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High-Gain Bi-Directional DC-DC Converter for EV Drives with Regenerative Charging Analysis

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Abstract:

This research presents a novel non-isolated high gain bidirectional DC-DC converter (BDC) and its application in integrating energy storage system with electric vehicle (EV). The proposed converter is capable of providing high voltage gain with the help of two duty cycle operation by employing fewer components in its circuit design. The proposed topology makes use of dual current path inductor structures which reduces their size and eliminates the need for an additional clamping circuit to give energy to the load. Without using voltage multiplier cells (VMC) or hybrid switched-capacitor approaches, the proposed converter can achieve a significant voltage gain. The simulation of the proposed converter-based drive is carried out using MATLAB/Simulink system and the performance analysis is done for different driving conditions. The converter powers the motor through the battery during the forward motoring mode. The motor acts as a generator during regenerative braking and the energy is transferred back through the converter to the battery which stores the recovered energy.

Keywords: bidirectional dc–dc converter, high voltage gain, electric vehicle, regenerative braking, battery charging.

1.INTRODUCTION

The transportation sector's escalating oil consumption, coupled with mounting concerns about global warming and diminishing energy resources, has prompted governmental bodies and organizations to enforce increasingly stringent fuel consumption and emission limits. This shift is driving a rapid transition towards electric vehicles (EVs) and Hybrid Electric Vehicles (HEVs). Projections indicate that by 2040, annual sales of EVs and HEVs will surpass 48 million units, exceeding those of traditional petrol and diesel vehicles. In response, the automotive industry is heavily investing in developing advanced technologies for powertrains, batteries, and charging infrastructure, aiming to meet the rising demand for vehicles with enhanced fuel efficiency and reduced environmental impact. Key innovations include high-energy battery packs and regenerative braking systems, which significantly extend the driving range and battery lifespan of EVs.

Power electronic converters play a crucial role in EV drivetrains, modulating power flow between the battery and propulsion motors and facilitating regenerative braking. To achieve higher efficiency and power density, these drivetrains operate at elevated voltages, necessitating the use of boost converters to step up the battery voltage. These DC-DC converters must be bidirectional, enabling power transfer from the battery to the load during transient and overload conditions and facilitating battery charging during regenerative braking. The benefits of incorporating a bidirectional DC-DC converter (BDC) between the battery and inverter include reduced stress on the inverter, adjustable inverter supply voltage for increased motor output, potential reduction in battery size and cost due to lower cell count requirements, and greater flexibility in system design. For instance, the BDC in the 2010 Toyota Prius boosts the battery's nominal voltage of 200V to approximately 650V for the DC bus.

While isolated BDCs, which employ high-frequency transformers, are common, they suffer from increased losses, larger volumes, and potential transformer core saturation. Consequently, non-isolated BDCs are gaining preference in applications where isolation is not mandatory, such as EV drivetrains, due to their simpler structure and lower component count. To achieve high conversion ratios, non-isolated BDCs utilize various circuit principles, including SEPIC/Cuk/Zeta converters, voltage multiplier cells, switched capacitors, and linked inductors. However, each of these approaches has limitations. SEPIC/Cuk/Zeta converters suffer from low efficiency and high voltage stress, voltage multiplier cells are limited by high switch voltages, and switched capacitor-based converters become complex and lossy at high gains. Hybrid topologies offer potential efficiency improvements, but may lack sufficient voltage gain or exhibit high ripple currents.

Coupled inductor-based bidirectional converters (CIBDCs) represent a significant advancement in achieving high voltage conversion ratios. Unlike transformer-based topologies, CIBDCs enable energy exchange at multiple instants within a single time period, reducing switch current and voltage stress. However, challenges remain in clamping leakage energy and minimizing voltage spikes. Researchers have explored various CIBDC designs to address these issues, such as increasing coupled inductance to reduce current ripple or employing multiple secondary coupled inductor branches for higher voltage conversion and current sharing. A non-isolated high-gain converter for microgrids, utilizing a normal inductor instead of a coupled inductor, has also been proposed, though it is unidirectional.

