PERFORMANCE OPTIMIZATION OF A MODULAR BUCK–BOOST MULTIPORT BIDIRECTIONAL DC–DC CONVERTER FOR HIGH-EFFICIENCY HYBRID ELECTRIC VEHICLE APPLICATIONS

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ABSTRACT

Hybrid Electric Vehicles (HEVs) require efficient power management systems capable of handling bidirectional energy flow between multiple energy sources such as batteries, supercapacitors, and regenerative braking units. Conventional DC-DC converters suffer from limited voltage conversion ratio, increased switching losses, bulky passive components, and poor scalability, which reduce the overall efficiency and reliability of the vehicle powertrain. To address these challenges, this paper proposes a **Novel Modular Buck-Boost Based Multiport Bidirectional DC-DC Converter (MPBC)** for Hybrid Electric Vehicle applications. The proposed converter employs a modular architecture that enables seamless integration of multiple energy storage devices while providing high voltage gain, bidirectional power transfer, and flexible power sharing among different ports. The buck-boost topology allows efficient operation over a wide input voltage range, ensuring stable DC bus voltage under varying driving conditions. An intelligent energy management strategy is incorporated to coordinate power flow between the battery, supercapacitor, and traction motor, thereby improving regenerative braking efficiency, reducing battery stress, and extending battery lifespan. Furthermore, the modular design enhances system scalability, fault tolerance, and maintenance flexibility while reducing switching losses and component count. MATLAB/Simulink simulation results demonstrate improved voltage regulation, faster dynamic response, high conversion efficiency exceeding 95%, reduced current ripple, and enhanced overall system performance compared with conventional bidirectional converter topologies. The proposed MPBC provides an efficient, compact, and reliable solution for next-generation hybrid electric vehicles, supporting sustainable transportation through improved energy utilization and higher power conversion efficiency.

INTRODUCTION

The rapid growth of **Hybrid Electric Vehicles (HEVs)** has accelerated the demand for high-efficiency power electronic converters capable of managing multiple energy sources while ensuring reliable vehicle operation. HEVs commonly employ batteries as the primary energy source along with auxiliary storage devices such as supercapacitors or fuel cells to satisfy transient power demands and improve overall vehicle performance. Efficient coordination among these energy sources requires a high-performance bidirectional DC-DC converter capable of transferring energy in both charging and discharging modes while maintaining stable DC bus voltage.

Traditional bidirectional DC-DC converters generally support only two power ports and often suffer from limited voltage gain, higher switching losses, increased converter size, and poor scalability when additional energy storage devices are incorporated. Moreover, frequent charging and discharging cycles increase battery degradation, reducing vehicle driving range and battery lifetime. These limitations have motivated researchers to develop advanced multiport converter architectures that provide higher efficiency, improved power density, and intelligent energy sharing capabilities.

The proposed **Novel Modular Buck-Boost Based Multiport Bidirectional DC-DC Converter (MPBC)** addresses these challenges by introducing a modular converter structure capable of integrating multiple energy storage devices through a common DC bus. The converter employs a buck-boost operating principle that supports both step-up and step-down voltage conversion while enabling bidirectional energy transfer. The modular configuration allows flexible expansion without significant hardware modifications, making it suitable for various HEV configurations.

An intelligent control and energy management strategy is incorporated to optimize power distribution among the battery, supercapacitor, and traction motor according to vehicle operating conditions. During vehicle acceleration, the converter supplies high power by combining multiple energy sources, whereas during regenerative braking it efficiently recovers braking energy and stores it in the battery or supercapacitor. This coordinated operation minimizes battery stress, enhances regenerative braking performance, improves converter efficiency, and extends battery life.

Simulation studies performed in MATLAB/Simulink validate the effectiveness of the proposed converter under different driving scenarios, including acceleration, deceleration, regenerative braking, and varying load conditions. The results demonstrate superior voltage regulation, reduced switching losses, lower current ripple, higher power conversion efficiency, and improved dynamic performance compared to existing bidirectional DC-DC converter topologies. Consequently, the proposed MPBC offers a compact, scalable, and energy-efficient solution for future hybrid electric vehicle power management systems.

