughout the day. The connections are added to enable electricity to flow from vehicles to grid. Conversely, when connections are used to charge EV batteries, it is referred to as Grid-to-Vehicle (G2V).

PHEVs (plug-in Hybrid Electric Vehicles) which are emerging as replacements for traditional vehicles, incorporate both V2G and G2V concepts. This allows energy transfer from the vehicle to the grid during peak hours, helping to alleviate power usage and regulate utility load leveling, and enables the vehicle to recharge from the grid during off-peak hours when demand is lower.

It is vital to realize the economical benefit from V2G technology. By providing energy to the grid during peak demand, vehicle owners can earn revenue or reduce energy costs, turning parked vehicles into assets that generate income. Additionally, V2G reduce the strain on utility infrastructure, lowering operational costs for grid operators, which may translate into lower electricity rates for consumers. By enhancing grid stability, optimizing energy distribution, and offering a new stream of economic value, V2G represents a transformative step in the integration of sustainable energy systems.

The key to maximizing the economic potential of V2G lies in the precise timing of grid power production to align with driving requirements while meeting the time-sensitive power "dispatch" demands of the electric distribution system. Grid electricity as used by PHEVs as an alternative to traditional transportation fuel. The performance of PHEVs depends significantly on their batteries, making efficient charging and discharging critical for maintaining battery life, safety and reliability. To enable this bidirectional energy flow, advanced power converters are essential. These converters manage seamless energy transfers between vehicles and the grid, ensuring optimal utilization of stored energy. This paper reproduces and proves a proposed configuration incorporating bidirectional power converters to facilitate efficient PHEV battery management, ensuring that V2G operations are both economically advantageous and technically robust.

The diagram shown in Fig 1 illustrates a bidirectional energy flow system where electric power transmission supplies energy to residential, corporate, and commercial spaces. These spaces are connected to a bidirectional charging and discharging unit that facilitates energy exchange with EVs. The unit allows EVs to not only charge from the grid but also discharge energy back into buildings or the grid when needed, enabling efficient energy utilization and potential grid support.

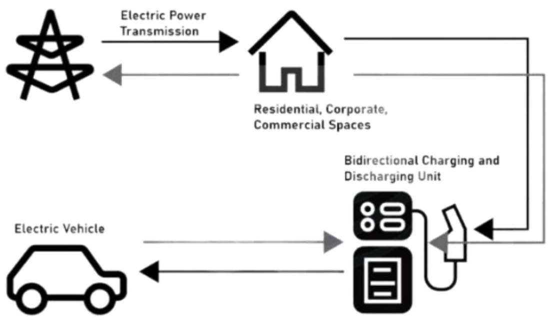

Fig. 1. Flow of energy system

In this paper, the team performed the simulation and analysis of a bidirectional AC/DC and a DC/DC converter to facilitate V2G applications. The configuration with power converter is derived for bidirectional power management of PHEV battery. The system is composed of 2 main parts: a single-phase bidirectional AC/DC converter and a buck boost DC/DC converter. The feasibility of the system is demonstrated through the charging and discharging of the battery.

This paper is organized as follows: Principle of Operation is introduced in Section II. System Configuration is explained in Section III. The design of the system is illustrated in Section IV. Detailed simulation result is shown in Section V. Conclusions are in Section VI.

II. PRINCIPLE OF OPERATION

The system comprises a single-phase bidirectional AC/DC converter and a bidirectional buck-boost DC/DC converter, connected via an intermediate filter. This filter ensures smooth power transfer and minimizes harmonics between the converters. The DC/DC converter operates in two modes: buck mode during charging and boost mode during discharging, facilitating bidirectional energy flow between the battery and the DC bus.

In buck mode, the converter reduces the DC bus voltage to match the lower voltage of the battery, enabling energy transfer from the grid to the battery for storage. Pulse Width Modulation (PWM) control is employed to regulate the charging current, maintaining safe and efficient charging conditions.

In boost mode, the converter increases the battery voltage to match the higher DC bus voltage, enabling energy flow from the battery to the grid. The current is similarly regulated using PWM control, ensuring precise operation and preventing overcurrent scenarios. This bidirectional operation ensures that the system can effectively support both charging (G2V) and discharging (V2G) applications.

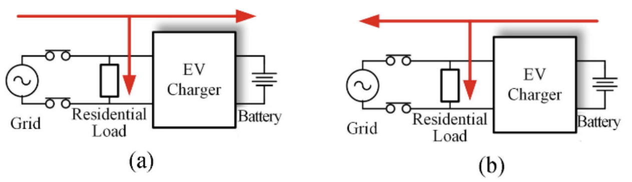

Fig. 2. Operating modes of the bidirectional EV charger. (a) G2V mode. (b) V2G mode.

