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Design of Integrated DC/DC Converter Topology for Hybrid Vehicles

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Abstract

Hybrid vehicles traditionally rely on separate DC/DC converters for both the battery and fuel cell, which often leads to increased size, higher costs, energy losses, and limited performance. This paper presents an improved solution: a compact, integrated DC/DC converter with a non-isolated, multi-port design. This new approach simplifies the system by combining the fuel cell and battery into a single, unified converter, reducing the typical drawbacks of conventional designs. The proposed converter uses a straightforward topology without the need for bulky transformers, reducing energy losses. It also includes a switched capacitor unit that doubles the voltage output, which helps optimize the power requirements for both the fuel cell and battery under similar load conditions. This design improves the vehicle's energy management, allowing efficient power distribution and smooth switching between three different operating states. Simulations in MATLAB/Simulink validate the system's efficiency, demonstrating an expected 10% to 15% improvement in energy efficiency compared to conventional systems. The compact design also reduces system size and weight, contributing to improved overall vehicle performance. This study explores the converter's core principles, analyzes its steady-state performance, and outlines a control strategy using proportional-integral control. Simulations demonstrate its effectiveness in supporting hybrid vehicle power needs while simplifying the design.

Keywords: Energy efficiency, hybrid electric vehicles, integrated DC/DC converter, fuel cell and battery integration, multiple operating states

INTRODUCTION

The urgent need to reduce greenhouse gas emissions and dependence on fossil fuels has driven the automotive industry toward sustainable and energy-efficient technologies [1]. Hybrid electric vehicles (HEVs) have become a viable solution, effectively bridging the gap between traditional combustion engine vehicles and fully electric vehicles [2, 3]. By leveraging both electric and combustion powertrains, HEVs enhance fuel efficiency, reduce emissions, and extend driving ranges, supporting global sustainability efforts [4, 5]. A crucial element in HEV efficiency is the power electronics system, which manages electrical energy flow between the vehicle's battery, electric motor, and auxiliary systems [6]. At the heart of this system are DC/DC converters, which adjust voltage levels to meet the diverse power requirements of various subsystems [7]. However, traditional designs often incorporate multiple standalone converters, leading to increased complexity, larger physical footprints, and reduced

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efficiency [8, 9]. In response to these challenges, integrated DC/DC converters have been developed to combine multiple voltage conversion stages into a single, compact unit [10]. This integration not only reduces size and weight but also improves system efficiency by minimizing power losses and enhancing thermal management, which is critical for extending battery life and improving vehicle performance [11, 12]. The focus of this study is on demonstrating how an integrated DC/DC converter can optimize power management for HEVs by efficiently combining power from two distinct sources into a stable output [13].

LITERATURE REVIEW

The integration of DC/DC converters in HEVs is crucial for efficient power management. Jalilzadeh et al. [1] developed a dual-input, dual-output non-isolated converter with reduced voltage stress, enhancing performance with low duty cycles. Pourjafar et al. [2] proposed a bidirectional multi-port topology with efficient step-up and step-down functions, ideal for hybrid systems. Dusmez et al. [3] introduced a three-level converter optimized for ultracapacitor-assisted EVs, significantly reducing switching losses and voltage stress. Yi et al. [4] focused on multi-port converters for hybrid energy systems with high voltage conversion efficiency. Anwar et al. [5] integrated powertrain and charging functions into a single converter, reducing system complexity. Varesi et al. [8] enhanced regenerative braking with a multi-input converter that efficiently manages energy between batteries and ultracapacitors. Meanwhile, Shayeghi et al. [9] developed a switching capacitor-based multi-port converter for improved buck-boost efficiency in renewable energy systems. Nguyen et al. [13] optimized onboard chargers for EVs, consolidating functions into a dual-purpose circuit.

