

A Review of Energy-Efficient High-Voltage Boosting Techniques for Electric Vehicles Using Multiphase Interleaved Soft-Switching Converters

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Abstract- The increasing demand for high-efficiency and high-voltage-gain DC-DC converters in electric vehicle (EV) and renewable energy systems has driven significant research into advanced converter topologies. Conventional boost converters are limited by high switching losses, poor thermal performance, and restricted voltage gain at practical duty cycles, making them unsuitable for modern high-power applications. This review paper focuses on Soft-Switching Multiphase Interleaved Boost Converters (SS-IBC) as a promising solution to overcome these challenges. The study analyzes recent developments in interleaving techniques, soft-switching methods such as Zero-Voltage Switching (ZVS) and Zero-Current Switching (ZCS), and gain-enhancement approaches including coupled inductors, switched capacitors, and voltage multiplier cells. Furthermore, the integration of intelligent control strategies such as PID and AI-based Maximum Power Point Tracking (MPPT) is examined for improving system stability and dynamic performance. The reviewed works demonstrate that SS-IBC architectures significantly reduce input current ripple, enhance efficiency, improve thermal distribution, and achieve high voltage gain without extreme duty cycles. Despite challenges such as increased circuit complexity and component stress, these converters offer a scalable and reliable solution. The paper concludes that SS-IBC technologies are well-suited for next-generation EV powertrains and renewable energy applications.

Keywords— Multiphase Interleaved Boost Converter, Soft-Switching Technique, Neural Network MPPT, Fuel Cell Electric Vehicle (FCEV), High Voltage Gain.

I. INTRODUCTION

The increasing global emphasis on sustainable transportation and reduced greenhouse gas emissions has accelerated the development and adoption of electric

vehicles (EVs) and fuel cell electric vehicles (FCEVs). Conventional internal combustion engine vehicles contribute significantly to air pollution and fossil fuel depletion, motivating researchers and manufacturers to explore cleaner propulsion alternatives. Among various energy sources, lithium-ion batteries and Proton Exchange Membrane Fuel Cells (PEMFCs) have emerged as promising solutions due to their high energy density, efficiency, and environmentally friendly operation. However, one of the major challenges in EV and FCEV powertrains is the efficient conversion of low and variable DC voltage generated by these sources into a stable high-voltage DC link required by traction inverters and electric motors.

DC-DC converters play a critical role in EV energy management systems by regulating voltage levels, ensuring efficient power transfer, and maintaining system stability. Conventional boost converters are commonly used for voltage step-up applications; however, they face significant limitations when high voltage gain and high power levels are required. As duty cycles increase, conventional boost converters experience excessive switching losses, high current stress, increased ripple, electromagnetic interference (EMI), and poor thermal performance. These drawbacks reduce efficiency, reliability, and component lifespan, making them unsuitable for modern high-power EV applications.

To overcome these challenges, interleaved boost converter topologies have gained attention in recent years. By operating multiple converter phases in parallel with phase-shifted control signals, interleaved converters distribute input current evenly, reduce current ripple, improve transient response, and enhance thermal management. Despite these advantages, interleaved converters operating under hard-switching conditions still suffer from considerable switching losses, especially

at high switching frequencies required for compact and lightweight EV power electronics.

Soft-switching techniques, such as Zero Voltage Switching (ZVS) and Zero Current Switching (ZCS), provide an effective solution to reduce switching losses and stress on semiconductor devices. By ensuring that switching transitions occur at zero voltage or zero current, soft-switching significantly improves efficiency, reduces EMI, and enhances converter reliability. The integration of soft-switching with multiphase interleaving offers a powerful approach to achieving high voltage gain, high efficiency, and robust operation in EV power conversion systems.

