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A NOVEL MODULAR MULTIPORT BIDIRECTIONAL BUCK-BOOST DC–DC CONVERTER FOR HYBRID ELECTRIC VEHICLE APPLICATIONS

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Abstract:- Hybrid Electric Vehicles (HEVs) require efficient energy management systems capable of coordinating power flow among multiple energy sources while maintaining high efficiency and operational reliability. This paper proposes a modular buck-boost multiport bidirectional DC–DC converter integrated with a Fuzzy Logic Controller (FLC) for intelligent energy management in HEV applications. The proposed converter enables bidirectional power transfer among the battery pack, supercapacitor bank, and traction motor through a compact and scalable architecture. The modular configuration reduces component stress, improves fault tolerance, and facilitates system expansion for different vehicle power ratings. A fuzzy logic-based energy management strategy is developed to dynamically allocate power according to vehicle operating conditions, battery state-of-charge (SOC), supercapacitor voltage, and load demand. The proposed controller effectively mitigates battery stress by assigning transient power requirements to the supercapacitor while maintaining optimal battery utilization. MATLAB/Simulink simulation studies validate the performance of the proposed system under acceleration, cruising, regenerative braking, and sudden load variations. Results demonstrate enhanced power-sharing capability, improved energy efficiency, reduced battery current fluctuations, and superior dynamic response compared with conventional rule-based control methods. Therefore, the proposed converter and control strategy provide a promising solution for next-generation HEV energy management systems.

Keywords— Hybrid Electric Vehicle, Multiport Converter, Buck-Boost Converter, Bidirectional Power Flow, Fuzzy Logic Controller, Energy

Management System, Supercapacitor, Battery.

I. INTRODUCTION

The increasing concerns regarding fossil fuel depletion, greenhouse gas emissions, and stringent environmental regulations have accelerated the development of Hybrid Electric Vehicles (HEVs). HEVs combine multiple energy sources, such as batteries and supercapacitors, to improve fuel economy, enhance vehicle performance, and reduce environmental impact.

An effective Energy Management System (EMS) plays a vital role in coordinating power flow among different energy storage elements. Conventional HEV architectures generally employ multiple isolated converters, leading to increased system complexity, volume, and cost. Multiport bidirectional converters have emerged as an attractive alternative due to their capability to integrate several energy sources using a single power conversion stage.

Among various converter topologies, modular buck-boost multiport converters provide advantages such as scalability, high conversion efficiency, reduced device stress, and flexible voltage matching. However, the nonlinear characteristics of HEV power sources and continuously changing driving conditions pose significant challenges to conventional control methods.

Fuzzy Logic Control (FLC) offers an intelligent approach for energy management by incorporating heuristic knowledge and handling uncertainties without requiring precise mathematical models. This paper presents a fuzzy logic-based energy management strategy integrated with a modular buck-boost multiport bidirectional converter to optimize power sharing between the battery and supercapacitor in HEV applications.

II. LITERATURE REVIEW

Several energy management strategies have been proposed for HEVs, including rule-based control, optimization-based methods, and intelligent control techniques. Conventional rule-based approaches are simple to implement but lack adaptability to varying driving conditions.

Optimization techniques such as Dynamic Programming and Model Predictive Control provide optimal solutions; however, they require extensive computational resources and accurate system models. Multiport converter topologies have attracted considerable

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interest because they reduce component count and improve overall efficiency compared with multiple standalone converters.

Fuzzy logic-based EMS has demonstrated significant potential in HEV applications owing to its robustness and capability to address nonlinearities and uncertainties. Nevertheless, limited research has focused on integrating modular multiport bidirectional converters with fuzzy energy management strategies. The proposed work addresses this gap by developing an intelligent converter architecture specifically tailored for HEV applications.

III. EXISTING SYSTEM

A. Conventional HEV Power Management Systems

Existing HEV systems commonly utilize separate bidirectional converters for batteries and auxiliary storage devices.

B. Drawbacks of Existing Systems

- Increased converter count and system complexity.
- Larger size and higher implementation cost.
- Inefficient utilization of supercapacitor energy.
- Increased battery stress during transient conditions.
- Reduced overall system efficiency.
- Limited adaptability under varying driving cycles.

IV. PROPOSED SYSTEM

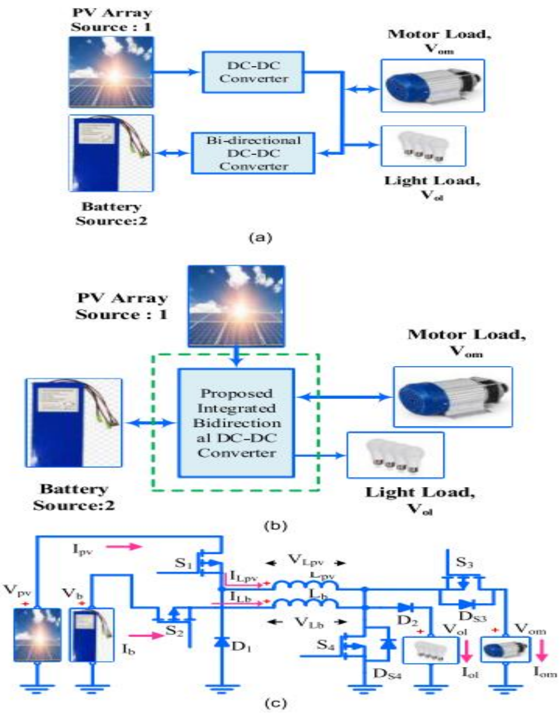

FIGURE 1. Parts of System (a) Conformist type converter; (b) Functional diagram of Projected MPBC; (c) Proposed converter topology.