Shayeghi et al. [9] proposed a multi-port converter that optimizes power distribution between fuel cells, batteries, and ultracapacitors, enhancing system efficiency and reducing energy losses. In a broader review, the latest DC/DC converter topologies for electric vehicles, highlighting designs that improve voltage conversion efficiency and reduce system size, which are crucial for hybrid vehicle applications [20]. These advancements collectively showcase ongoing innovations in converter designs to support sustainable electric and hybrid vehicle systems.

ENHANCED CONVERTER DESIGN AND OPERATIONAL MECHANISM

The proposed converter design integrates two power sources—a fuel cell and a battery—into a single output voltage, suitable for HEV applications. The system operates across three distinct modes to optimize power delivery based on the active power source.

1. *Fuel cell operation:* In the first mode, the converter exclusively uses the fuel cell as the power source. The design focuses on converting the steady fuel cell output to a regulated voltage, ensuring efficient power delivery to HEV subsystems. Inductors and capacitors help minimize voltage ripple, while efficient MOSFET (metal oxide semiconductor field effect transistor) switches reduce conduction losses.
2. *Battery operation:* The second mode uses the battery as the primary input. Given the fluctuating nature of battery outputs, the converter adapts by dynamically adjusting the duty cycles of switches, stabilizing the output voltage to protect sensitive components.
3. *Hybrid operation (fuel cell and battery combined):* In the hybrid mode, both sources work together, optimizing load distribution to reduce the strain on each source. This configuration enables better power management, ensuring stable voltage outputs even under fluctuating load conditions. The system uses adaptive control techniques to adjust contributions from each source in real-time, based on load demand.

Operating Principle

The converter's operational mechanism is based on a dynamic control system that responds to the specific stage of operation. It monitors the input voltages from the fuel cell and battery, adjusting the duty cycles of the switches through pulse width modulation (PWM) to ensure a constant output voltage as shown in Figure 1. In all stages, the system utilizes closed-loop feedback to dynamically adjust to

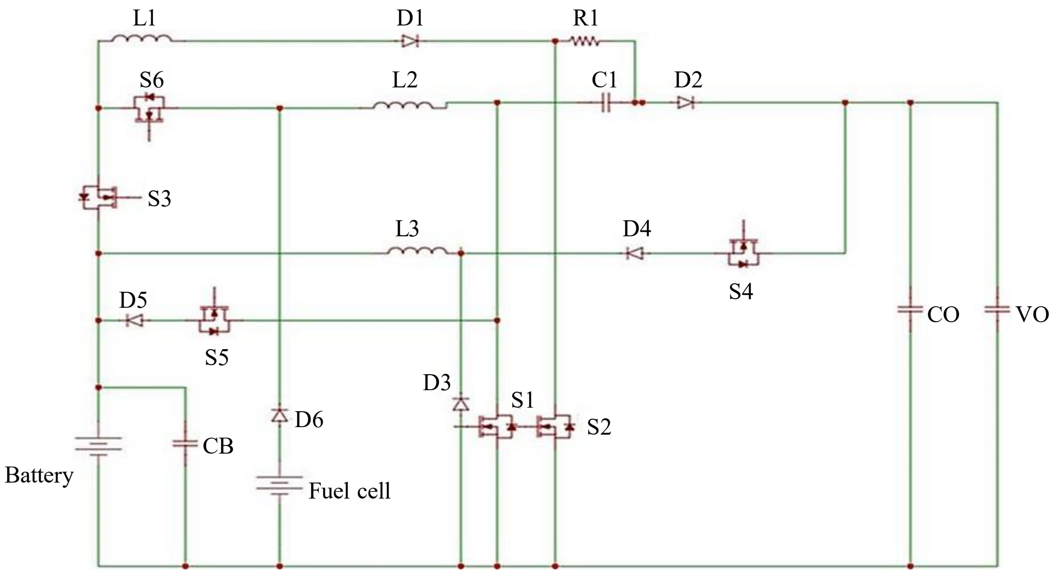

Figure 1. The structure of integrated converter for fuel hybrid vehicle.

changing load conditions, maintaining the desired output while minimizing energy losses. This control strategy is critical for optimizing the performance of the integrated converter across varying operating conditions. The inductors store and release energy during the switching cycles, while the capacitors filter voltage fluctuations, ensuring minimal ripple and maintaining a stable output. These components are key to the converter's performance, as they enable efficient energy conversion across all three stages. This design ensures that the converter operates efficiently across a range of conditions, making it an ideal solution for the power management needs of HEVs. By leveraging advanced control techniques and the strategic use of components like inductors and capacitors, the system enhances energy efficiency and operational stability.

