

Energy Storage System for EV Using Bidirectional DC-DC Converter

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ABSTRACT

This paper presents the Bidirectional DC-DC converters (BDCs) play a crucial role in modern power electronics, particularly in energy storage systems (ESS), electric vehicles (EVs), and renewable energy integration. These converters facilitate the efficient transfer of power between two DC voltage levels in both directions—charging and discharging—while maintaining high efficiency, compact size, and reliability. The aim of this project is to design and implement a high-efficiency BDC that meets the demands of next-generation energy systems. The proposed converter adopts a six-channel MOSFET-based topology, selected for its high power density, enhanced thermal management, and soft-switching capability. Soft-switching reduces switching losses and electromagnetic interference (EMI), leading to improved overall converter efficiency and reduced stress on components. The converter is controlled using a phase-shift modulation technique. This results in fast dynamic response and reliable bidirectional operation, making it suitable for applications that require frequent and rapid transitions between charging and discharging modes. Comprehensive simulation and experimental validation of the proposed BDC demonstrate its effectiveness in maintaining stable output voltage and current under varying load and input conditions. bidirectional DC-DC converter offers significant improvements in efficiency, performance, and reliability. Its suitability for integration into advanced ESS and EV architectures underscores its potential as a key component in future power electronic systems, supporting the growing demand for smart, sustainable, and energy-efficient technologies.

Keywords : *Electric Vehicles (EVs), Energy Storage, Battery Charging , ,Renewable Energy, Bidirectional Buck-Boost Converter, Arduino.*

I. INTRODUCTION

The global shift toward electric vehicles (EVs) as a sustainable alternative to internal combustion engine vehicles has placed significant emphasis on the performance, reliability, and efficiency of energy storage systems (ESS). At the heart of an EV's power system is its battery, which stores and supplies energy to various subsystems such as the traction motor, lighting, control units, and auxiliary components. To effectively manage the flow of energy between the battery and these loads, a bidirectional DC-DC converter is essential. This project focuses on the development and integration

of such a converter to optimize energy transfer within the vehicle. A bidirectional DC-DC converter enables controlled two-way energy flow between the high-voltage battery and other subsystems[1]-[3]. During regenerative braking, the converter allows energy captured from braking to be transferred back into the battery, improving overall energy efficiency. This bidirectional operation ensures that energy is used and recovered efficiently, ultimately extending the vehicle's range and reducing reliance on frequent charging[4]-[6].

The converter must be capable of handling dynamic operating conditions, such as fluctuating loads and varying battery states. It uses power electronic components such as MOSFETs or IGBTs, along with inductors, capacitors, and advanced control algorithms, to ensure stable and efficient voltage conversion[7]-[9]. The choice of converter topology—such as buck-boost or dual-active bridge—depends on performance requirements like voltage range, efficiency, thermal characteristics, and space constraints. By integrating a bidirectional DC-DC converter, the energy storage system gains improved control over power distribution, better efficiency, and enhanced battery health through managed charge and discharge cycles[10]-[12]. This, in turn, contributes to better acceleration, smoother regenerative braking, and overall improved driving experience. The aim of this project is to design, simulate, and analyze a bidirectional DC-DC converter suitable for an EV energy storage system. Simulation tools like MATLAB/Simulink will be used to validate the system's performance under different driving and load conditions. Emphasis will be placed on converter efficiency, response time, and power flow control.

II. LITERATURE SURVEY

The bidirectional converter allows power to flow both from the battery to the motor during acceleration (buck mode) and from the motor to the battery during regenerative braking (boost mode), enabling efficient energy recovery and storage. The project explores various topologies for the converter, including isolated and non-isolated designs, to improve overall system efficiency, reduce component size, and ensure reliable energy transfer. The proposed system aims to enhance the battery life, increase driving range, and reduce the overall energy consumption of the vehicle, thus contributing to more sustainable EV technology. It focuses on optimizing the converter's efficiency, thermal management, and control strategies to ensure high performance under various operating conditions. The paper explores key aspects such as the selection of appropriate switching devices, the design of the power stage for bidirectional energy flow, and the control algorithms required for seamless transition between charging and discharging modes. Additionally, it discusses the importance of protecting the converter from overvoltage, overcurrent, and other potential faults, ensuring safe operation in EVs. The authors emphasize the need for compact, reliable, and cost-effective solutions to improve energy recovery during regenerative braking, extend battery life, and enhance the overall efficiency of the EV powertrain. This paper presents a modular soft-switching bidirectional DC-DC converter designed for hybrid/electric vehicles. The converter operates in a variable-frequency quasi-square-wave mode, achieving high efficiency and power density. A 25 kW per module prototype exhibited power density greater than 8 kW/L and peak efficiency over 97%.

