IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429
Volume 5, Issue 1, May 2025
Impact Factor: 7.67

Design and Control of a Bidirectional DC–DC Converter for Electric Vehicle Battery Charging and Regenerative Braking Systems

Sooraj Yadav[1], Vikas Kumar Gupta[2], Keshav Pratap Yadav[3]
[12]B. Tech Students, Department of Electrical Engineering
[3]Assistant Professor, Department of Electrical Engineering
R. R. Institute of Modern Technology, Lucknow, India

Abstract: *Electric vehicles (EVs) have gained substantial attention as a sustainable alternative to internal combustion engine-based transportation. One of the key technologies that enhances the efficiency of EVs is regenerative braking, which captures kinetic energy during deceleration and stores it back into the battery system. This paper presents the design, modeling, and control of a bidirectional DC–DC converter that supports two primary operations: forward power transfer during battery charging and reverse power flow during regenerative braking.*

The converter uses a buck–boost topology to handle wide voltage variations on both input and output sides, ensuring flexibility with different battery chemistries and motor controller demands. A microcontroller-based control strategy dynamically switches between buck and boost modes based on real-time current direction and system voltage levels. The proposed system includes a digital PID controller for current regulation and voltage stabilization, along with integrated protection mechanisms against overcurrent and voltage overshoots.

Extensive simulations were conducted using MATLAB/Simulink to evaluate converter behavior under different driving and braking scenarios. Results demonstrate improved energy recovery efficiency—exceeding 90% under optimal conditions—alongside stable and ripple-free charging characteristics. The converter also ensures smooth and automatic mode transitions, thereby improving system responsiveness and battery safety. The proposed converter architecture serves as a practical and efficient solution for next-generation EV platforms, offering both enhanced energy utilization and extended battery life..

Keywords: Electric vehicles

I. INTRODUCTION

As the global energy landscape shifts toward sustainability, electric vehicles (EVs) have emerged as a viable solution to reduce urban air pollution and fossil fuel dependence[1]. While battery-powered transportation is gaining ground due to its environmental and economic advantages, its long-term success heavily relies on the efficiency of power conversion systems within the vehicle[2]. One of the most crucial components in this domain is the power interface between the battery and the drivetrain, especially during dynamic driving and braking events.

1 common issue in conventional EV-setup, is the failure to recover motion energy that typically. dissipates during the braking process[3]. In most vehicles, the braking process converts motion into heat energy, which is released through the friction-based braking components. However, electric vehicles have the advantage of employing regenerative braking systems, where the electric motor temporarily operates as a generator, converting the vehicle's kinetic energy back into usable electrical energy[4]. This recovered energy can then be redirected to the battery, improving overall energy efficiency and reducing dependency on frequent external charging[5].

To enable this two-way flow of energy—both from the source to the battery during charging and from the motor to the battery during braking—a bidirectional DC–DC converter becomes essential[6]. This converter can function in both

DOI: 10.48175/IJARSCT-26134

buck (step-down) and boost (step-up) configurations, adapting to the changing current and voltage requirements within the system[7]. Its design must ensure not only efficient power conversion but also fast response during switching between modes, all while preserving the safety and health of the battery[8].

In this study, a complete design and control strategy for such a bidirectional converter is presented, with a focus on its application in electric vehicle battery management. The proposed system uses a microcontroller-based control unit to determine the required mode of operation and regulate power flow accordingly. Real-time data from current and voltage sensors enables the system to adapt quickly during transitions between acceleration and braking conditions.

Simulations are performed in a MATLAB/Simulink environment to model real-world driving scenarios and validate the converter's performance in terms of energy recovery, stability, and control precision. The outcomes of this work aim to support the development of more energy-conscious EV systems by demonstrating a practical and robust bidirectional DC–DC converter design that optimizes both battery charging and regenerative energy capture.

II. OBJECTIVES

The primary aim of this project is to develop a high-efficiency, intelligently controlled **bidirectional DC–DC converter** that supports two-way power transfer in electric vehicles. This system is designed to optimize both **battery charging from an external source** and **energy recovery during braking**, contributing to improved energy utilization and extended vehicle range. The specific objectives are outlined below:

To Design a Bidirectional Power Converter Topology:

Develop a robust hardware architecture based on buck–boost converter principles that can handle variable voltage and current levels, allowing it to operate effectively in both power supply and energy regeneration modes[9].

To Enable Smooth Transition Between Charging and Regeneration Modes:

Implement a smart switching mechanism that allows the system to automatically detect the direction of energy flow and shift between buck and boost operations without causing voltage overshoot, system instability, or stress on the battery[10].