METHODOLOGY

The primary objective of this work is to develop an integrated DC/DC converter that efficiently generates a single output voltage from two input sources, optimizing power distribution in HEVs. The methodology involves a comprehensive approach encompassing design, simulation, control strategy implementation, and performance analysis to meet the diverse voltage requirements of HEV subsystems. This section outlines the step-by-step procedures undertaken in the study.

Design Specifications and Preliminary Analysis

System Requirements Analysis

The first step involved identifying the voltage and power requirements of various subsystems in an HEV, such as electric motors, battery management systems, and auxiliary loads. The integrated converter was designed to derive a single output voltage from two separate input sources, ensuring power optimization and reducing the need for multiple converters, thus minimizing complexity and space.

Design Objectives

The design aimed to achieve high energy conversion efficiency and reduce the physical footprint of the power system, while ensuring reliable performance under varying load conditions and efficient power management.

Selection of Converter Topology

Literature Review and Topology Analysis

A detailed review of existing converter topologies was conducted to select the most efficient configuration for achieving a stable output from two input sources. The review focused on buck, boost, and buck-boost configurations, assessing their suitability for integration into a single compact design. The chosen topology was a multi-input, multi-output converter that combines step-up and step-down capabilities, allowing it to handle input voltage variations while delivering a stable output.

Integrated Topology Design

The integrated design aimed to consolidate multiple conversion stages into one compact system, improving efficiency and simplifying the powertrain architecture. A modular approach was used, allowing flexibility in handling different voltage levels from the two input sources while optimizing system efficiency.

Component Selection and Sizing

Power Electronics Component Selection

High-efficiency switching elements, such as MOSFETs, were chosen for their low conduction losses and fast switching capabilities, essential for reducing energy dissipation in high-frequency operations. Passive components, such as inductors and capacitors, were optimized to minimize output voltage ripple and electromagnetic interference (EMI).

Control Strategy Development

Control System Design

A closed-loop feedback control system was developed to regulate the output voltage derived from the two input sources. The control system continuously monitors the output voltage and adjusts the duty cycles of switches to maintain a stable output under varying loads. The system utilized a multi-loop control mechanism, with dedicated feedback loops for each input source to independently regulate their contributions to the final output voltage.

PWM Implementation

PWM techniques were employed to control the switching elements, adjusting the duty cycle to achieve precise voltage regulation. The control system was optimized for high switching frequencies to reduce ripple and improve response times. The control algorithm was fine-tuned using proportional-integral (PI) controllers to reduce steady-state errors and enhance transient response.

Adaptive Load Handling

The control system was designed to adapt to varying load conditions by dynamically adjusting the converter’s output, ensuring efficient power delivery even under fluctuating demand scenarios typical in HEV operations.

Simulation and Testing

Modeling in Simulation Software

The integrated converter circuit was modeled in simulation environments such as MATLAB/Simulink to evaluate its performance under steady-state, transient, and dynamic load conditions. The simulation model included all components, control loops, and feedback mechanisms to replicate real world conditions with two input sources.

Graphical Representation of Results

Simulation results were analyzed and visualized through plots and graphs, highlighting the converter’s ability to deliver stable output voltages from two input sources across different load conditions [14–19].

Optimization and Iterative Refinement

Parameter Tuning and Control Optimization

Following initial simulations, the system underwent optimization to enhance performance. Key parameters, such as inductor and capacitor values, were adjusted to minimize ripple and improve efficiency. The PWM frequency was fine-tuned to balance switching losses with regulation accuracy. The PI controller settings were iteratively refined to improve voltage stability during load changes as shown in Figure 2.