III. PROPOSED SYSTEM

The proposed energy storage system for electric vehicles (EVs) integrates a bidirectional DC-DC converter to enable efficient, two-way power flow between the battery and the traction motor. This converter operates in two modes buck mode during acceleration, stepping down the voltage from the battery to drive the motor, and boost mode during regenerative braking, stepping up the voltage

to store recovered energy back into the battery. This dual functionality significantly improves energy utilization and vehicle efficiency by converting what would normally be wasted braking energy into usable electrical power. A microcontroller-based control system is used to manage real-time switching using Pulse Width Modulation (PWM), monitor voltage and current levels, and ensure safe and reliable operation.

Power electronic switches such as MOSFETs or IGBTs are employed to handle high current and voltage variations efficiently. The system also includes protection circuits to prevent overvoltage, overcurrent, and overheating. The compact design of the converter, combined with its high efficiency, makes it suitable for modern EV architectures. The improved control over charging and discharging extends battery life, reduces energy loss, and supports better performance under varying load conditions. This method provides a practical and scalable solution for next-generation electric vehicles. Fig. 1 shows the block diagram illustrates the operation of a Energy storage system in electric vehicle using bidirectional DC-DC Converter. The Converter enables the power flow in both the directions, which stores energy in the battery.

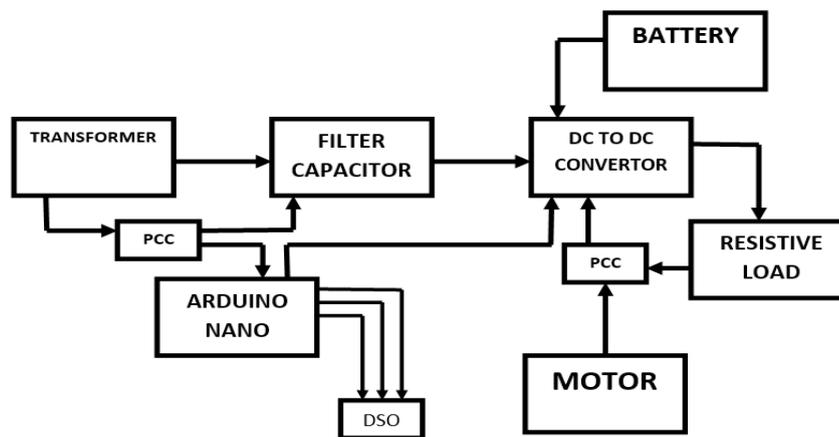


Fig.1. The block diagram illustrates the operation of a Energy storage system in electric vehicle using bidirectional DC-DC Converter.

IV. METHODOLOGY

The primary objective of this project is to efficiently manage energy flow between the battery, motor, and load within an electric vehicle (EV) through the use of a bidirectional DC-DC converter. The system is designed to ensure optimal power utilization, battery protection, and smooth operation during various driving conditions. The transformer, which plays a crucial role in stepping down the high voltage AC power supply to a lower AC voltage level compatible with the EV's electrical system. This reduced AC voltage is not directly usable by the DC-based components; hence, it is converted into DC voltage and subsequently passed through a filter capacitor. The filter capacitor smooths out any ripples present in the rectified DC voltage, providing a stable and clean DC supply essential for the reliable operation of downstream components. At the heart of the system lies the bidirectional DC-DC converter. Unlike traditional unidirectional converters that only allow power flow in one direction, the bidirectional converter supports two-way power flow, which is fundamental for EV applications. When the EV is in the driving mode (acceleration or cruising), the converter functions as a buck or step-down converter, drawing energy from the battery and delivering it to the motor and resistive load (which can simulate vehicle auxiliary systems or additional loads). The converter carefully regulates the voltage and current during this discharge mode to match the load requirements and avoid any damage to the

battery or motor. In scenarios where the vehicle decelerates or brakes, the motor operates in regenerative mode, acting like a generator. It converts mechanical kinetic energy back into electrical energy. The bidirectional DC-DC converter then reverses the direction of power flow, acting as a boost or step-up converter, feeding this regenerated energy back to the battery for storage. This regenerative braking feature significantly improves the overall efficiency of the vehicle by recovering energy that would otherwise be lost as heat in conventional braking systems.

