Multi-Input Boost Converter with Enhanced Voltage Gain for HEV Applications

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Abstract - A high step-up multi-input DC–DC converter for hybrid electric vehicle (HEV) applications is designed and simulated in this project. The system integrates a fuel cell, photovoltaic (PV) source, and an energy storage system (ESS) to obtain enhanced voltage gain and reliable power supply. The fuel cell serves as the primary source, while the PV unit supports battery charging and improves overall efficiency. A power management strategy is implemented to ensure proper energy sharing and continuous operation under different source conditions. Simulation results verify the effectiveness of the proposed converter.

Key Words*: *Multi-Input DC–DC Converter, Hybrid Electric Vehicle (HEV), Power Management, Fuel Cell, Photovoltaic (PV).

1.INTRODUCTION :

Rapid depletion of fossil fuels and increasing environmental concerns have accelerated the development of alternative energy-based transportation systems. Hybrid Electric Vehicles (HEVs), Plug-in Hybrid Electric Vehicles (PHEVs), and Electric Vehicles (EVs) are considered promising solutions due to their reduced emissions and improved energy efficiency [2][6]. Conventional EVs primarily depend on an energy storage system (ESS), which limits driving range and increases charging duration [2]. Although bidirectional chargers enable vehicle-to-grid (V2G) functionality, battery-only systems still suffer from performance limitations.

To improve reliability and driving capability, fuel cells (FCs) have been integrated into HEV architectures [13]. Fuel cells offer clean energy generation with water and heat as by-products, along with high efficiency and good current density characteristics. However, challenges such as high cost and slow transient response restrict their standalone usage. Therefore, hybridization with batteries is essential to enhance dynamic performance, reduce stress on the fuel cell, and improve overall fuel economy[6].

Several power electronic interface topologies have been reported in the literature for multi-source EV and HEV systems[1][8]. Some converters provide single-stage voltage boosting but suffer from high switch stress and complex control strategies[5][9]. Other multi-input converters allow integration of multiple sources but may lack bidirectional capability or exhibit reduced reliability due to a large number of switching devices[4][8]. In certain configurations, improper energy flow between PV, FC, and battery limits system flexibility[7].

Effective power management plays a crucial role in HEV applications[13]. The control system must regulate power sharing among renewable sources, battery storage, and the traction motor while ensuring optimal operation of the fuel cell and photovoltaic (PV) modules[1][8]. Maximum Power Point Tracking (MPPT) techniques are necessary to maximize energy extraction from PV systems[8]. Additionally, bidirectional energy flow is required to charge or discharge the battery based on load demand and source availability[10][11].

In this project, a three-input DC–DC converter is developed to integrate a photovoltaic source, fuel cell, and battery system[7][12]. The proposed configuration enhances voltage gain compared to conventional topologies and enables flexible power distribution among sources[9]. The battery operates in both charging and discharging modes to support power balancing[10]. The system is modeled and analyzed in MATLAB/Simulink, and simulation results demonstrate the feasibility and effectiveness of the proposed approach.

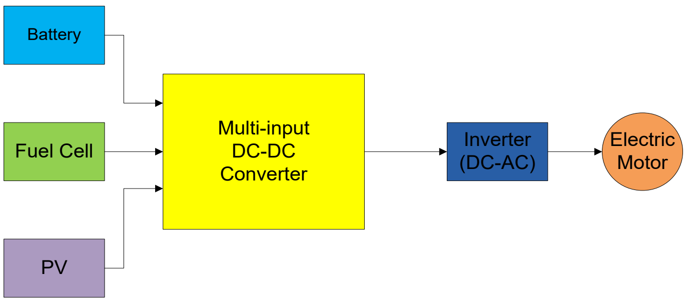


Fig1.general Structure of multi-powered HEV

2. Proposed Converter Topology

The proposed three-input DC–DC boost converter topology is designed to integrate multiple energy sources for hybrid electric vehicle applications[1][8][12]. The converter architecture is derived from conventional boost converter principles and is modified to support multi-source operation with enhanced voltage gain[5][9]. The system incorporates a fuel cell, a solar PV source, and a battery, enabling efficient energy storage and utilization[7][13]. This configuration makes the converter well suited for hybrid energy systems requiring flexible power management.

In the proposed topology, the solar PV and fuel cell act as independent input sources, and their output characteristics directly influence the overall system performance[8][13]. Inductors L_1 and L_2 are connected in series with the PV and fuel cell sources, respectively, and function as input filters. These inductors convert the voltage sources into controlled current sources, ensuring smoother input currents and improved dynamic response[4][11]. The equivalent resistances of the PV and fuel cell sources are represented by r_1 and r_2. The load connected to the DC bus is modeled as an equivalent resistance R_{Load}.