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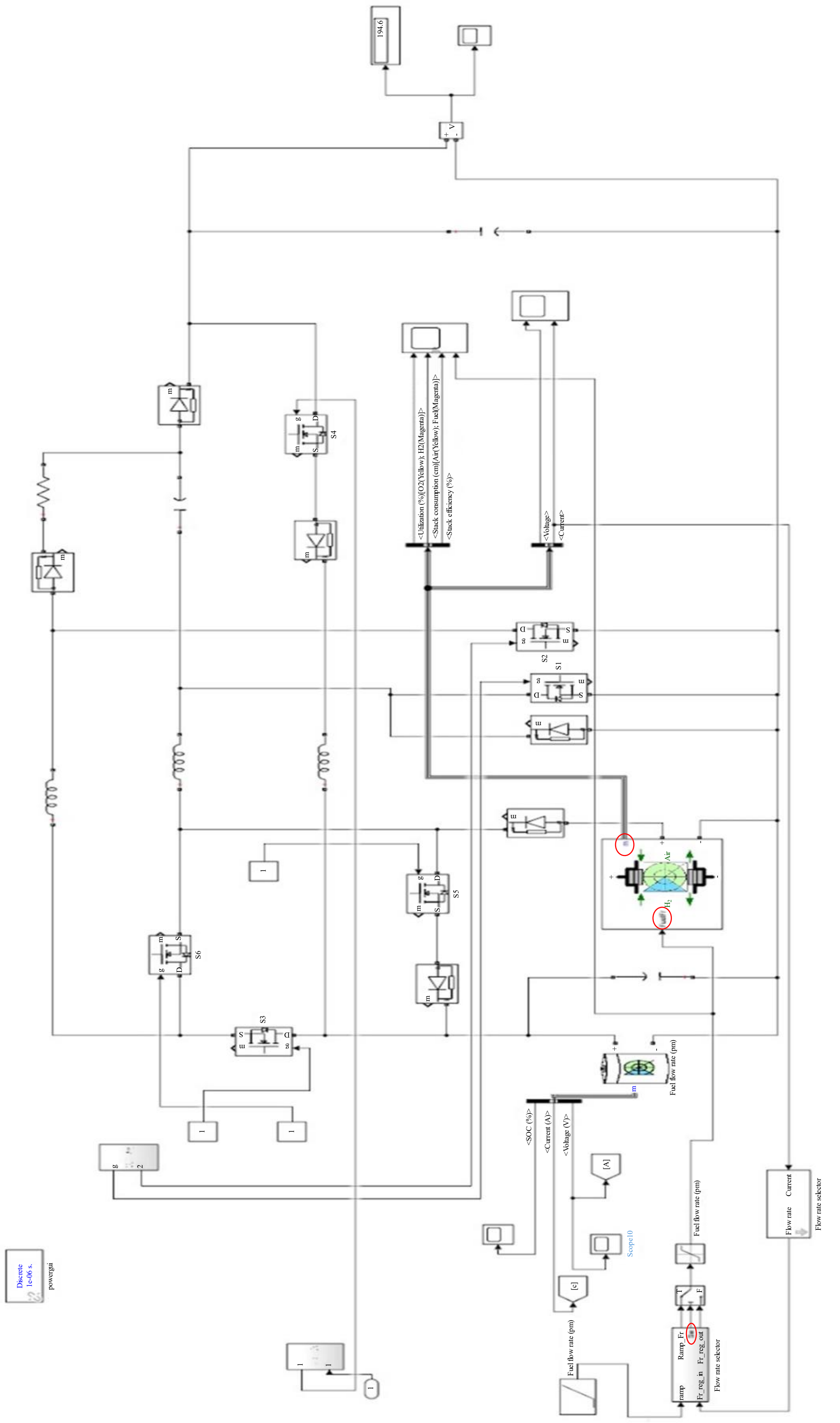

Figure 2. Simulation diagram.