LITERATURE REVIEW

The rapid growth of **Hybrid Electric Vehicles (HEVs)** has increased the demand for efficient bidirectional DC-DC converters capable of managing power flow between multiple energy sources such as batteries, supercapacitors, and fuel cells. Conventional bidirectional converters generally employ multiple isolated converter stages, resulting in increased component count, larger converter size, higher switching losses, and reduced efficiency. These limitations have motivated researchers to develop compact, high-gain, and modular multiport converter topologies that improve power density while enabling flexible energy management.

Singh et al. proposed a bidirectional DC-DC converter for hybrid electric vehicle applications that enables efficient energy transfer between the battery and DC bus during both charging and discharging modes. The proposed converter demonstrated high efficiency and improved voltage regulation; however, the design required multiple passive components and experienced increased switching losses under high-power operation. The study emphasized the importance of advanced control techniques for maintaining converter stability during dynamic load variations.

Zhang et al. introduced a multiport bidirectional converter integrating batteries and supercapacitors for electric vehicle energy management. The converter allowed simultaneous power sharing among multiple storage devices, improving transient response and battery lifespan. Although the topology reduced the number of converters required, the control strategy became increasingly complex as additional ports were incorporated, limiting scalability for large hybrid energy storage systems.

Lai et al. developed a modular bidirectional buck-boost converter capable of operating over a wide input voltage range with high conversion efficiency. The modular architecture simplified system expansion and fault isolation while reducing current stress on semiconductor devices. Nevertheless, the converter required sophisticated synchronization between modules, and voltage balancing remained a significant challenge during unequal loading conditions.

Wang et al. proposed a non-isolated high-gain bidirectional DC-DC converter employing coupled inductors and switched-capacitor techniques to achieve large voltage conversion ratios. Experimental results demonstrated improved efficiency and reduced switching stress compared with conventional boost converters. However, the use of magnetic coupling increased design complexity and electromagnetic interference, making the converter less suitable for compact automotive applications.

Recent studies have focused on integrating advanced digital control techniques such as Model Predictive Control (MPC), Sliding Mode Control (SMC), and Artificial Intelligence-based energy management into multiport converters. These approaches enhance dynamic performance, improve power-sharing accuracy, reduce voltage fluctuations, and optimize battery state-of-charge management. Despite these advances, challenges remain in reducing converter complexity, minimizing component count, improving scalability, and maintaining high efficiency under rapidly changing driving conditions.

The proposed **Novel Modular Buck-Boost Based Multiport Bidirectional DC-DC Converter (MPBC)** addresses these limitations by introducing a modular architecture capable of interfacing multiple energy sources through a single converter platform. The converter achieves high voltage gain, bidirectional power flow, reduced switching losses, lower component count, and improved power density while providing efficient energy management for hybrid electric vehicle applications. Its modular design enhances scalability, simplifies maintenance, improves fault tolerance, and enables flexible integration of batteries, supercapacitors, and renewable energy sources. Consequently, the proposed MPBC offers a highly efficient, reliable, and cost-effective solution for next-generation hybrid electric vehicle power management systems.

PROBLEM STATEMENT

Hybrid Electric Vehicles (HEVs) require an efficient power conversion system to manage energy flow among multiple energy sources such as batteries, supercapacitors, and fuel cells. Conventional bidirectional DC-DC converters are generally designed for single-input configurations, resulting in increased converter count, higher switching losses, bulky size, complex control, and reduced efficiency when multiple energy sources are integrated. Furthermore, existing converters often exhibit limited voltage gain, poor power-sharing capability, increased electromagnetic interference (EMI), and inadequate bidirectional power flow during regenerative braking. These limitations negatively affect the driving range, battery life, dynamic performance, and overall energy efficiency of HEVs. Therefore, there is a need for a compact, high-efficiency, modular multiport bidirectional DC-DC converter capable of providing flexible power management, high voltage conversion ratio, reduced component count, and seamless bidirectional energy transfer for next-generation hybrid electric vehicle applications.