III. SYSTEM CONFIGURATION

A. Overall System Setup

The system consists of two main stages: a single-phase bidirectional AC-DC converter and a bidirectional buck-boost DC-DC converter. In the first stage, a 230 V, 60 Hz AC supply is converted to 380 V DC using a single-phase bidirectional AC-DC converter. The AC-DC converter employs an LCL filter at its output to reduce high-frequency harmonics and ensure smooth DC voltage. This filter combines inductors and a capacitor to improve power quality by mitigating ripple currents and voltage distortions caused by the switching actions of the converter.

In the second stage, a bidirectional buck-boost DC-DC converter manages the charging and discharging of the EV battery. A low-pass filter is integrated at the output of the DC-DC converter to stabilize the voltage and minimize current ripples, ensuring efficient and safe energy transfer. The battery, rated at 1.2 kW charging power and 120 V, is modeled as part of a PHEV. A proportional-integral (PI) controller regulates the charging current and voltage, ensuring system stability and efficiency. Fig. 2 shows the operating mode the charger in G2V mode and V2G mode.

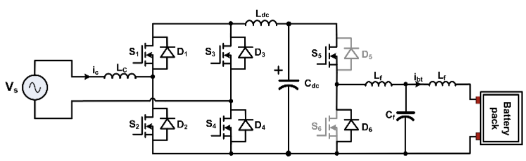

Fig. 3. Proposed Configuration for V2G and G2V Energy Transfer

B. Storage Battery

The battery is modeled using Thevenin's equivalent circuit, as shown in Fig 4. This model includes an equivalent capacitor (C) to represent energy storage, which accounts for the battery's ability to store and release energy based on its voltage levels. The circuit includes a series resistance (R_s), representing the internal resistance of the battery that causes voltage drops during charging and discharging, which is usually a small value. Additionally, a parallel combination of a resistor (R_b) and the capacitor (C_1) models the self-discharge behavior of the battery, where R_b represents the leakage paths over time. Together, they stabilize the battery voltage during switching operations. This equivalent model, when interconnected with power converters, facilitates efficient energy transfer, and provides an accurate simulation of the battery's performance in charging, discharging scenarios.

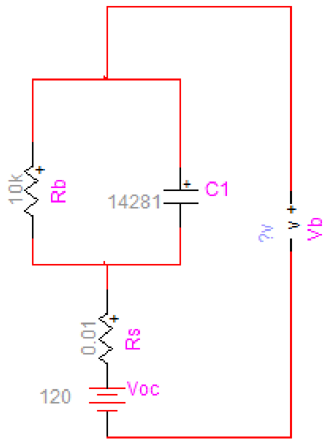

Fig. 4. Thevenin's Equivalent Circuit of Storage Battery

The interconnection of the EV battery with the converter and grid is achieved through a combination of power electronics converters, filters, and control systems to ensure efficient and reliable bidirectional energy flow.

The battery is connected to the buck-boost converter through a low-pass filter. This filter smooths out the ripples in current and voltage caused by the switching actions of the buck-boost converter, stabilizing the DC voltage and reducing high-frequency noise. The inductor limits the rate of current change, minimizing current ripple, while the capacitor filters out high-frequency voltage fluctuations, further stabilizing the DC voltage.

A DC link filter is placed between the AC-DC converter and the DC-DC converter. It consists of an inductor and a capacitor, with the capacitor positioned across the DC link. The capacitor provides voltage stabilization by acting as an energy reservoir to smooth out transients and maintain a steady DC voltage. This reduces the voltage ripple caused by switching actions, ensuring downstream components receive a stable input. The inductor works alongside the capacitor to filter out ripple current and transients, further minimizing ripple and maintaining the quality of the DC link voltage for optimal system performance.

IV. SYSTEM DESIGN

The system design consists of a single-phase bidirectional AC-DC converter, a bidirectional DC-DC boost converter, and a battery energy storage system. The detailed design of each component is provided in the subsequent sections.

A. Design of AC/DC Converter

The AC/DC converter in this system plays a crucial role in converting the AC grid power (230 V, 60 Hz) to DC power (380 V) for charging the EV battery. A single-phase bidirectional AC/DC converter is used, employing a controlled rectifier for efficient power conversion. The converter operates in two modes:

- **Charging Mode**: Rectifies AC power from the grid to DC power for charging the battery.
- **Discharging Mode**: Allows the battery to discharge power into the grid by controlling the flow of current in the reverse direction.