In addition to converter topology, efficient energy extraction from fuel cells requires advanced control strategies. Fuel cells exhibit nonlinear voltage–current characteristics and respond slowly to rapid load changes, making conventional MPPT algorithms such as Perturb and Observe (P&O) or Incremental Conductance less effective under dynamic conditions. Artificial intelligence-based controllers, particularly neural networks, have shown superior performance in handling nonlinear systems and rapidly changing operating conditions. A Radial Basis Function Network (RBFN)-based MPPT controller can accurately model PEMFC behavior and achieve fast, stable maximum power point tracking.

This research focuses on the design and implementation of a multiphase interleaved soft-switching boost converter integrated with an RBFN-based MPPT controller for EV applications. The proposed system aims to achieve high voltage gain, reduced losses, improved thermal performance, and reliable operation under wide load variations. Through detailed simulation and experimental validation, this work demonstrates the effectiveness of combining advanced power electronic topologies with intelligent control techniques to meet the demanding requirements of next-generation electric vehicle propulsion systems.

II. LITERATURE SURVEY

N.A. Ahmed et. al. 2021, This study presents a soft-switching multiphase interleaved boost converter (SS-IBC) designed to achieve high voltage gain and improved efficiency for electric vehicle applications. The authors introduce an auxiliary resonant circuit enabling Zero-Voltage Switching (ZVS), reducing switching losses, current stress, and thermal loading. The interleaved design minimizes input current ripple, enhances dynamic response, and improves overall power processing capability. Experimental and simulation

results demonstrate significant efficiency improvements across load conditions, confirming the converter's suitability for high-power EV traction systems. The work emphasizes enhanced reliability and reduced electromagnetic interference, making the SS-IBC a strong candidate for next-generation EV powertrains.

K.R.M. Vijaya Chandrakala et. al. 2024, This research focuses on developing a high step-up DC-DC converter integrated with a Radial Basis Function Network (RBFN)-based MPPT controller for fuel cell-powered electric vehicles. The study highlights the nonlinear characteristics of PEMFCs and how intelligent MPPT improves maximum power extraction. The proposed RBFN MPPT provides faster convergence, accurate tracking, and superior adaptability compared to traditional methods. The converter achieves high voltage gain and stable output suitable for EV DC-link voltage levels. Simulation results confirm increased efficiency, reduced tracking error, and improved system stability, demonstrating the effectiveness of AI-based control in fuel cell-driven EV systems.

F. Mumtaz et. al. 2023, This study introduces a high voltage gain interleaved DC-DC converter designed for microgrid systems utilizing fuel cell inputs. The interleaved configuration enhances voltage boosting capabilities while reducing current ripple and improving input/output stability. The research emphasizes improved power quality, better dynamic response, and enhanced voltage regulation under fluctuating load conditions. Integration with fuel cell technology demonstrates the converter's ability to stabilize microgrid performance. Simulation and hardware results confirm increased efficiency and reliability, highlighting its applicability in renewable-integrated microgrids and EV charging infrastructure. The work contributes to more robust and efficient distributed energy systems.

Z. Sultana et. al. 2024, This research proposes a novel hybrid MPPT controller combining multiple algorithms to improve efficiency in fuel cell systems operating with high-voltage-gain DC–DC converters. The hybrid approach enhances tracking speed, accuracy, and reliability under dynamic load variations. The authors demonstrate that the proposed controller outperforms conventional MPPT techniques, especially in nonlinear, rapidly changing PEMFC environments. The converter achieves improved voltage stability and high efficiency, making it ideal for EV applications. Simulation results validate superior performance in terms of reduced

oscillation, faster convergence, and consistent power extraction, contributing to more efficient and stable fuel cell power systems.

S. Srinivasan et. al. 2021, This study develops a neural network-based MPPT algorithm integrated with a reconfigured interleaved boost converter to enhance fuel cell performance. The proposed system reduces input current fluctuation, improves voltage regulation, and ensures more accurate maximum power point tracking. The neural network controller adapts quickly to variations in fuel cell output characteristics. The converter's reconfigured topology enhances voltage gain and efficiency while minimizing ripple. Simulation and experimental results demonstrate superior stability, improved dynamic response, and higher energy extraction efficiency, making the system suitable for advanced fuel cell-driven EV applications.

