Novel Control Strategy for Bidirectional DC-DC Converter in Electrical Vehicle

Dr Bapayya Naidu Kommula[1], Kunapureddy Veera Venkata Satya Sai [2], Ganja Satish[3], Yilla Gangadhara Siva Surya[4] , Kasibatta Gowtham[5]

ABSTRACT

This project implements a hybrid electric vehicle system with a novel bidirectional DC-DC converter (BDC) that interfaces between the main energy storage (ES1), auxiliary energy storage (ES2), and DC bus at different voltage levels. The proposed BDC can operate in both step-up and step-down modes. The step-up mode represents a dual low voltage source powering mode, while the step-down mode represents a high voltage DC link energy-regenerating mode. Both modes are controlled for bidirectional power flow. This model can independently control power flow between the dual low voltage source buck/boost modes. The circuit configuration, operation, steady-state analysis, and closed-loop control of the proposed BDC are examined according to its three power transfer modes. A fuzzy logic controller is implemented and the system results are validated through MATLAB/SIMULINK software.

Index Terms—Bidirectional dc/dc converter (BDC), dual battery storage, hybrid electric vehicle, Fuzzy logic controller.

I. INTRODUCTION

Worldwide environmental change and declining energy supply have catalyzed innovations in vehicle technology. Researchers are investigating advanced technologies for potential applications in future vehicles. Among these promising applications, fuel-cell hybrid electric vehicles (FCV/HEV) offer efficiency and sustainability. Previously, Ehsani et al. analyzed FCV/HEV dynamics to optimize the electric propulsion system's torque-speed profile. Emadi et al. examined the operational characteristics of various vehicles, including HEVs, FCVs, and more electric vehicles, for different driving conditions. To meet high vehicular power demands, Emadi et al. also proposed power electronics-intensive solutions. Schaltz et al. allocated load power among the fuel cell stack, battery, and ultra capacitors using two energy management strategies. Thounthong et al. studied fuel cell (FC) performance and the benefits of hybridization for control systems. Chan et al. reviewed electric, hybrid, and fuel cell vehicles, focusing on structures and modeling for energy management. Khaligh and Li surveyed energy storage topologies for HEVs and plug-in HEVs (PHEVs), analyzing and comparing battery, ultra capacitor (UC), and FC technologies. They also examined hybrid energy storage systems integrating two or more storage devices. Rajasekar discussed the status and needs of key electric drive components: batteries, motors, and power electronics. Lai et al. implemented a bidirectional DC/DC converter topology with two-stage interleaved operation. This improved the voltage conversion ratio for EVs and DC micro grid systems. Additionally, Lai examined a DC/DC converter topology with a high voltage conversion ratio for connecting EV batteries to a DC micro grid. In fuel-cell hybrid electric vehicles, the primary battery is commonly used to start the FC and power the propulsion motor. The battery compensates for the FC stack's inherently slow response by providing peak power during acceleration. High power density super capacitors (SCs) also eliminate power transients during acceleration and braking. In general, SCs can store regenerative braking energy and release it during acceleration, thereby supplying extra power. The high power density of super capacitors extends battery and FC stack life and improves overall FCV efficiency.

Fig.1.Typical functional diagram for a FCV/HEV power system.

- This study proposes two new bi-directional converter (BDC) topologies for fuel cell vehicle/hybrid electric vehicle (FCV/HEV) power systems: an interleaved voltage-doubler structure and a synchronous buck-boost circuit. The topologies have two key operating modes: a low-voltage dual-source powering mode and a high-voltage DC bus energy-regenerating mode. In the low-voltage mode, the converter can independently control power flow between any two low-voltage sources. A previous study briefly presented a similar topology, but did not provide detailed analysis. In contrast, this investigation thoroughly analyzes the operation and closed-loop control of the new topology and presents simulation results for all operating modes. The proposed converter operates over a wide voltage range, expanding on the topology from the previous work.
- The key features of the proposed converter are:
- Interfaces multiple DC sources at various voltage levels
- Controls power flow between the DC bus and two low-voltage sources, and between the low-voltage sources
- Increases static voltage gain, reducing switch voltage stress
- Has a reasonable duty cycle for a wide voltage difference between high-side and low-side ports

II. PROPOSED TOPOLOGY

The proposed bidirectional DC-DC converter (BDC) topology with dual battery energy storage is illustrated in Fig. 2.1. In the figure, VH represents the high-voltage DC bus voltage, while VES1 and VES2 denote the voltages of the main and auxiliary energy storage systems (ES1 and ES2), respectively. To control the current flow in ES1 and ES2, two bidirectional power switches (SES1 and SES2) are utilized in the converter structure. A charge pump capacitor (CB) acts as a voltage divider, consisting of four active switches (Q1-Q4) and two-phase inductors (L1, L2). This voltage divider improves the static voltage gain between the high-voltage DC bus (VH) and the low-voltage dual sources (VES1, VES2). The additional CB reduces the switch voltage stress on the active switches, eliminating the need to operate at an extreme duty ratio. Furthermore, the three bidirectional power switches (S, SES1, SES2) enable four-quadrant operation to control power flow between the dual low-voltage sources (VES1, VES2) and block both positive and negative voltages.