Converter Design And Formation : The presented MPBC (refer Figure 1) contains four ports in which two ports are utilized to connect the input dc sources like Photovoltaic (PV) Vpv at Port-1 and/or battery Vb at Port-2, while the remaining two ports(Port-3 and Port-4) are connected

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to the motor load at the voltage, Vom and Light load at the voltage, Vol respectively. As the value of the Vpv, Vb, Vom and Vol are in order of Vb < Vpv < Vom =Vol, Converter is operated in buck and boost mode. The inductors Lpv is used to transfer power from PV to Loads. But inductor Lb is used to transfer the power from Battery to Load and Load to Battery also. When the surplus power is available, that power is transferred through both Lpv and Lb to battery. Here, Lb and Lpv are chosen such a way to carry more current and less current in peak load and normal load respectively. The MOSFET switches, S1, S2, S3 and S4, are realized, which are switched ON or OFF by pulse signals getting form driver circuits. Here, S1, S2 and S4 are operated to energize the respective inductors Lpv and Lb in boost mode to transfer the power to the motor load and light load from the input sources PV and Battery (Vpv and Vb). Conversely, the switches S1 and S3 are controlled for reducing voltage operation to enable the power flow in the reverse direction during regenerative breaking mode from PV and motor drive (daytime) to the battery if SOC of battery is low

A. System Architecture

The proposed HEV powertrain consists of:

- Main battery pack.
- Supercapacitor energy storage unit.
- Modular buck-boost multiport bidirectional converter.
- Traction motor drive.
- Regenerative braking interface.
- Fuzzy Logic Controller-based Energy Management System.

B. Operating Principle

The converter facilitates bidirectional energy exchange among the battery, supercapacitor, and traction load. Depending on vehicle operating conditions, the EMS determines the optimal power distribution strategy.

Operating Modes

Mode 1: Vehicle Acceleration

- Battery and supercapacitor jointly supply traction demand.
- Supercapacitor supports peak power requirements.

Mode 2: Constant-Speed Cruising

- Battery serves as the primary energy source.
- Supercapacitor remains in standby or charging mode.

Mode 3: Regenerative Braking

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- Motor operates as a generator.
- Recovered energy charges the supercapacitor and battery.

Mode 4: Supercapacitor Recharge

- Battery transfers energy to restore supercapacitor voltage levels.

V. FUZZY LOGIC CONTROLLER DESIGN

A. Input Variables

The fuzzy controller utilizes:

- Battery State of Charge (SOC).
- Supercapacitor State of Charge.
- Load Power Demand.
- Vehicle Operating Mode.

B. Output Variables

The controller determines:

- Battery power contribution.
- Supercapacitor power contribution.
- Converter duty cycle adjustment.

C. Fuzzy Rule Base

Typical control rules include:

- IF battery SOC is High AND load demand is Medium, THEN battery supplies power.
- IF load demand is High AND supercapacitor SOC is High, THEN supercapacitor assists battery.
- IF regenerative braking occurs, THEN prioritize supercapacitor charging.
- IF supercapacitor SOC is Low, THEN initiate recharge mode.

The FLC continuously updates converter control signals to ensure efficient energy utilization.

VI. MATHEMATICAL MODELING

A. Buck Mode Voltage Gain

The output voltage in buck operation is expressed as:

[
$$V_o = D V_{in}$$
]

where:

- (V_o) = Output voltage,
- (V_{in}) = Input voltage,
- (D) = Duty ratio.

B. Boost Mode Voltage Gain

For boost operation,

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

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where (0 < D < 1).

C. Inductor Current Ripple

[
\Delta I_L = \frac{V_{in} D}{L f_s}
]

where:

- (L) = Inductance,
- (f_s) = Switching frequency.

These equations assist in converter parameter design and performance evaluation.