The bidirectional operation ensures flexibility in energy transfer and recovery. The converter employs a phase control strategy with a fixed pulse-width modulation (PWM) of 10, where the positive and negative voltages of the AC grid are compared to determine switching times. This ensures efficient power conversion and synchronized operation during both charging and discharging.

Critical components are designed as follows:

- **DC-Link Capacitor (Cdc):** Stabilizes the DC bus voltage and reduces voltage ripple, calculated using:

$$C_{dc} = \frac{P}{2\pi f V_{dc}\, \Delta V_{dc}} \quad (1)$$

With P=1.2 kW, f=60 Hz, Vdc=380 V, and Cdc=200 mF, the resulting ripple voltage is minimized to 0.084 V.

- **Grid-side inductor (Lg):** Limits grid current ripple, calculated using:

$$L_g = \frac{V_g}{4 f_s \Delta I} \quad (2)$$

where Vg=230 V, fs=10 kHz, and Lg=300 mH. This results in a low ripple current of 0.192 A, ensuring compliance with grid harmonic distortion standards.

- **Converter-side inductor (Lc):** Filters high-frequency switching ripples:

$$L_c = \frac{V_{dc}}{4 f_s \Delta I_c} \quad (3)$$

With Vdc=380 V, fs=10 kHz, and Lc=2.1 mH, resulting in a ripple current of 0.452 A.

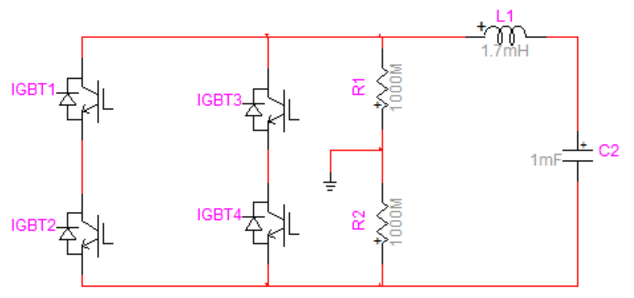

Fig. 5. AC/DC Converter circuit

B. Design of DC/DC Converter

The bidirectional DC/DC converter is designed to manage the charging and discharging of the EV battery efficiently. It utilizes two switches: K_1 operates in buck mode during charging to step down the voltage from 380V to the battery voltage (120V), while K_2 operates in boost mode during discharging to step up the battery voltage for energy transfer back to the grid. The control strategy for the converter is based on a PI controller that control the battery output current (I_b). The measured battery current is compared with the reference current ($I_{b,ref}$), and the PI controller generate the control voltage signal (V_{ref}) by utilizing the current error, as the following equations:

$$I_e = I_{b,ref} - I_b \quad (4)$$

$$V_{ref} = V(t-1) + K_p\big(I_e(t) - I_e(t-1)\big) + K_i I_e(t) \quad (5)$$

Where Kp, and Ki are the proportional and integral gains of the voltage control. The PI controller is designed by employing the Ziegler-Nichols method to ensure a stable and fine-tuned design system. The output of the controller (V_{ref}) is compared with fixed frequency saw-tooth carrier waveform to get the switching signals of the switches.

An LCL filter is integrated at the output of the DC/DC converter to reduce high-frequency switching noise and smooth the output current. The filter design includes:

- **Inductor L1=2 mH:** Placed between the converter and capacitor.
- **Inductor L2 =6mH:** Connected on the load side for additional filtering.
- **Capacitor C1 =1µF:** Stabilizes the voltage and provides energy storage.

The filter's total impedance is optimized for stability and low THD, with resonance frequency calculated as:

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{1}{C_1(L_1 + L_2)}} \quad (6)$$

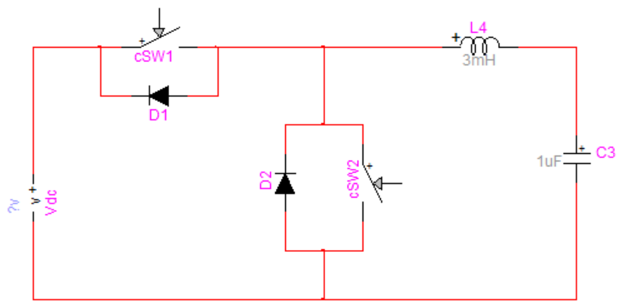

Fig. 6. DC/DC Converter circuit

C. Design of Storage Battery

Battery plays a critical role in the design of this system, serving as the primary means of energy storage and ensuring immediate energy availability when needed. A lead-acid model of the battery is implemented due to its reliability, cost-effectiveness, and widespread use in energy storage applications[4]. The Thevenin equivalent of the battery is used to model the battery's electrical behavior, which includes the internal resistance and voltage source, providing an accurate representation of its performance during charging and discharging cycles. The model is shown in Fig 4.