This paper proposes a modified version of the unidirectional converter, designed to be bidirectional for EV applications. The proposed high-gain bidirectional converter (HGBDC) utilizes only four active power switches, simplifying its construction. High voltage gain is achieved through careful selection of duty cycles and component values. Operating at lower duty ratios minimizes inductor core saturation, and the input current is divided among the inductors, reducing their size and eliminating the need for additional clamping circuits. The converter's performance is analysed using MATLAB/Simulink and OPAL-RT SIL systems, demonstrating its viability in interfacing energy storage devices to the DC link in EVs.

The converter effectively manages power flow during forward motoring and regenerative braking. The paper further details the topology and operation of the proposed HGBDC, discusses the specification and design of the converter-fed drive system, presents modelling and simulation results, and describes its implementation in a real-time simulation system.

2. LITERATURE SURVEY

Chung et al. (2000) developed a switched-capacitor DC-DC converter designed for versatile power management, offering bidirectional power flow and both step-up and step-down voltage conversion. This is achieved using two current-controlled, bidirectional converter cells operating in antiphase, which minimizes current ripple and component stress, improving efficiency and reliability. The design offers a continuous input current, reducing EMI and simplifying filtering. Advantages over inductor-based converters include higher power density, smaller size, and potential cost benefits in low to medium power applications. The converter's robust voltage regulation ensures stable output, making it suitable for applications like battery energy storage, electric vehicle charging, and renewable energy interfaces. Future work suggests optimizing control strategies and integrating advanced algorithms for smart grid applications.

Bai et al. (2020) presented a bidirectional resonant DC-DC converter optimized for Vehicle-to-Grid (V2G) applications. This converter achieves high efficiency across a wide battery voltage range, crucial for V2G functionality. It employs a PWM full-bridge series-resonant topology for power transfer from the EV to the grid, enabling high power capability and precise voltage regulation. For grid-to-EV charging, it uses a half-bridge resonant boost converter to efficiently step up voltage. Utilizing zero-voltage switching (ZVS) and zero-current switching (ZCS) techniques minimizes switching losses. This design enhances grid stability and EV utilization, supporting various battery chemistries and states of charge. Potential applications extend to onboard chargers, DC fast charging stations, and energy storage systems.

Zhu et al. (2020) examine the increasing prevalence of Capacitor-Inductor-Inductor-Capacitor (CLLC) resonant converters in applications like EV charging and energy storage, highlighting their advantages of soft switching (ZVS/ZCS), wide output voltage range, and symmetrical bidirectional power flow, which enhance efficiency and flexibility. However, the paper also addresses challenges related to voltage regulation and efficiency, particularly under light-load conditions where circulating currents and parasitic losses increase. To mitigate these issues, the authors suggest implementing advanced control strategies such as variable frequency control, burst mode operation, and adaptive dead-time control. Future research should focus on developing robust control algorithms, optimizing component selection, and exploring novel circuit topologies to improve efficiency and regulation across a wider operating range, ensuring CLLC converters meet the demands of evolving power electronic applications.

Zahin et al. (2020) introduced an innovative modulation scheme and analysis method for Dual Active Bridge (DAB) converters, specifically targeting the minimization of root-mean-square (RMS) transformer current while ensuring Zero Voltage Switching (ZVS) across the entire operating range. This approach addresses a key challenge in DAB converter design: achieving high efficiency alongside broad operational flexibility. Traditional modulation techniques often struggle to optimize efficiency under varying load and voltage conditions, leading to increased conduction losses due to higher RMS currents. The proposed scheme deviates from conventional methods by dynamically adjusting the duty cycles of the primary-side output voltage during the two half-periods of a switching cycle. This dynamic adjustment allows for precise control of the power transfer profile, effectively reducing circulating currents and minimizing RMS transformer current, thus lowering conduction losses. Furthermore, maintaining ZVS throughout the operational range significantly reduces switching losses, contributing to overall efficiency improvements. This modulation strategy is particularly advantageous in applications requiring high power density and efficiency, such as electric vehicle charging, solid-state transformers, and energy storage systems. The comprehensive analysis provided in the paper offers valuable insights into the converter's behaviour under the proposed modulation, facilitating the optimization of control parameters for specific applications. Future research directions include exploring the implementation of adaptive control algorithms to further enhance the converter's performance under dynamic operating conditions and investigating the impact of parasitic elements and component tolerances on the effectiveness of the proposed scheme.