The converter employs four controlled power switches S_1, S_2, S_3, and S_4, along with diodes D_1, D_2, D_3, and D_4, to establish different operating modes based on source availability and load demand[1][7]. An additional capacitor C_1 is introduced to enhance the voltage boost capability of the converter, while the output capacitor C_o is used to filter the DC bus voltage and reduce output voltage ripple[5][9]. The converter operates in continuous conduction mode (CCM), which ensures smooth inductor currents and minimizes current ripple, thereby improving efficiency and overall system performance[11].

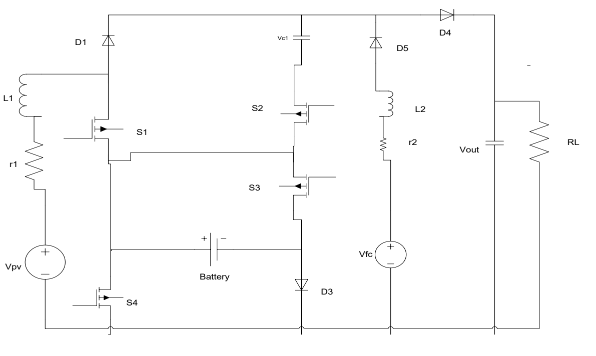


Fig2.Three-input DC-DC boost converter

3.Operation Modes

The operating principle of the proposed multi-input DC–DC boost converter is explained by classifying its operation into three distinct states based on the condition of the battery[1][12]. The converter is designed to operate in continuous conduction mode to ensure smooth current flow and reduced ripple[11]. The steady-state analysis of each operating state is carried out using the volt–second balance principle on the inductors and the charge balance principle on the capacitors[4].

A. State I: Load Supplied by PV and Fuel Cell (Battery Idle Mode)

In this operating state, the load power demand is fulfilled only by the solar PV panel and the fuel cell, while the battery remains inactive[13]. The battery neither delivers nor absorbs power, and hence it does not affect the power flow during this state. The converter establishes a fixed current path using appropriate switching combinations to enable power transfer from the PV and fuel cell to the DC load[1][7].

During one switching period, the converter operates in three sub-modes. In the first sub-mode, both inductors connected to the PV and fuel cell are energized by their respective sources. In the second sub-mode, partial energy stored in the inductors is transferred to the intermediate capacitor while maintaining continuous power flow. In the final sub-mode, the stored energy is boosted to the output through the DC–DC conversion process. By applying the volt–second balance principle to the inductors, the expressions for the intermediate capacitor voltage and output voltage are obtained[4].

$$L_1 : d_1\ [V_{PV} - r_1 i_{L1}] + (d_3-d_2)\ [V_{PV} - r_1\ i_{L1} - V_{c1}] + (1-d_2)\ [V_{PV} - r_1\ i_{L1}] = 0 \quad (1)$$

$$V_{c1} = \frac{V_{PV} - r_1\, i_{L1}}{d_2 - d_1} \quad (2)$$

$$L_2 : d_2\ [V_{FC} - r_2\, i_{L2}] + (1-d_2)\ [V_{FC} + V_{c1} - r_2\, i_{L2} - V_o] = 0 \quad (3)$$

$$V_o = \frac{(d_2-d_1)(V_{FC}-r_2 i_{L2})+(1-d_2)(V_{FC}-r_1 i_{L1})}{(1-d_2)(d_2-d_1)} \quad (4)$$

Since the battery is not involved in this state, the battery current and power remain zero.

$$C_1 : (d_2 - d_1)\, i_{L1} - (1-d_2)\, i_{L2} = 0. \quad (5)$$

$$C_o : (1-d_2)\, i_{L2} = \frac{V_o}{R_{Load}}. \quad (6)$$

$$i_{batt} = 0 \quad (7)$$

$$P_{batt} = 0. \quad (8)$$

B. State II: Load Supplied by PV, Fuel Cell, and Battery (Battery Discharging Mode)

In the second operating state, the battery actively participates in supplying power to the load along with the PV and fuel cell[10][11]. This state is typically activated when the load demand exceeds the power available from the renewable sources[8]. An additional current path is enabled to allow energy transfer from the battery to the DC bus[10].