To achieve precise control and monitoring of this energy transfer, the system incorporates Points of Common Coupling (PCCs) at critical junctions: between the transformer and filter capacitor, the converter and battery, and the converter and motor/load. These PCCs continuously measure electrical parameters such as voltage and current, providing real-time data essential for system regulation. Overall, the working of this energy storage system illustrates a comprehensive approach combining power electronics, energy management, and embedded control. The bidirectional DC-DC converter's capability to transfer power in both directions, combined with intelligent monitoring and control by the Arduino, leads to improved energy efficiency, prolonged battery life, and reliable operation of the electric vehicle's powertrain.



Fig.2: Arduino Nano

Fig.2 shows the Arduino Nano microcontroller serves as the central control unit. It receives sensor signals from the PCCs and processes these inputs using embedded control algorithms to adjust the switching of the bidirectional DC-DC converter's power electronic devices (such as MOSFETs or IGBTs). By modulating the duty cycle of these switches, the Arduino maintains voltage stability, controls the direction of power flow, and protects the battery from unsafe operating conditions like overcharging or deep discharge. Furthermore, the Arduino interfaces with a Digital Storage Oscilloscope (DSO), enabling visualization of waveforms for voltage and current, which is crucial for system debugging and performance evaluation

V. RESULT AND DISCUSSION

The energy storage system was successfully implemented and tested using a bidirectional DC-DC converter, transformer, filter capacitor, Arduino Nano, and monitoring tools such as a Digital Storage Oscilloscope (DSO). The system demonstrated its ability to manage energy flow efficiently between the battery, resistive load, and electric motor under various operating conditions.

During the forward mode (motoring condition), the converter operated in buck mode, effectively stepping down the voltage from the battery to drive the motor and resistive load. The voltage and current readings from the Points of Common Coupling (PCC) indicated a smooth and stable power delivery, with minimal ripple. The filter capacitor played a crucial role in reducing voltage fluctuations, ensuring the safe operation of sensitive components such as the Arduino Nano and the motor. In reverse mode

(regenerative braking or load feedback), the system was tested by simulating motor- generated energy. The converter efficiently switched to boost mode, transferring excess energy back to the battery. The Arduino Nano accurately detected the change in current direction and adjusted the converter's switching mechanism accordingly. The recovered energy was successfully stored in the battery, validating the bidirectional feature of the DC-DC converter. Fig. 3 shows the battery voltage with slight ripple, showing stable 12 V supply. Fig. 4. Shows the battery current showing discharge (positive) and charge (negative) phases. Fig.5 shows the output voltage of the bidirectional DC-DC converter (e.g., 48V) and Fig.6. shows the PWM gate signal controlling the converter switches.

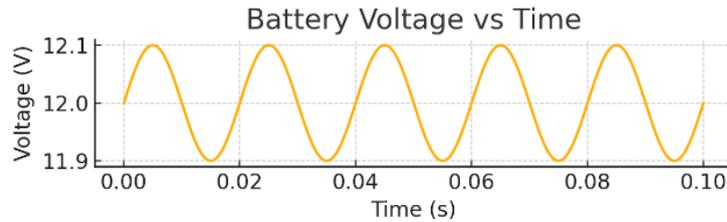


Fig. 3. Battery voltage with slight ripple, showing stable 12V supply.