Energy is measured in kilowatt-hours (kWh) and is stored in an equivalent capacitor(C_1). The formula is shown below. V_{ocmax} symbolizes the maximum voltage at the terminal of the battery when it is fully charged. Similarly, V_{ocmin} represents the minimum voltage at the terminal of the battery when it is fully discharged.

$$C_1 = \frac{(kWh \cdot 3600 \cdot 1000)}{0.5\,(V_{ocmax}^2 - V_{ocmin}^2)} \tag{7}$$

The symbol R_s represents the internal resistance of the battery. It is typically a very small value. In this analysis, R_s is chosen to be 0.01Ω. R_b and C_1 are placed in parallel. It represents the self-discharging of the battery. R_b is chosen to be 10kΩ. Calculated C_1 is 14281F. V_{oc} is set to be 120V. The battery here is considered 1.2kW for 12 hours. Variations are in the voltage of 106 V to 136 V. This approach enables precise integration of the battery into the system, ensuring optimal performance and longevity while supporting seamless bidirectional energy flow for Vehicle-to-Grid (V2G) and Grid-to-Vehicle (G2V) operations.

V. SIMULATION AND PERFORMANCE EVALUATION

A. Overview of the Simulation

The simulation aims to validate the design and functionality of the bidirectional DC/DC converter for V2G applications. The system was modeled and simulated using EMTP to study its behavior in both buck (charging) and boost (discharging) modes. The simulation evaluates the system's voltage regulation, control performance, efficiency, and stability.

The simulation included the following components and features:

- Key system components: bidirectional buck-boost converter, battery, and grid interface.
- Control strategies for both operation modes, using a PI controller to regulate battery output current.
- A saw-tooth PWM scheme for switch actuation.

As shown in Fig. 7, the EMTP model of the overall system was designed to include the key components such as the bidirectional converter, battery, and grid interface. Additionally, Fig. 8 shows the EMTP model for the control strategy implemented in the bidirectional DC/DC converter, which uses a PI controller to manage the battery output current during both charging and discharging modes.

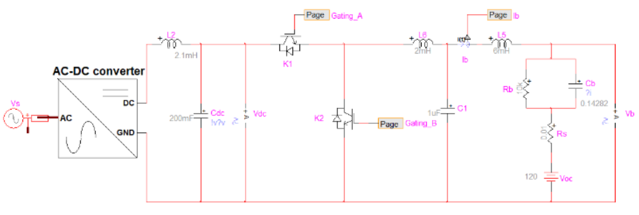

Fig. 7. EMTP model for the overall system

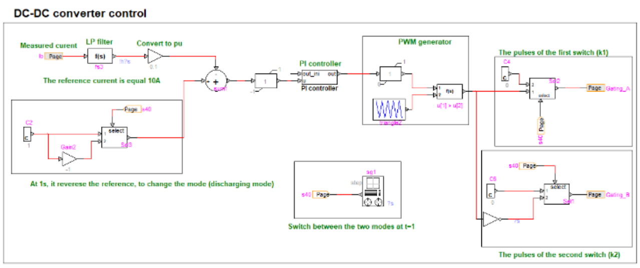

Fig. 8. EMTP model for the control of bidirectional DC-DC converter

B. Model Description

The bidirectional DC/DC converter was modeled with complementary switching of MOSFETs K1 and K2. The battery and grid interface are modeled as voltage sources, with current flow controlled by the converter's operating mode.

C. System Parameters

The parameters used in the simulation for the AC-DC converter are summarized in the table below:

Table 1: simulation parameters

Parameter		value
AC-DC converter	Grid AC voltage	230 V
	Output DC voltage	380 V
	Grid frequency	60 Hz
	Line-side inductor	300 mH
	Filter inductance	2.1 mH
	Filter capacitance	200 mF
DC-DC converter	Switching frequency	5 kHz
	PI Controller Gains - Kp	0.001
	PI Controller Gains - Ki	6
	Output current	10 A
	First Filter inductance	2 mH
	Filter capacitance	1 mF
	Second filter capacitance	6 mH
	Rb	10kΩ

Storage Battery	Cb	0.14282 F
	Rs	0.01 Ω
	Open circuit voltage	120 V

D. *Simulation results*

The simulation was performed over 1 second, where the converter operated in charging mode for the first 0.5 seconds and switched to discharging mode for the remaining 0.5 seconds. The simulation results are presented in Figs. 9-12.