This operating state consists of four switching sub-modes within one switching cycle. During these sub-modes, the inductors are alternately charged by the combined input sources and discharged to the intermediate and output capacitors. The coordinated switching action ensures proper power sharing among the PV, fuel cell, and battery[1][12]. Applying the volt–second balance principle to the inductors results in the output voltage and intermediate capacitor voltage[4].

$$L_1 = d_1\,[V_{PV} + V_{batt} - r_1 i_{L1}] + (d_2 - d_1)\,[V_{PV} - r_1 i_{L1}] + (d_3 - d_2)\,[V_{PV} - r_1 i_{L1} - V_{c1}] + (1-d_3)\,[V_{PV} - r_1 i_{L1}] = 0 \quad (9)$$

$$V_{C1} = \frac{V_{PV} + d_1\ V_{batt} - r_1\, i_{L1}}{d_3 - d_2} \quad (10)$$

$$L_2 : d_1\,[V_{FC} + V_{batt} - r_2\, i_{L2}] + (d_3 - d_1)\,[V_{FC} - r_2\, i_{L2}] + (1-d_3)\,[V_{FC} + V_{C1} - r_2 i_{L2} - V_0] = 0 \quad (11)$$

$$V_0 = \frac{(d_3-d_2)(V_{FC}+d_1V_{batt}-r_2 i_{L2})+(1-d_3)(V_{PV}+d_1V_{batt}-r_1 i_{L1})}{(1-d_3)(d_3-d_2)} \quad (12)$$

$$C_1 : (d_3-d_2)\, i_{L1} - (1-d_3)\, i_{L2} = 0 \quad (13)$$

$$C_0 : (1-d_3)\, i_{L2} = \frac{V_0}{R_{Load}}. \quad (14)$$

The battery current and power contribution during this state are represented by

$$I_{batt} = d_1\,(i_{L2} + i_{L1}) \quad (15)$$

$$P_{batt} = V_{batt}\,[d_1(i_{L2} + i_{L1})] \quad (16)$$

C. State III: Load Supplied by PV and Fuel Cell with Battery Charging

In the third operating state, the solar PV panel and fuel cell supply power to the load while simultaneously charging the battery[8][10]. This mode is enabled when excess power is available from the renewable sources or when the battery state-of-charge is low. The direction of battery current is reversed compared to the discharging mode[11].

Similar to the second operating state, this condition includes four switching sub-modes within one switching period. In these sub-modes, energy stored in the inductors is appropriately distributed between the output load and the battery. By applying the volt–second balance principle, the steady-state voltage relationships for this mode are obtained[4].

$$L_1 = d_1\,[V_{PV} - r_1 i_{L1}] + (d_2-d_1)\,[V_{PV} - r_1 i_{L1} - V_{C1}] + (1-d_2)\,[V_{PV} - r_1 i_{L1} - V_{batt}] = 0 \quad (17)$$

$$V_{C1} = \frac{(V_{PV} - (1-d_2)V_{batt} - r_1 i_{L1}}{d_2 - d_1} \quad (18)$$

$$L_2 : d_2[V_{FC} - r_2 i_{L2}] + (d_3-d_2)(V_{FC} - r_2 i_{L2} - V_{batt}] + (1-d_3)[V_{FC} + V_{C1} - r_2 i_{L2} - V_0] = 0 \quad (19)$$

$$V_0 : \frac{(V_{FC} - (d_3-d_2)V_{batt} - r_2 i_{L2})}{(1-d_3)} + \frac{(V_{PV} - (1-d_2)V_{batt} - r_1 i_{L1})}{(d_2-d_1)} \quad (20)$$

$$C_1 = (d_2-d_1)i_{L1} - (1-d_3)i_{L2} = 0 \quad (21)$$

$$C_0 : (1-d_3)i_{L2} = \frac{V_0}{R_{Load}} \quad (22)$$

The battery charging current and power expressions

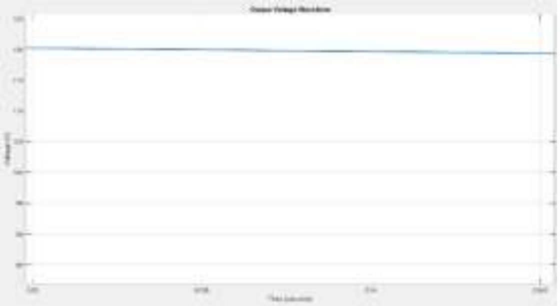
$$i_{batt} = (d_3-d_2)(i_{L2}+i_{L1}) + (1-d_3)i_{L1} \quad (23)$$