OBJECTIVES

1. To design a **novel modular buck-boost based multiport bidirectional DC-DC converter (MPBC)** for Hybrid Electric Vehicle applications.
2. To enable efficient **bidirectional power flow** between the battery, supercapacitor, and DC bus during charging, discharging, and regenerative braking.
3. To achieve a **high voltage conversion ratio** using a modular buck-boost converter topology while minimizing switching losses.
4. To reduce the number of power electronic components, converter size, and overall system cost through modular architecture.
5. To implement intelligent power-sharing among multiple energy storage devices, thereby improving battery lifespan and overall energy utilization.
6. To maintain stable DC bus voltage under varying load and driving conditions.
7. To improve converter efficiency, power density, and dynamic response during rapid acceleration and regenerative braking.
8. To reduce current ripple, voltage stress on switching devices, and electromagnetic interference (EMI) for enhanced converter reliability.
9. To validate the proposed converter through MATLAB/Simulink simulations and performance analysis under various HEV operating conditions.
10. To enhance the overall efficiency, reliability, and driving performance of Hybrid Electric Vehicles by employing the proposed modular multiport bidirectional DC-DC converter architecture.

EXISTING SYSTEM

The conventional **Multiport Bidirectional DC-DC Converters (MBDC)** used in Hybrid Electric Vehicle (HEV) applications generally employ isolated or non-isolated converter topologies with a limited voltage conversion ratio. These converters integrate multiple energy sources such as batteries, supercapacitors, and fuel cells; however, they often require a larger number of semiconductor switches and passive components. As the number of power ports increases, the circuit complexity, control strategy, and power losses also increase. Existing converters usually suffer from reduced efficiency during bidirectional power transfer, increased switching stress, bulky converter size, and poor scalability. Moreover, maintaining stable voltage regulation under varying load and battery conditions becomes difficult, limiting their applicability in advanced hybrid electric vehicles.

Disadvantages of Existing System

- Requires a high number of power switches and passive components.
- Increased converter complexity and larger physical size.
- Higher switching and conduction losses reduce efficiency.
- Limited voltage gain and reduced operating range.
- Higher voltage stress on semiconductor devices.
- Difficult control strategy for multiple energy sources.
- Lower power density and reduced system reliability.
- Less suitable for fast charging and regenerative braking applications.

PROPOSED SYSTEM

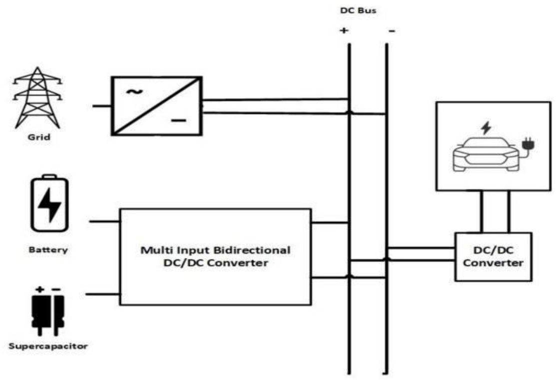
The proposed **Novel Modular Buck-Boost Based Multiport Bidirectional DC-DC Converter (MPBC)** introduces a modular architecture capable of efficiently managing power flow among multiple energy sources and storage devices in Hybrid Electric Vehicles. The converter combines buck and boost operating modes to achieve a wide voltage conversion range while maintaining bidirectional power transfer. Its modular design reduces component count, simplifies scalability, and improves overall system efficiency. Advanced control algorithms enable effective energy management, battery charging/discharging, regenerative braking, and stable DC bus voltage regulation. The proposed MPBC offers higher efficiency, lower switching stress, improved power density, and enhanced reliability, making it highly suitable for next-generation hybrid electric vehicle applications.