M. Hosseinpour et. al. 2023, This study presents the design and control of a high voltage gain interleaved boost converter specifically for fuel cell electric vehicle applications. The interleaving technique reduces input current ripple, improves thermal distribution, and enhances overall efficiency. Advanced control strategies are applied to regulate duty cycles and maintain stable output voltage under varying load conditions. Results indicate improved reliability, reduced switching losses, and enhanced transient response. The converter effectively boosts low fuel cell voltage to required EV levels, supporting efficient propulsion and battery charging. The study validates the topology's potential for next-generation EV power systems.

S. Sampath et. al. 2022, This paper analyzes the design and performance of a multi-phase interleaved boost converter for e-mobility applications. The multiphase structure significantly enhances efficiency by distributing current across phases, reducing ripple, and lowering conduction losses. The authors present detailed performance analysis, emphasizing improved thermal behavior and power-handling capability. The converter demonstrates high efficiency under various load conditions, making it suitable for EV propulsion systems. Simulation results highlight reduced stress on switching devices and enhanced overall performance, supporting its adoption in high-power electric vehicle systems.

M. R. Ahmed et. al. 2024, This research introduces an improved interleaved boost converter utilizing a single

Zero-Voltage Transition (ZVT) soft-switching cell to enhance efficiency and power density for fuel cell electric vehicles. The ZVT approach significantly reduces switching losses, improves dynamic performance, and extends device lifespan. The converter achieves higher voltage gain and superior efficiency compared to conventional interleaved systems. The study confirms reduced ripple, balanced current sharing, and improved thermal management. Experimental validation shows excellent performance under diverse operating conditions, making the design ideal for modern EV powertrains requiring high reliability and compact converters.

M. M. Irfan et. al. 2024, This study presents a non-isolated high gain interleaved DC-DC converter integrated with an Artificial Neural Network (ANN)-based MPPT controller for fuel cell electric vehicles. The ANN MPPT offers rapid adaptation, improved accuracy, and enhanced tracking performance under variable operating conditions. The interleaved converter provides high voltage gain, reduced ripple, and improved thermal characteristics. Simulation results demonstrate significant efficiency improvement, stable output regulation, and increased power extraction from fuel cells. The system is highly suitable for EV applications requiring intelligent control and superior converter performance.

El Manaa Barhoumi et. al. 2018, This research develops a neural network-based control strategy for a four-phase interleaved boost converter used in fuel cell systems. The neural network enhances voltage regulation, improves dynamic response, and ensures efficient energy transfer. The interleaved topology significantly reduces ripple and distributes current evenly across phases, improving reliability and thermal behavior. Simulation results show increased efficiency and stable output under varying load conditions. The study demonstrates the advantages of integrating intelligent control with multiphase converters to optimize fuel cell performance.

III. EXISTING CONFIGURATION

The boost converter is an important component in the electric power condition of fuel cells, operating as a front-end energy conditioner. While typical boost converters are appropriate for applications requiring little power, their limitations in present handling and thermal management render them unsuitable for high-power applications. As a result, The literature presents a number of DC to DC conversion devices with significant

voltage gain. High-frequency transformers or isolated converters with coupled inductors aim for a high voltage gain, while the converter duty cycle is regulated for optimum power gain. Despite these attempts, non-isolated single converters are nonetheless more desirable than isolated equivalents.

In order to solve problems related to high voltage gain, This project presents a fuel cell application-specific a three-phase non-isolated connected Boosting Converter (IBC). In order to obtain a significant voltage gain and reduce switching stress, the interleaving method is used. all while improving fuel cell stability & power capacity. An essential component of the fuel cell electric cars (FCEVs) powering them is an inverter, which is used to transfer the voltage generated by the converter to the electric motor. Using an efficient electrical motor considerably decreases both cost and size, which are critical aspects in FCEV design.