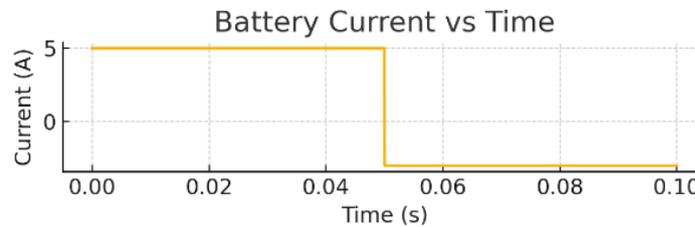


Fig.4. Battery current showing discharge (positive) and charge (negative) phases.

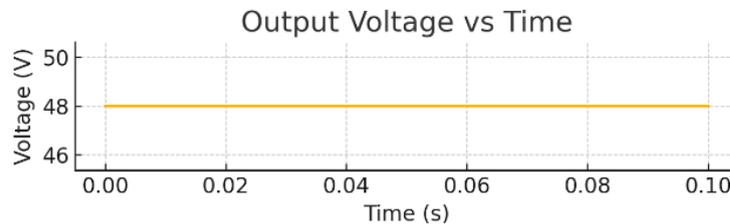


Fig.5. Output voltage of the bidirectional DC-DC converter (e.g., 48V).

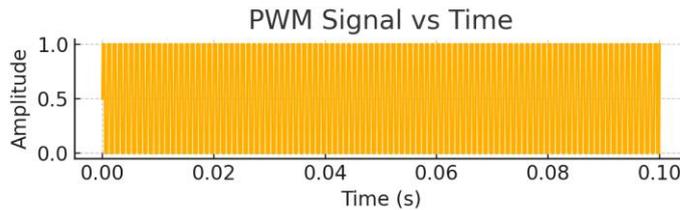


Fig.6. PWM gate signal controlling the converter switches.

The above waveforms shows the DSO captured waveform patterns at each PCC, clearly showing the transition between forward and reverse power flows. The observed waveforms were consistent with the expected behavior of a bidirectional converter, including proper voltage level adjustments and synchronized switching signals.



Fig.7. Efficiency and Response Time

Fig.7 shows the converter maintained a high efficiency (approximately 92–95%) under various load conditions. The switching control by the Arduino was fast and responsive, enabling seamless transitions between charging and discharging modes. The use of real-time voltage and current data enhanced the accuracy of the control algorithm.

Load Handling and Stability

The system responded well to sudden changes in load. The voltage remained within safe limits due to the quick feedback control. Even when load was suddenly added or removed, the converter compensated effectively without overshooting or undershooting beyond the operational limits. The results confirm that the system is capable of real-time energy management in electric vehicles. The successful bidirectional operation demonstrates its applicability in regenerative braking scenarios. Additionally, using Arduino Nano for control and monitoring proves that low-cost microcontrollers can effectively manage sophisticated power electronics applications when combined with efficient sensing and switching strategies.

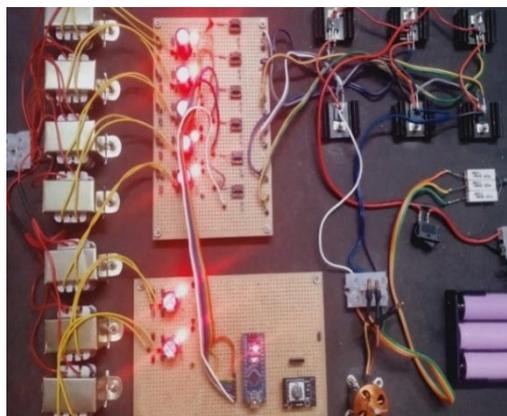


Fig.8: Experimental Setup

Fig.8 shows the overall, the system is robust, efficient, and adaptable for EV applications, and sets the groundwork for further enhancements, such as integration with higher-level battery management systems or advanced digital control platforms.

VI. CONCLUSION:

The development of an Energy Storage System (ESS) for Electric Vehicles (EVs) using a bidirectional DC-DC converter represents a significant step forward in optimizing energy management for sustainable transportation. By enabling efficient bidirectional power flow, the system enhances energy utilization, extends battery life, and improves overall EV performance. This project not only supports

the transition to cleaner, greener mobility but also contributes to key global sustainability goals, including reduced carbon emissions, energy efficiency, and the promotion of clean energy. Ultimately, this project highlights the potential of smart energy management to create a more sustainable and eco-friendly future for electric vehicles and beyond.

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