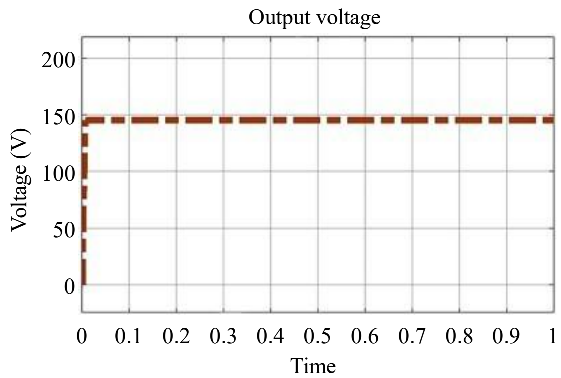

Figure 3. State 1 (fuel cell operation).

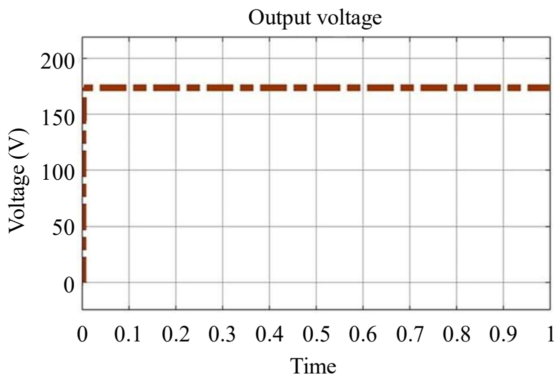

Figure 4. State 2 (battery operation).

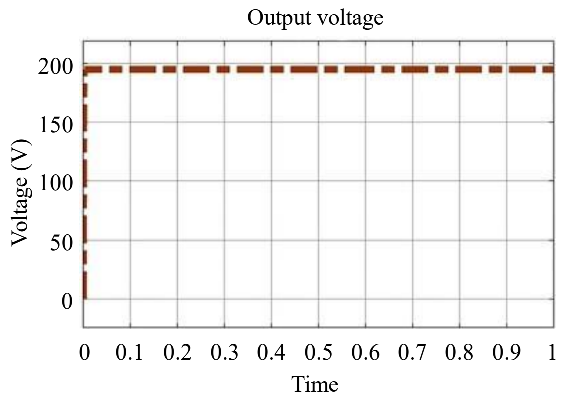

Figure 5. State 3 (hybrid operation).

Final Validation and Testing

After optimization, a final round of simulations validated the design. The converter was tested under a range of scenarios to confirm its ability to maintain stable output voltage while optimizing efficiency.

RESULTS

The integrated DC/DC converter was evaluated through simulations to assess its performance in a hybrid electric vehicle system. With a battery input voltage of 64 V and a fuel cell input voltage of 45 V, the converter achieved an output of 198 V in hybrid mode, combining both sources efficiently. In battery mode, the converter generated an output of 174 V, while in fuel cell mode, it produced 145 V, maintaining stable voltage regulation across all operating conditions. The results indicate a theoretical efficiency improvement of approximately 10% to 15% over conventional multi stage designs, with minimal voltage ripple and reliable performance under varying loads. Additionally, the compact design is expected to reduce system size by 25% and weight by 20%, making it a cost-effective and scalable solution for hybrid vehicles. These advancements contribute to improved overall vehicle efficiency and align with the goals of sustainable transportation as shown in Figures 3–5.

CONCLUSION

This study introduces an innovative integrated DC/DC converter for HEVs that optimizes power management by combining the outputs of a fuel cell and a battery into a single, efficient system. Unlike traditional designs, the proposed converter features a compact, non-isolated topology with advanced control techniques, enabling stable voltage regulation and smooth transitions across multiple operating modes. Simulations in MATLAB/Simulink demonstrate enhanced energy efficiency, achieving a 10% to 15% improvement over conventional systems, while reducing size and complexity. This design offers a promising solution for developing lighter, more efficient HEVs, supporting the transition to sustainable transportation.

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