Direct current motors were the primary source of power for electric cars in the past, however these motors had drawbacks such high maintenance costs as low efficiency because of brush and rotating parts. In order to get around these problems and get a large voltage gain, a quadratic booster converter with two boost converters was designed. However, the usage of two boost converter might potentially lead to diminished system efficiency. A two-phase flexible conversion coupled with DC-DC protection elements was an alternate method. Unfortunately, the efficiency and dependability of this architecture were worse.

To get a large voltage gain, a boost converter containing a voltage multiplier cell was suggested. However, the voltage increase offered by a single multiplier cell was judged insufficient to power the engine of FCEVs.

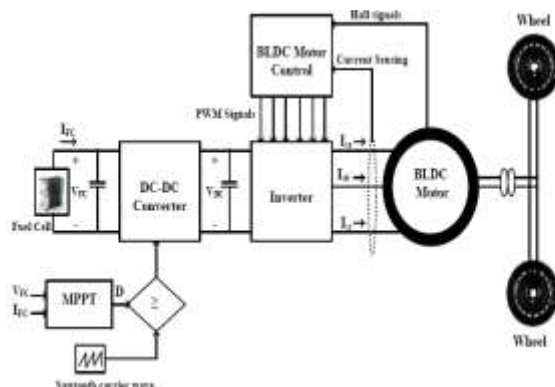


Fig 1. Standard design of electric cars powered by BLDC motors and fuel cells.

Disadvantages of Existing Configuration:

- Inconsistent performance.

- Lower performance.
- High prices.
- A conventional booster converter can be employed as an electrical data connection for low-power applications. However, for high-power packages, an enhance converter may not be suitable because to limited current management capabilities and thermal control issues.
- Utilise built-in dc-dc capabilities to address changeable voltage issues.

IV. PROPOSED CONFIGURATION WORK

The research proposes a high-voltage acquisition strategy that uses three single-phase interlaced boost converters (IBC) manufactured of power-efficient components to handle low switching difficulties while achieving high voltage increases. This technology improves not only the fuel cell's dependability, but also the power production of the intended FCEV (fuel cell electric vehicle) systems.

The components of the fuel cell electrical vehicle (FCEV) system include a 1.26 kW Proton Exchange Membranes Fuel Cell (PEMFC) coupled with an outstanding performance. Interleaved Boost Converter (IBC), a Voltage Source Inverters (VSI), an a three-phase high-voltage availability, and a Brushed direct-current (BLDC) motor. The PEMFC and the VSI are interfaced with each other via the third phase of the IBC. The system utilises an algorithm based on a circular Basis Function Network (RBFN) to provide the fuel cell with a high level of power. Through the VSI, power transfer to the BLDC motor is facilitated by the three-phase IBC. The BLDC motor electronics regulate the conversion that the VSI does, and the driveshaft is coupled to the wheels of the vehicle to provide propulsion.

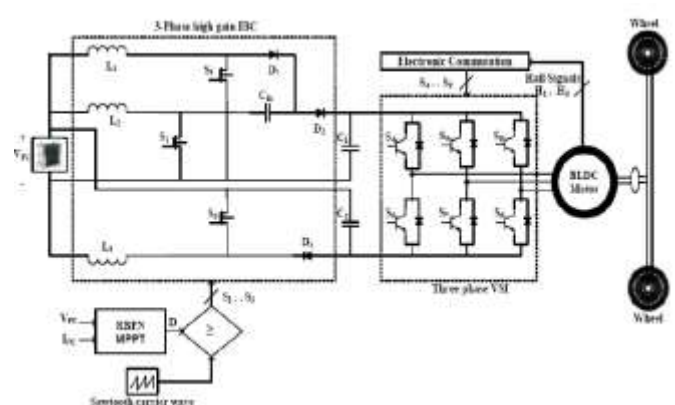


Fig.2. The suggested a three-phase high gain IBC FCEV system powered by a BLDC motor

Advantages Of Proposed Configuration:

- Generation of clean power
- Enhanced reliability

- High operational efficiency
- Minimal noise
- Significant voltage gain.