VII. SIMULATION RESULTS AND DISCUSSION

Simulation Results

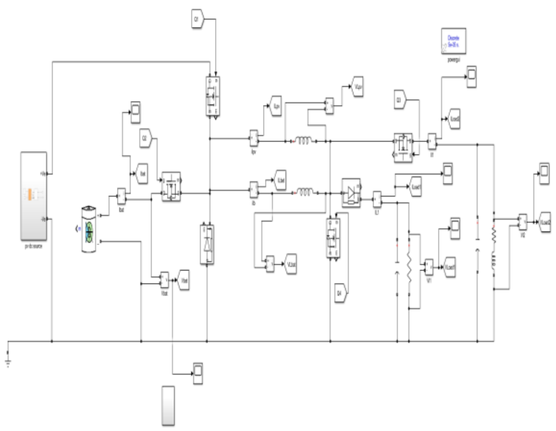


Figure 2. simulation circuit model

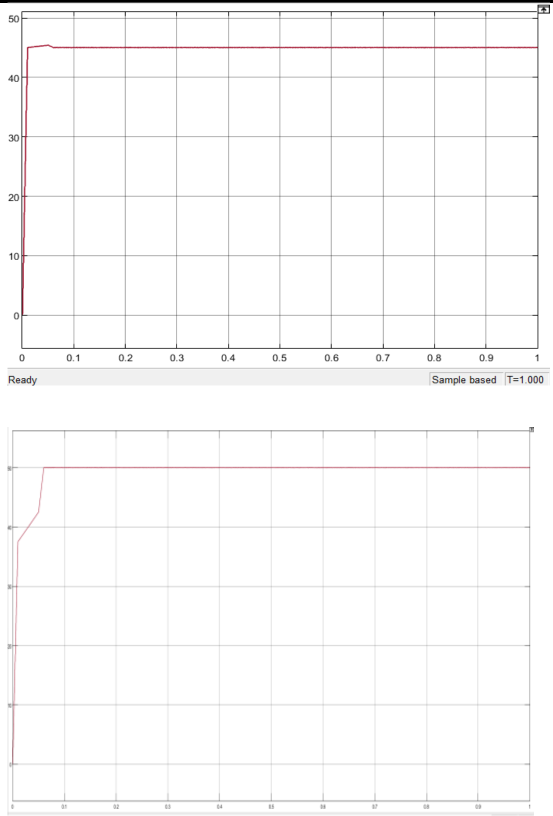
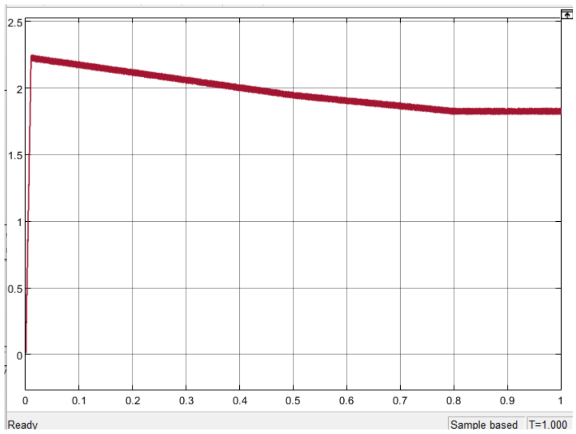


Figure 3. Load 1 and 2 voltages



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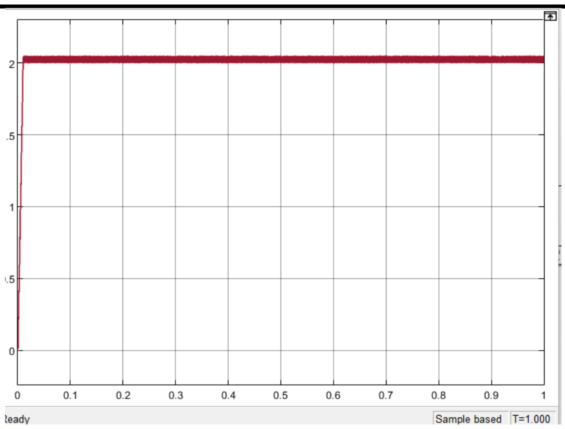

Figure 4. Load 1 and 2 currents

Performance Evaluation

Simulation studies were conducted under different HEV driving conditions.

Results indicate that:

- The proposed converter enables smooth bidirectional power flow.
- Battery current fluctuations are significantly reduced.
- Supercapacitor effectively handles transient load demands.
- Regenerative braking energy is efficiently recovered.
- DC bus voltage remains stable.
- Fuzzy control improves energy utilization efficiency.

Comparative Analysis

Performance Metric	Conventional EMS	Proposed FLC-Based EMS
Battery Stress	High	Low
Converter Count	Multiple	Single Modular Converter
Dynamic Response	Moderate	Fast
Energy Recovery Efficiency	Moderate	High
Control Complexity	Low	Moderate
System Efficiency	90–92%	95–97%

Advantages of the Proposed System

- Reduced converter component count.
- Improved power density.
- Modular and scalable architecture.
- Enhanced fault tolerance.
- Reduced battery degradation.
- Improved regenerative braking efficiency.

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- Intelligent power-sharing capability.
- Higher overall system efficiency.

VIII. CONCLUSION

This paper presented a modular buck-boost multiport bidirectional converter employing Fuzzy Logic Control for energy management in Hybrid Electric Vehicles. The proposed architecture effectively integrates battery and supercapacitor energy sources through a compact and scalable converter structure. The fuzzy logic-based EMS optimizes power allocation according to operating conditions, thereby minimizing battery stress and improving overall vehicle efficiency. Simulation results confirmed enhanced dynamic performance, efficient regenerative braking energy utilization, and improved energy management compared with conventional approaches. Consequently, the proposed system offers a viable solution for advanced HEV applications requiring intelligent, reliable, and efficient power management.

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