$$P_{batt} = V_{batt}[(d_3-d_2)(i_{L2}+i_{L1}) + (1-d_3)i_{L1}]. \quad (24)$$

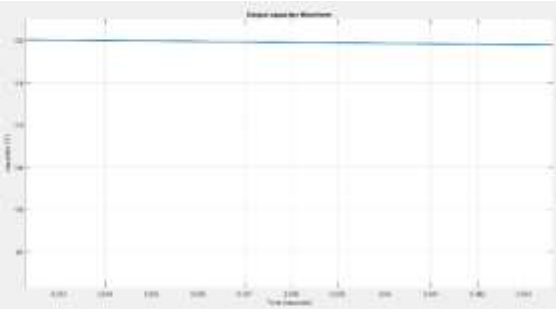
4.Experimental Results

The proposed step-up multi-input DC–DC converter provides an efficient and compact solution for Hybrid Electric Vehicle (HEV) applications by integrating a fuel cell, solar PV panel, and battery through a single conversion stage[1][7][8]. The converter effectively boosts low input voltages to the required high DC output while reducing component count, thereby minimizing power losses and improving overall efficiency[5][9]. Its flexible power-sharing capability ensures reliable and continuous power delivery under varying operating conditions[12]. The system was successfully modeled and validated in MATLAB/Simulink[1], and the developed MATLAB App enables easy operating mode selection and performance monitoring. Overall, the proposed design demonstrates improved efficiency, reliability, and practicality for multi-source energy management in HEVs.

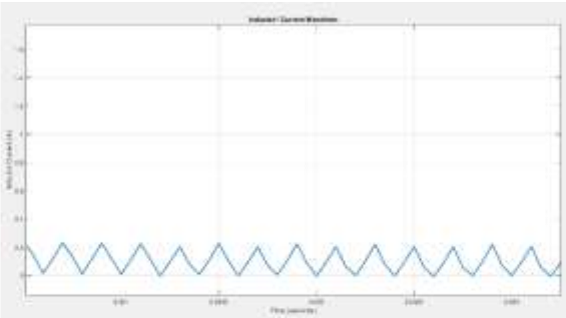
First operation state(The load is supplied by PV and FC while battery is not used)



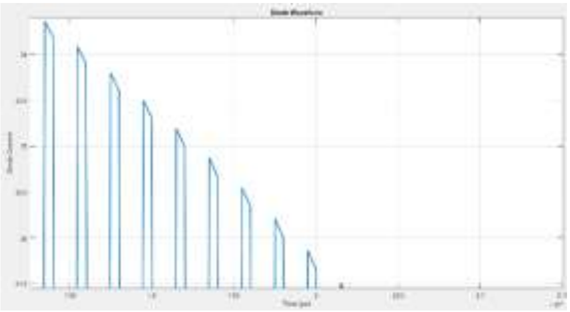
a). output voltage



b) output capacitor

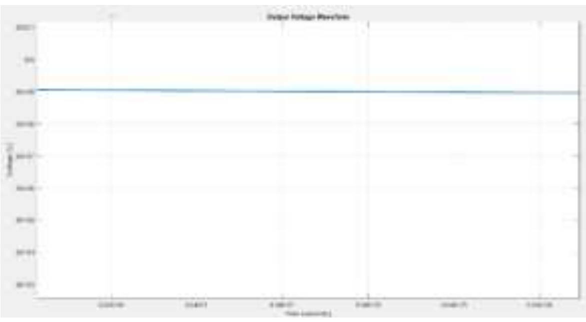


c) inductor current_1

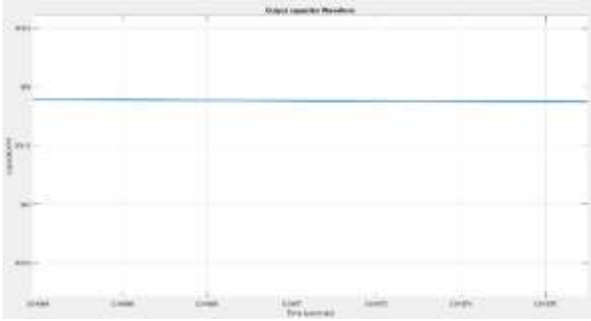


d).Diode current_2

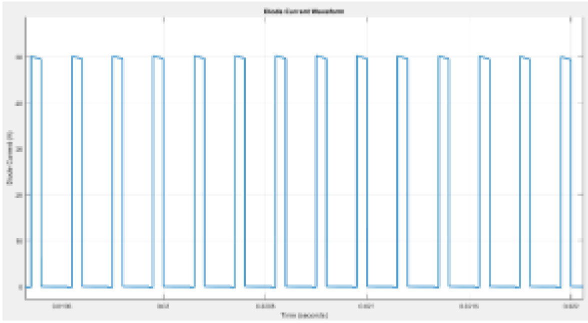
Second operation state(The load is supplied by PV and FC and battery)