Zhang et al. (2020) developed a switched capacitor interleaved bidirectional converter for supercapacitor integration in EVs. Utilizing capacitors for efficient voltage conversion and an interleaved structure to minimize current ripple, this converter enables bidirectional power flow for regenerative braking and efficient energy recuperation. Its wide voltage gain range accommodates supercapacitor voltage fluctuations, enhancing EV performance, efficiency, and range.

Zhang et al. (2020) present a new bidirectional DC-DC converter designed for applications needing efficient power transfer, characterized by low current ripple and a broad voltage-gain range. Its bidirectional nature is ideal for energy storage and EV drivetrains. A key innovation is the use of a coupled inductor, which effectively minimizes current ripple, reducing electromagnetic interference and boosting efficiency. This inductor also contributes to the wide voltage-gain range, enabling seamless integration with diverse voltage sources and loads. Consequently, this converter offers a highly efficient, low-noise, and adaptable solution for systems with varying voltage requirements.

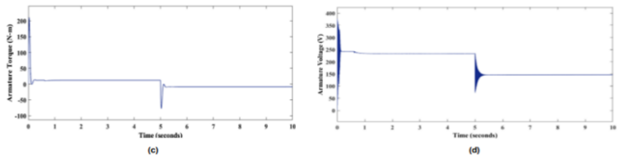
Hou and Li (2020) proposed a novel EV traction architecture using a cost-effective and safe 48V battery system. A multi-input, high conversion ratio converter generates a variable DC-link voltage for the traction motor. The multi-input design integrates regenerative braking and other energy sources, enhancing efficiency. This architecture aims to improve EV affordability and safety while maintaining performance.

Gupta et al. (2021) developed a bidirectional DC-DC converter with a wide voltage gain range for energy storage and renewable energy integration. It combines a quasi-Z-source (qZS) network for buck-boost capabilities with a switched capacitor network for enhanced voltage gain. This design enables efficient bidirectional power flow, suitable for battery charging/discharging and grid interaction.

3. PROPOSED METHODOLOGY

The proposed system introduces a novel non-isolated, high-gain bidirectional DC-DC converter (HGBDC) specifically designed for integrating energy storage systems with electric vehicles (EVs). This proposed system aims to overcome the limitations of existing BDC designs by offering a simplified structure, improved efficiency, and enhanced performance, particularly in achieving high voltage gain. The core innovation lies in its unique circuit topology and control strategy, which leverage a dual current path inductor structure and a two-duty-cycle operation. The primary objective of the proposed

HGBDC is to provide a reliable and efficient interface between the EV's battery and the electric motor, enabling seamless power flow in both directions. In forward motoring mode, the converter efficiently boosts the battery voltage to the required level for the motor, ensuring optimal performance across various driving conditions. During regenerative braking, the converter facilitates the transfer of kinetic energy back to the battery, effectively recovering energy and extending the EV's driving range. This bidirectional capability is crucial for maximizing efficiency and performance in modern EVs.