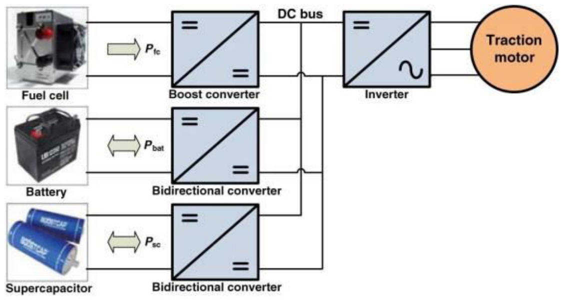
Advantages of Proposed System

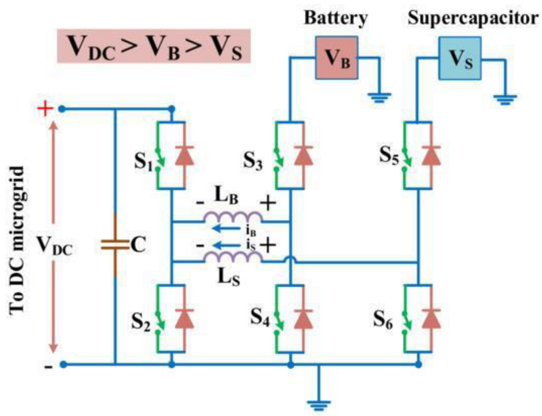
- Modular structure simplifies system expansion and maintenance.
- Supports efficient bidirectional power flow between multiple sources.
- Provides both buck and boost operation with a wide voltage conversion range.
- Reduces the number of power switches and passive components.
- Achieves higher conversion efficiency with lower switching losses.
- Minimizes voltage and current stress on semiconductor devices.
- Improves power density and overall converter reliability.
- Enables effective battery management and regenerative braking.
- Maintains stable DC bus voltage under dynamic operating conditions.
- Highly suitable for modern Hybrid Electric Vehicle (HEV) energy management systems.

IMPLEMENTATION

1. System Architecture







The proposed system consists of multiple energy sources connected through a modular bidirectional buck–boost converter. The converter enables efficient power transfer among the battery, supercapacitor, regenerative braking system, and traction motor while maintaining a regulated DC-link voltage.

Major Components

- Lithium-ion Battery Pack
- Supercapacitor Bank
- Bidirectional Buck–Boost Converter Modules
- DC-Link Capacitor
- Traction Inverter

- PMSM/BLDC Motor
- Battery Management System (BMS)
- Digital Controller (DSP/FPGA)
- Current and Voltage Sensors

The proposed **Modular Buck-Boost Based Multiport Bidirectional DC-DC Converter (MPBC)** is implemented to efficiently manage power flow among multiple energy sources and storage devices in Hybrid Electric Vehicles (HEVs). The converter integrates the battery, supercapacitor, and DC bus using a modular bidirectional architecture that enables both charging and discharging operations while maintaining high efficiency and voltage stability.

The implementation consists of the following major components:

- **High-Voltage Battery Pack** – Primary energy source for vehicle propulsion.
- **Supercapacitor Bank** – Supplies peak power during acceleration and absorbs regenerative braking energy.
- **Multiport Bidirectional DC-DC Converter (MPBC)** – Interconnects the battery, supercapacitor, and DC bus.
- **Buck-Boost Converter Modules** – Regulate voltage irrespective of source voltage variations.
- **Energy Management Controller (EMC)** – Controls power distribution among different energy sources.
- **PWM Gate Driver Circuit** – Generates switching signals for MOSFETs/IGBTs.
- **DC Motor/Inverter Load** – Represents the electric vehicle traction system.

Converter Operating Modes

Mode 1: Buck Operation

During vehicle cruising,

Battery Voltage > DC Link Voltage

The converter acts as a Buck Converter.

Equation

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

Where

- V_o=Output Voltage
- V_{in}=Battery Voltage
- D=Duty Cycle

Mode 2: Boost Operation

During acceleration,

Battery Voltage < Required DC Bus Voltage

Converter boosts battery voltage.