During both charging and discharging modes, the grid voltage remained stable and within the acceptable limits. This was achieved by the control system effectively regulating the power flow. As shown in Fig. 9, the grid voltage remained within the acceptable operational range throughout the simulation, indicating the system's ability to maintain grid stability during bidirectional energy transfer.

The current waveform in the grid was sinusoidal and balanced in both modes, as expected from a well-functioning V2G system. The THD measurements during charging and discharging modes were relatively low, indicating good quality of current transfer. The THD was measured at 5.9% during charging mode and 6.3% during discharging mode. These low THD values confirm that the converter and control system are effectively regulating the current, as shown in Fig. 10, where the grid current waveforms and their associated THD values are depicted.

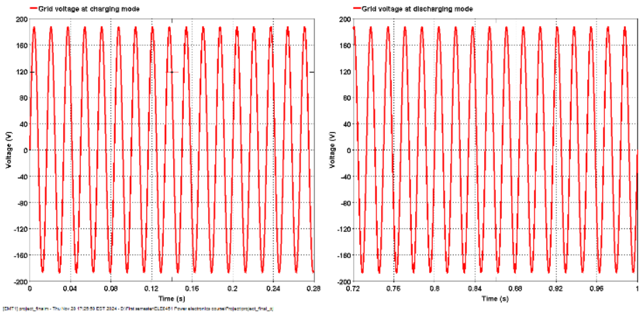

Fig. 9. Grid voltage during charging and discharging modes

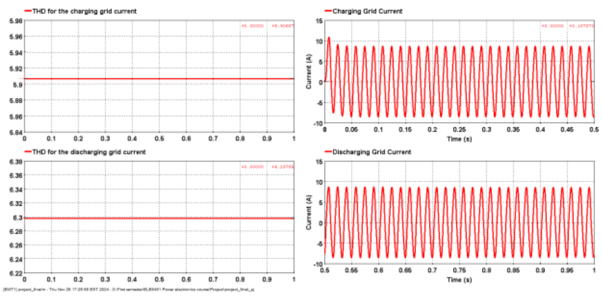

Fig. 10. Waveform and THD of the grid current in charging and discharging modes

The DC bus voltage remained stable throughout the simulation, as depicted in Fig. 11. This consistent voltage performance reflects the converter's ability to maintain the appropriate DC link voltage during the switching between the charging and discharging modes.

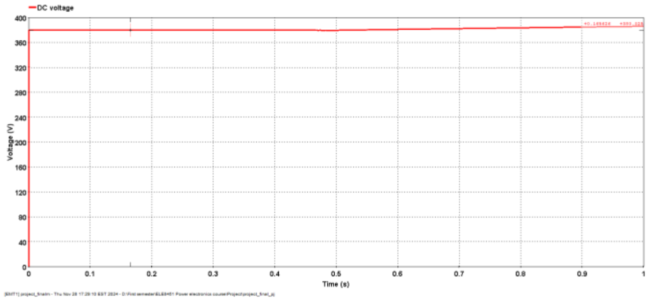

Fig. 11. DC bus voltage waveform during charging and discharging modes

During the charging phase, the battery voltage increased steadily as it received energy from the grid. The battery current followed the reference signal accurately, ensuring efficient energy storage. In the discharging phase, the current reversed direction, supplying power back to the grid. The battery voltage decreased as expected during energy discharge. The battery voltage and current waveforms, shown in Fig. 12, demonstrate the effectiveness of the PI control strategy in regulating the battery's behavior during both modes.

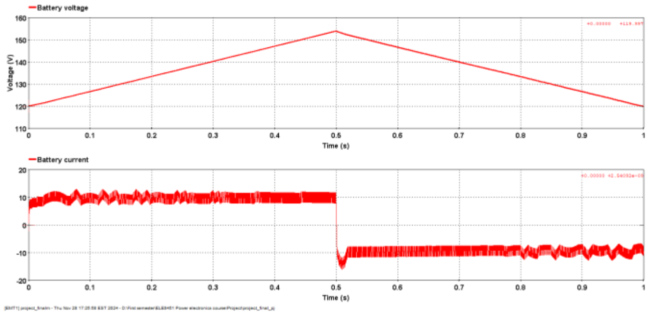

Fig. 12. Battery voltage and current waveforms in charging and discharging modes

VI. Conclusions

The simulation results validate the bidirectional DC/DC converter's design and performance for V2G applications. The system exhibited:

- Stable grid voltage and low harmonic distortion.
- Accurate control of battery voltage and current.
- Smooth mode transitions with efficient bidirectional energy transfer.

These outcomes demonstrate the system's reliability, efficiency, and suitability for V2G operations.

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