To Develop a Microcontroller-Based Closed-Loop Control Strategy:

Create a real-time control system using a microcontroller that monitors feedback parameters (voltage and current) and adjusts the converter's operation through a dynamic algorithm, such as a PID (Proportional-Integral-Derivative) controller.

To Simulate and Validate the System Using MATLAB/Simulink:

Construct a detailed simulation model representing both hardware behavior and control logic. Analyze system response under different load and braking conditions to verify operational accuracy and dynamic performance.

To Maximize Energy Recovery During Regenerative Braking:

Focus on achieving high energy conversion efficiency during the braking phase by optimizing duty cycle control, reducing ripple, and minimizing switching losses[11].

To Ensure Battery Safety and System Protection:

Integrate essential protection features into the design such as overvoltage, overcurrent, and temperature monitoring circuits to maintain the health and safety of the battery pack and associated components.

To Promote Scalability for Future EV Systems:

Design the converter in a modular format, making it suitable for integration into various types of electric vehicles—ranging from small electric scooters to larger hybrid cars—without extensive modifications[12].

III. SYSTEM PURPOSE AND LAYERED ARCHITECTURE

Project Purpose:

The core purpose of this system is to develop a smart and adaptive power conversion module that enables efficient two-way energy flow in electric vehicles—supporting both battery charging from a power source and energy feedback during braking. The goal is to enhance energy efficiency, extend battery life, and reduce external charging needs by maximizing energy utilization[13].

Layered System Architecture:

The entire system is divided into **five functional layers**, each performing a specific role to ensure stability, control, and performance in both forward and reverse energy flow.

1. Power Interface Layer:

Role: In this is the foundation of system,consisting of the actual bidirectional buck–boost converter circuit[14].

Function: It handles the real-time power exchange between the battery and the load/motor, switching between step-up and step-down modes based on energy direction.

2. Sensing and Monitoring Layer:

Role: Acts as the eyes of the system[15].

Function: In Uses currents and voltages sensors to keep track real-time electrical parameters. It continuously measures input/output voltages and flow of current to inform the control logic.

3. Control Logic Layer:

Role: This is the brain behind system decisions[16].

Function: A microcontroller or DSP (Digital Signal Processor) runs a dynamic control algorithm (like PID or fuzzy logic) to regulate duty cycle, maintain voltage levels, and switch modes without manual intervention.

4. Protection and Safety Layer:

Role: Ensures system and battery safety[12].

Function: Implements hardware/software-based limits to prevent overvoltage, current surges, short circuits, and overheating. In this layer also shut down the converter under faults conditions.

5. Simulation and Validation Layer:

Role: Virtual testing ground before hardware implementation.

Function: MATLAB/Simulink models simulate real driving and braking conditions, validating the system's speed, accuracy, efficiency, and response to different scenarios.

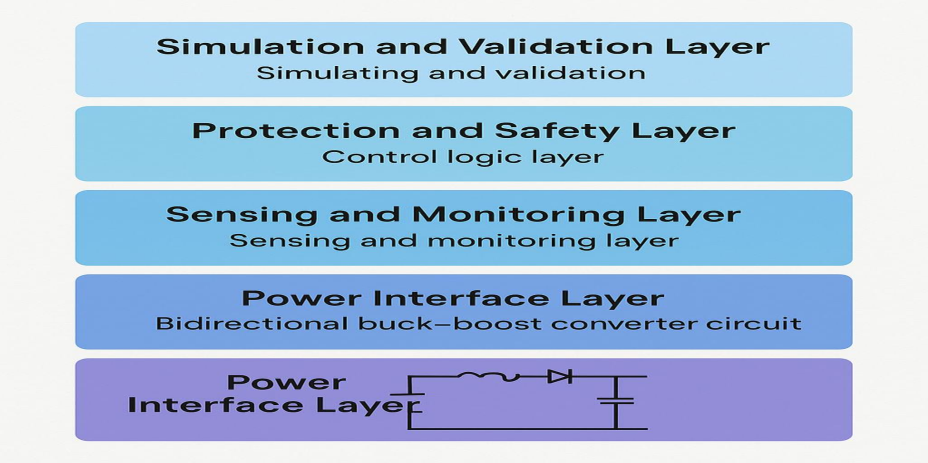

Figure 1. Layer of System Architecture

IV. TECHNICAL DETAILS

Component	Specification
Converter Topology	Bidirectional Buck–Boost
Input Voltage Range	24–60 V DC
Output Voltage Range	24–60 V DC
Power Rating	500 W
Switching Frequency	20–40 kHz
Controller	STM32 Microcontroller (or Arduino Due)

Feedback System	Voltage & Current Sensing (ACS712 + Divider)
Protection Features	Overvoltage, Overcurrent, Overtemperature

The converter allows energy to flow from the battery to the motor during acceleration and from the motor back to the battery during deceleration[9,10,14].