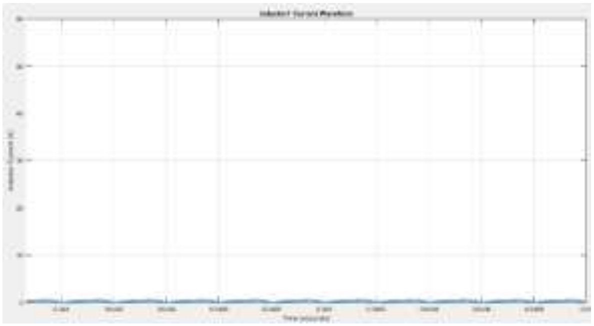
a).output voltage



b)output capacitor

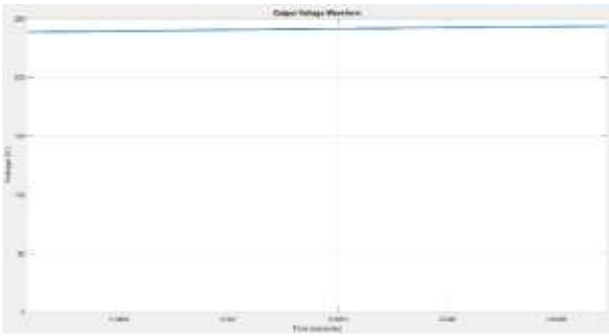


c)Diode Current_2(ID2)

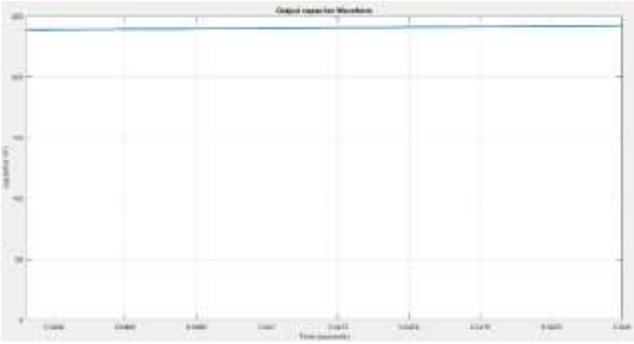


d)inductor current

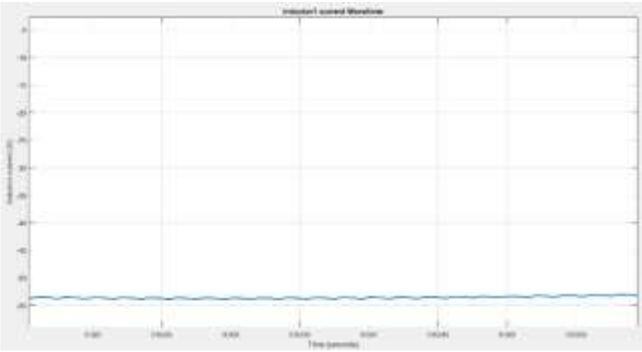
Third operation state(The load is supplied by PV and FC and while battery is in charging mode)



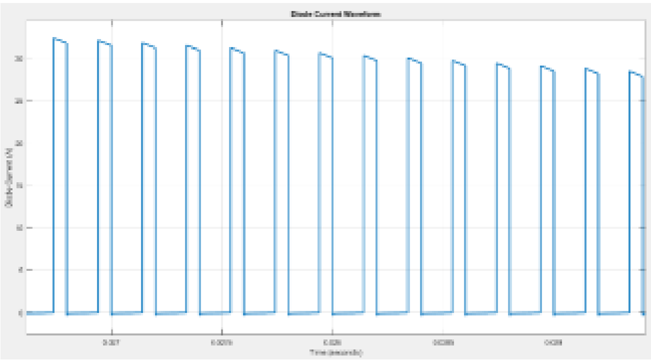
a).output voltage



b).output capacitor



c)inductor current



d)Diode current(ID2)

5. CONCLUSIONS

This work presented the design and simulation of a high-gain multi-input DC–DC converter for Hybrid Electric Vehicle applications[1][8][12]. The proposed system integrates a fuel cell, solar PV panel, and battery through a single conversion stage to achieve regulated high DC output with reduced component count and improved efficiency[5][9]. Simulation results in MATLAB/Simulink confirm stable operation, effective power sharing, and reliable performance under different operating conditions. The developed MATLAB App further enhances usability by enabling simple mode selection and real-time performance monitoring, demonstrating the practicality of the proposed system for HEV power management

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