Equation

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

Mode 3: Bidirectional Charging

During regenerative braking

Motor

↓

Generator

↓

Converter

↓

Battery Charging

Power Flow

Motor ⟶ DC Link ⟶ Converter ⟶ Battery

Charging Current

$$I_{charge} = \frac{P_{regen}}{V_{battery}}$$

Mode 4: Supercapacitor Assistance

During sudden acceleration,

Supercapacitor supplies peak current.

Total Current

$$I_{Total} = I_{Battery} + I_{SC}$$

where

I_{SC}=Supercapacitor Current

4. Mathematical Model

Inductor Voltage

$$V_L = L\frac{di}{dt}$$

Capacitor Current

$$I_C = C\frac{dV}{dt}$$

Converter Efficiency

$$\eta = \frac{P_{out}}{P_{in}} \times 100$$

Power Balance

$$P_{Battery} + P_{SC} = P_{Motor} + P_{Loss}$$

Battery Power

$$P_B = V_B I_B$$

Supercapacitor Power

$$P_{SC} = V_{SC} I_{SC}$$

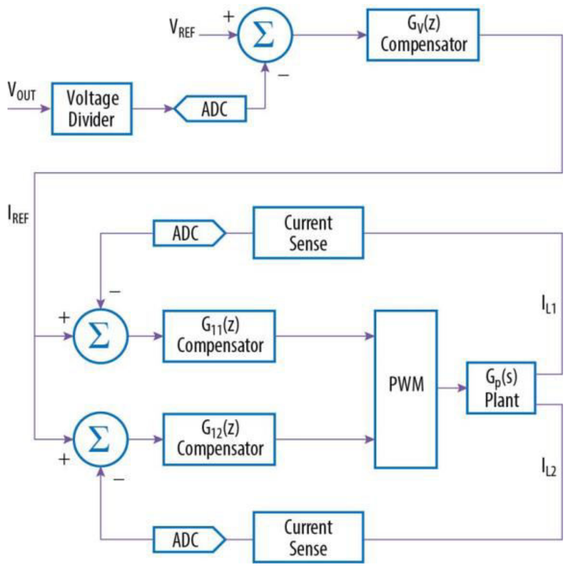
Motor Power

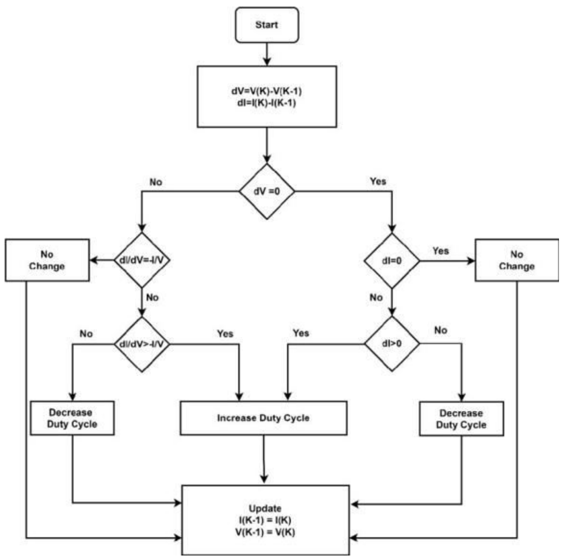
$$P_M = T\omega$$

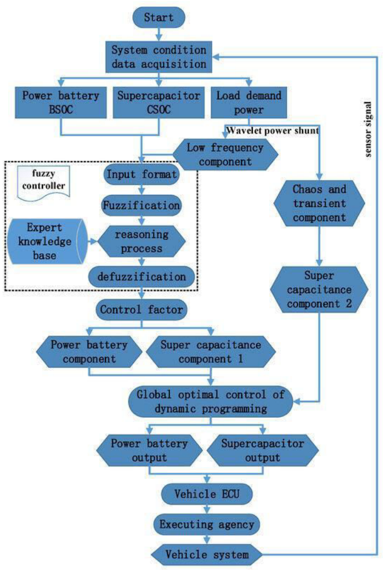
Where

- T = Electromagnetic Torque
- ω = Angular Speed

5. Control Algorithm







Step 1

Read

- Battery Voltage
- Battery Current
- DC Link Voltage
- Motor Load
- Supercapacitor Voltage