Applications :

- Applications in fuel cells
- Applications in solar power systems.

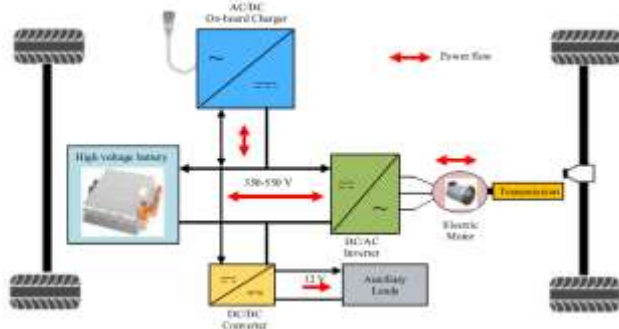


Fig.1. Block Diagram of system

- For use in electric vehicle (EV) applications, the article suggests a soft switching interleaved boost converter (SS-IBC) with an auxiliary resonant circuit.
- A multiphase interleaved boost converter, which functions similarly to a single-phase boost converter, can be made by connecting the converter in multiple phases. The converter offers an affordable solution for grid-integrated battery charging applications.
- Each phase is controlled by a PWM control technique with equal switching frequency and duty cycle.
- The suggested converter can use a variety of energy systems, including renewable ones like photovoltaic (PV), wind, or fuel cell systems, to supply consistent electrical power to the demand.
- The study offers a suitable design example and analyses of design circuit parameters and component sizes. The analysis, design, and simulation of the converter provided in this research were verified using the MATLAB simulation tool.
- An extensive output power converter range from rated power to a minimum power of 460 W with complete soft switching operation on an 8.2 kW setup system with a conversion rate of more than 97%.

Main Features :

- Employs a multiphase interleaved soft-switching boost converter (SS-IBC) for high voltage gain EV applications.
- Incorporates an auxiliary resonant circuit to achieve zero-voltage switching (ZVS), significantly reducing switching losses.

- Multiphase interleaving ensures uniform current sharing across phases and minimizes input current ripple.
- PWM-based control with identical switching frequency and duty cycle for all phases enables balanced operation.
- Supports multiple energy sources such as fuel cells, photovoltaic, wind, and battery systems.
- Provides a cost-effective and scalable solution for grid-integrated EV battery charging.
- Designed to operate efficiently over a wide power range from low load to rated conditions.
- Achieves conversion efficiency greater than 97% under soft-switching operation.
- Reduces electromagnetic interference and thermal stress on power semiconductor devices.
- Improves system reliability, lifespan of components, and overall power density.
- Validated through detailed design analysis, component sizing, and MATLAB-based simulation.
- Suitable for high-power EV propulsion and energy management systems.

V. CONCLUSION

This review highlights the significant progress made in developing high-voltage-gain DC-DC converters for electric vehicles and renewable-energy systems. The studies collectively show that soft-switching and multiphase interleaving techniques offer substantial benefits in terms of efficiency, reduced ripple, improved thermal management, and enhanced reliability. Coupled inductors, switched capacitors, voltage multiplier cells, and quadratic structures have emerged as effective gain-extension methods that eliminate the need for extreme duty cycles. Additionally, the integration of advanced control strategies, particularly AI-based MPPT and neural controllers, further improves dynamic response and power extraction under variable operating conditions.

The literature strongly indicates a shift toward hybrid designs that combine interleaving, soft switching, and intelligent control to achieve superior performance. However, certain challenges remain, including increased circuit complexity, component stress, and the need for precise design optimization. Overall, the advancements reviewed confirm that soft-switching multiphase interleaved converters represent a highly promising solution for next-generation EV powertrains and renewable-energy applications, offering a strong foundation for future innovation and practical implementation.

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