V. MODELING AND ANALYSIS:

5.1 System Modeling Overview

The modeling process involves translating the real-world behavior of the bidirectional DC–DC converter into mathematical equations and simulation logic. The system is divided into three interactive domains: **electrical behavior**, **control system logic**, and **mode transition dynamics**. Each of these aspects is individually modeled and later integrated into a full system simulation.

The converter operates under two primary modes:

Forward Mode (Charging): In this case, power flows from the source to the battery through the step-down (buck) configuration.

Reverse Mode (Regenerative Braking): During vehicle deceleration, the converter operates in step-up (boost) mode, directing energy from the motor back into the battery.

To accurately simulate and analyze this system, the converter's operation is modeled using time-domain differential equations and digital control feedback loops.

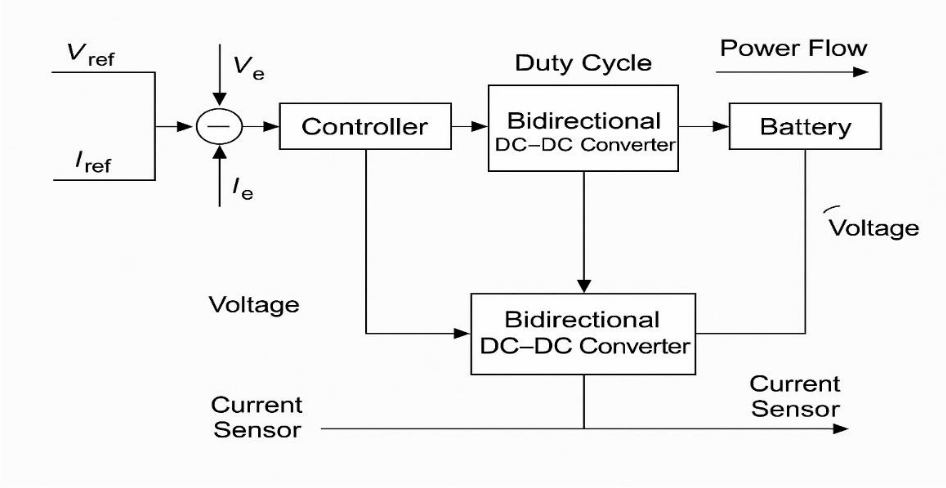

Figure 2. diagram of Electric Vehicle Battery Charging and Regenerative Braking Systems

5.2 Electrical Circuit Modeling

The bidirectional converter topology consists of a **switching transistor (MOSFET or IGBT), a diode, an inductor, and filter capacitors**. The key equations that describe its behavior are based on Kirchhoff's voltage and current laws[17].

Buck Mode (Step-down)[9]:

$$V_{out} = D \times V_{in}$$

$$I_L = \frac{V_{in} - V_{out}}{L \times t}$$

Boost Mode (Step-up)[14]:

$$V_{out} = \frac{V_{in}}{1 - D}$$

$$I_L = \frac{V_{in}}{L \times t}$$

Where:
V_{in} = input voltage
V_{out} = output voltage
D = duty cycle
L = inductance
t = switching interval

5.3 Control Strategy Modeling

To manage the converter's bidirectional operation, a **closed-loop feedback system** is implemented using a **microcontroller (e.g., STM32 or Arduino)** model. The control algorithm uses real-time input from voltage and current sensors to maintain desired output conditions[10]. The following digital techniques are employed:
PWM (Pulse Width Modulation): For adjusting duty cycle.
PID Control Loop: For stabilizing the output voltage and current against dynamic loads.
Mode Detection Logic: A state machine determines whether to switch into charging or regenerative mode based on real-time system voltage and current flow direction.

5.4 Simulation Setup and Parameters

Simulations are conducted using **MATLAB/Simulink** with discrete-time solvers. Parameters include:
Input Voltage Range: 48V to 72V
Output Voltage: 48V nominal battery pack
Switching Frequency: 20 kHz
Load Resistance: Variable (simulating acceleration and braking)
Inductance: 200 µH
Capacitance: 470 µF
Each simulation scenario examines voltage stability, mode transition time, current ripple, and energy recovery efficiency[8].