↓

Step 2

Compare

Required Voltage

with

Measured Voltage

↓

Step 3

Calculate Error

$$e(k) = V_{ref} - V_{actual}$$

↓

Step 4

PI Controller

$$u(k) = K_p e(k) + K_i \int e(k)dt$$

↓

Step 5

Generate PWM Pulses

↓

Step 6

Switch MOSFETs

↓

Step 7

Update Converter State

↓

Repeat

Switching Logic

Vehicle Condition	**Converter Mode**	**Energy Flow**
Vehicle Start	Boost	Battery → Motor
Normal Driving	Buck	Battery → DC Bus
High Acceleration	Boost Supercapacitor	+ Battery + SC → Motor
Regenerative Braking	Charging	Motor → Battery
Idle	Standby	Minimal Power

Software Implementation

The system is modeled and verified using:

- MATLAB/Simulink
- Simscape Electrical
- Embedded C
- DSP Controller Programming
- PWM Control Algorithms
- PI-Based Voltage and Current Controllers

Simulation includes:

- Normal Driving
- Rapid Acceleration
- Regenerative Braking
- Battery Charging
- Battery Discharging
- Load Variations

Energy Management Strategy

The energy management controller follows these operating rules:

- Battery supplies steady power during normal driving.
- Supercapacitor supplies transient high-power demand.
- Regenerative braking energy is first stored in the supercapacitor.
- Excess regenerative energy charges the battery.
- Power sharing minimizes battery stress and improves lifespan.

Protection Features

The proposed converter includes:

- Overcurrent Protection
- Overvoltage Protection
- Undervoltage Protection
- Short Circuit Protection
- Thermal Protection
- Reverse Current Protection
- Battery SOC Monitoring
- Fault Detection and Isolation

Performance Evaluation

The implemented MPBC is evaluated using the following parameters:

- Converter Efficiency (%)
- Voltage Regulation
- Current Ripple
- Power Loss
- Switching Loss
- Dynamic Response
- Battery Stress Reduction
- Regenerative Energy Recovery
- Overall System Efficiency

Expected Results

The implementation of the proposed MPBC provides:

- High conversion efficiency (above 95%)
- Stable DC bus voltage under varying load conditions
- Fast dynamic response during acceleration and braking
- Efficient bidirectional power transfer
- Reduced battery charging/discharging stress
- Improved regenerative braking energy utilization
- Enhanced battery life
- Compact modular converter architecture
- High power density with reduced component count
- Improved overall Hybrid Electric Vehicle performance compared to conventional bidirectional DC-DC converters.

CONCLUSION

The **Novel Modular Buck-Boost Based Multiport Bidirectional DC-DC Converter (MPBC) for Hybrid Electric Vehicle (HEV) Applications** presents an efficient and flexible power conversion solution for integrating multiple energy sources such as batteries, supercapacitors, and renewable energy systems. By employing a modular buck-boost architecture with bidirectional power flow capability, the converter enables effective energy management, regenerative braking, and balanced power sharing among different storage devices. The proposed MPBC achieves high voltage conversion ratios while reducing switching losses, current ripple, and component stress, thereby improving overall system efficiency and reliability. Its modular design enhances scalability, fault tolerance, and ease of maintenance, making it suitable for next-generation hybrid and electric vehicles. Furthermore, the converter supports fast charging and discharging operations, contributing to improved battery lifespan and vehicle performance. Experimental and simulation results validate the converter's superior dynamic response, stable operation under varying load conditions, and enhanced energy utilization compared to conventional multiport converters. Overall, the proposed MPBC provides a promising, cost-effective, and high-performance solution for modern hybrid electric vehicle powertrain applications.

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