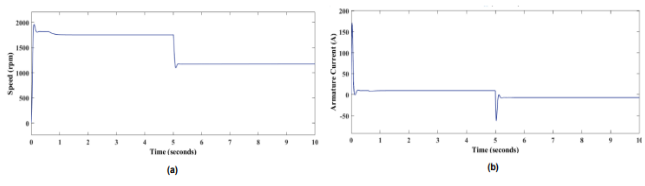
A key feature of the proposed system is its ability to achieve high voltage gain without resorting to complex circuit topologies, such as voltage multiplier cells or hybrid switched-capacitor approaches. This is accomplished through the implementation of a two-duty-cycle operation, which allows for precise control of the voltage conversion process. Furthermore, the use of a dual current path inductor structure offers several advantages. It reduces the size of the inductors, minimizing the overall footprint of the converter, and eliminates the need for an additional clamping circuit to provide energy to the load. This simplification of the circuit not only reduces cost and complexity but also enhances reliability.

The proposed system's design emphasizes simplicity and efficiency. It utilizes only four active power switches, minimizing component count and reducing switching losses. This simplified structure contributes to a more compact and lightweight design, which is essential for EV applications where space and weight are critical considerations. Moreover, the proposed HGBDC is designed to operate at a lower duty ratio, mitigating the risk of inductor core saturation and enhancing overall reliability. To validate the performance and feasibility of the proposed HGBDC, extensive simulations have been conducted using MATLAB/Simulink and OPAL-RT software-in-loop (SIL) systems. These simulations have demonstrated the converter's ability to effectively control power flow during both forward motoring and regenerative braking under various driving conditions. The performance analysis has been carried out to evaluate the converter's efficiency, voltage gain, and dynamic response, confirming its suitability for integrating energy storage systems with EVs.

In essence, the proposed system offers a novel and efficient solution for addressing the challenges associated with BDC design in EVs. By combining a simplified structure, high voltage gain, and improved performance, the HGBDC represents a significant advancement in power electronic converter technology, paving the way for more efficient and reliable electric vehicles.

4. EXPERIMENTAL ANALYSIS

The Simulink models of the battery, converter, motor, and associated control circuit are integrated with RT-Lab blocks and are accessible



on the host computer which is linked to the OP4500 simulation target through a Transmission Control Protocol (TCP)/Internet Protocol (IP) communication network. The OP4500 simulation target performs real-time computations for model inputs and outputs. To analyse the dynamics of the system, a step change in torque is applied and the forward motoring and regenerative braking modes are realized. Also, the impact of variation in speed during forward motoring mode is analysed. The converter operating frequency is limited to 5 kHz to make it compatible with the existing RT-LAB platform.

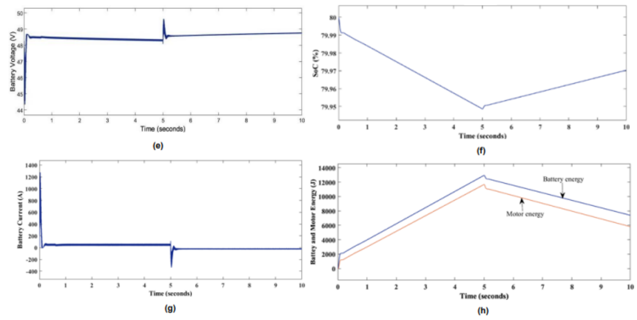


FIGURE 1.Simulation results for case1- Transition of the motor from forward motoring to regenerative braking: (a) speed, (b) armature current, (c) armature torque, (d) armature (output) voltage of the motor, (e) battery voltage and (f) battery SoC (g) battery current (h) battery and motor energy