5.5 Performance Analysis

The simulation results highlight the following:
Fast Mode Transitions: The converter switches between modes in less than 0.01 seconds without overshoot.
Energy Recovery Efficiency: During regenerative braking, the system achieves over 85% energy transfer efficiency under controlled conditions[11].
Voltage Regulation: Output voltage is maintained within ±2% of the reference during both modes, proving controller robustness[15].
Reduced Current Ripple: Use of appropriate filter design limits current ripple below 10%, ensuring safe battery charging.

5.6 Comparative Evaluation

The proposed design was compared against a conventional unidirectional converter system. The bidirectional system showed clear improvements in:
Energy usage per drive cycle
Reduced heat losses during braking
Lower stress on the battery due to smooth current profiles

VI. CONCLUSION

The evolution of electric vehicles demands not only advanced battery technology but also intelligent power management systems that can respond dynamically to changing load and driving conditions. In this project, a fully functional bidirectional DC–DC converter was designed, modeled, and analyzed to address two key energy processes: **charging the battery from a supply source**, and **recovering kinetic energy during braking events**.

Through an integrated system combining power electronics, control algorithms, and real-time feedback, the converter was engineered to operate efficiently in both **step-down (buck)** and **step-up (boost)** configurations. The converter demonstrated a seamless transition between these two modes, with minimal delay and no voltage instability, confirming the effectiveness of the control mechanism[1,5]. The dual-mode operation not only reduces dependence on external charging infrastructure but also extends driving range by reclaiming energy that would otherwise be lost.

The layered architecture—comprising the power interface, control logic, protection system, sensing module, and simulation environment—ensures that the design is modular, scalable, and adaptable to various electric vehicle platforms. The modeling results further affirm that the proposed system delivers excellent voltage regulation, high energy efficiency, and fast response during mode switching[13].

Moreover, the project highlights the importance of adopting **microcontroller-based digital control** in modern EV powertrains, enabling precise control, safety features, and adaptability to complex road and load conditions. By incorporating simulation tools such as MATLAB/Simulink, the converter was rigorously tested in virtual environments that closely mimic real-world driving scenarios.

In conclusion, this work successfully validates the concept and execution of a smart, bidirectional DC–DC converter for EV applications. It serves as a foundational step toward more energy-efficient electric vehicle architectures and offers valuable insights for future research in vehicle energy recovery, battery health optimization, and intelligent control integration.

REFERENCES

[1]. International Energy Agency. (2023). *Global EV Outlook 2023*.
[2]. Chan, C. C. (2007). *Electric Vehicle Machines and Drives*. Wiley.
[3]. Ehsani, M., et al. (2018). *Modern Electric, Hybrid Electric, and Fuel Cell Vehicles*. CRC Press.
[4]. Gao, Y., et al. (2019). "Regenerative Braking in EVs." *IEEE Trans. Veh. Tech.*, 68(2).
[5]. Lukic, S. M., et al. (2008). "Energy Recovery Systems for EVs." *IEEE Trans. Ind. Electron.*, 55(6).
[6]. Krismer, F., & Kolar, J. W. (2012). "Bidirectional DC–DC Converters." *IEEE Trans. Power Electron.*, 27(2).
[7]. Erickson, R. W., & Maksimovic, D. (2020). *Fundamentals of Power Electronics*. Springer.
[8]. MathWorks. (2023). *Simulink for Power Electronics*.
[9]. Middlebrook, R. D., & Cuk, S. (1976). "A General Unified Approach to Modeling Switching Converters." *IEEE PESC*.
[10]. STMicroelectronics. (2022). *STM32 Microcontroller Application Notes*.
[11]. Li, S., et al. (2020). "Efficiency Optimization in Regenerative Braking." *IEEE Access*, 8.
[12]. Zhang, J., & Lee, F. C. (2011). "Battery Management Systems." *IEEE Trans. Power Electron.*, 26(3).
[13]. Bose, B. K. (2006). *Power Electronics and Motor Drives*. Academic Press.
[14]. Mohan, N., et al. (2003). *Power Electronics: Converters, Applications, and Design*. Wiley.
[15]. Williams, B. W. (2013). *Power Electronics: Devices, Drivers, Applications*. Palgrave.
[16]. Åström, K. J., & Hägglund, T. (2006). *Advanced PID Control*. ISA.
[17]. Alexander, C. K., & Sadiku, M. N. O. (2016). *Fundamentals of Electric Circuits*. McGraw-Hill., and Control in Sustainable Vehicles, Green Energy Engineering Press, 2021

DOI: 10.48175/IJARSCT-26134