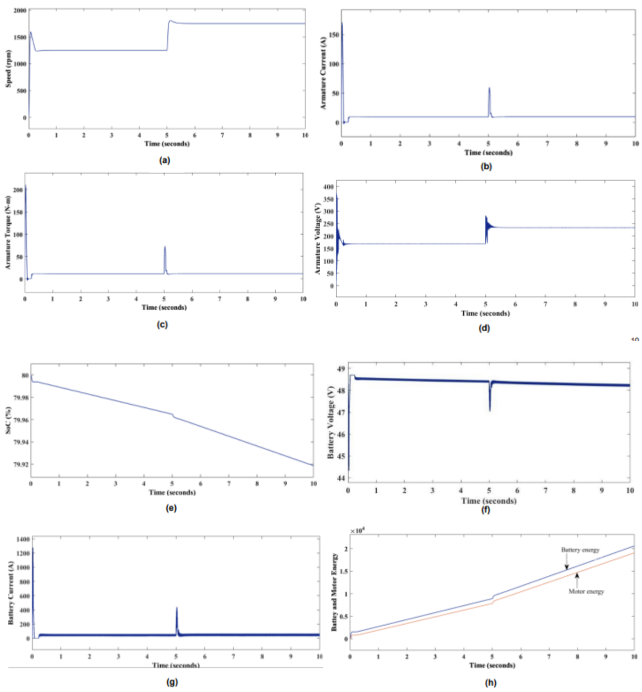


FIGURE 2. Simulation results for case 2- step change in speed during forward motoring: (a) speed, (b) armature current, (c) armature torque, (d) armature voltage, (e) battery SoC, (f) battery voltage, (g) battery current and (h) battery and motor energy

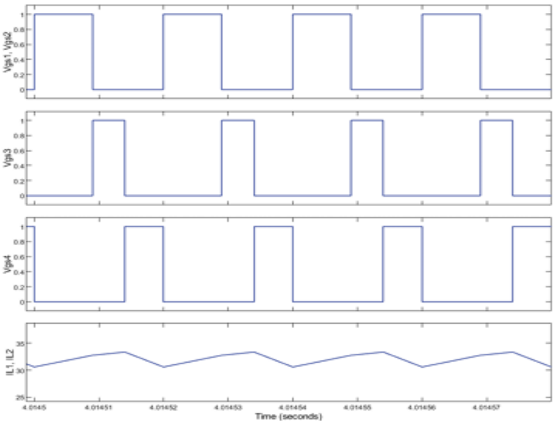


FIGURE 3. Switching signals for S1, S2, S3, S4 and inductor currents in boost mode of operation.

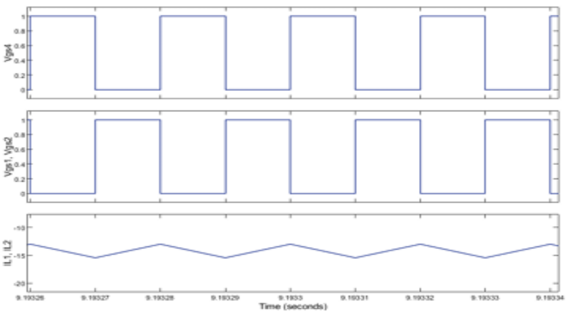


FIGURE 4. Switching signals for S1, S2, S3, S4 and inductor currents in boost mode of operation.

From Figure 3 and figure 4 There is Two different cases are considered for analyzing the dynamics of the system:

(i) transition of the motor operation from forward motoring to regenerative braking.

(ii) a step change in speed during forward motoring.

5. CONCLUSION

This research successfully presented the design and validation of a High Gain Bidirectional Converter (HGBDC) tailored for electric vehicle applications, effectively addressing the critical need for efficient battery interfacing and regenerative braking capabilities. The converter's performance, rigorously analyzed through both MATLAB/Simulink and RT-LAB simulations, demonstrated its ability to seamlessly transition between motoring and regenerative braking modes while achieving a high voltage gain with a simplified two-duty-cycle control strategy. This balanced design, prioritizing both performance and component efficiency, offers a practical solution for integrating energy storage systems into EV DC links. Furthermore, the potential for enhanced efficiency through the adoption of SiC power switches was highlighted, alongside the consideration of soft switching techniques to mitigate high-frequency losses, albeit with increased complexity. This work lays a solid foundation for future advancements in EV power electronics, paving the way for more efficient and robust bidirectional converters that contribute to the broader adoption of electric transportation. Future research should focus on real-world testing, detailed efficiency and cost analysis, and control system optimization, in order to fully realize the potential of this promising HGBDC design."

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