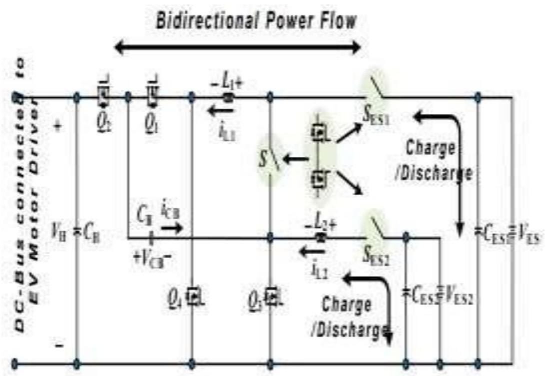

Fig.2.1. Proposed BDC topology with dual-battery energy storage.

This bidirectional power switch is implemented via two metal-oxide-semiconductor field-effect transistors (MOSFETs), pointing in opposite directions, in series connection. To explain the concept for the proposed converter, all the conduction statuses of the power devices involved in each operation mode are displayed in Table 2.1. Accordingly, the four operating modes are illustrated as follows to enhance understanding.

TABLE 2.1.

Operating Modes	ON	OFF	Control Switch	Synchronous Rectifier (SR)
Low-voltage dual-source-powering mode (Accelerating, $x_1=1, x_2=1$)	S_{ES1}, S_{ES2}	S	Q_3, Q_4	Q_1, Q_2
High-voltage dc-bus energy-regenerating mode (Braking, $x_1=1, x_2=1$)	S_{ES1}, S_{ES2}	S	Q_1, Q_2	Q_3, Q_4
Low-voltage dual-source buck mode (ES1 to ES2, $x_1=0, x_2=0$)	S_{ES1}, S_{ES2}	Q_1, Q_2, Q_4	S	Q_3
Low-voltage dual-source boost mode (ES2 to ES1, $x_1=0, x_2=0$)	S_{ES1}, S_{ES2}	Q_1, Q_2, Q_4	Q_3	S
System shutdown	-	S_{ES1}, S_{ES2} Q_1, Q_2, Q_3, Q_4	-	-

CONDUCTION STATUS OF DEVICES FOR DIFFERENT OPERATING MODES

2.1. Low-Voltage Dual-Source-Powering Mode

Fig. 2.2 shows The circuit diagram and steady-state waveforms illustrate the converter operating under the low-voltage dual-source-powering mode. In this mode, switch S is OFF while SES1 and SES2 are ON, allowing the two low-voltage sources (VES1, VES2) to supply power to the DC bus and loads. The high-side switches Q1 and Q2 function as synchronous rectifiers (SRs) and the low-side switches Q3 and Q4 actively switch at a 180° phase-shift angle. When the duty ratio exceeds 50%, four circuit states are possible, as shown in Fig. 2.3. The working principle and switch statuses in the low-voltage dual-source mode are:

1. State 1 [t0 < t < t1]: In this state, Q1 and Q3 are ON while Q2 and Q4 are OFF for an interval of (1-Du)Tsw. Current iL1 decreases linearly from its initial value because the voltage across L1 equals the difference between the lower source voltage VES1 and the charge-pump voltage VCB. Meanwhile, source VES2 charges inductor L2.

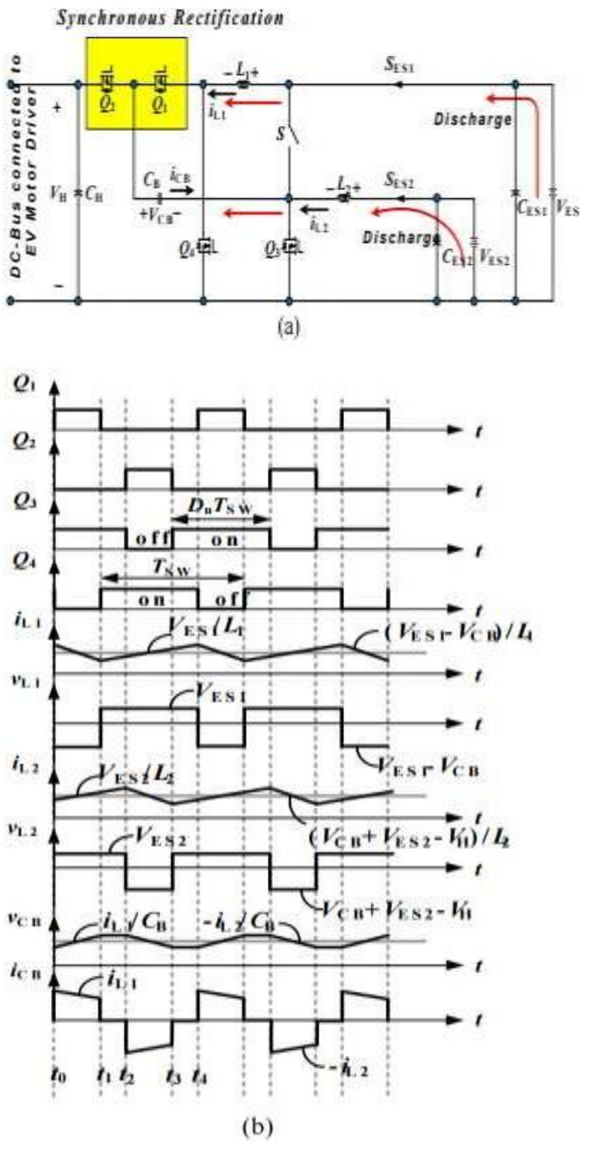

Fig. 2.2. Low-voltage dual-source-powering mode of the proposed BDC: (a) circuit schematic and (b) steady-state waveforms.

thereby generating a linear increase in the inductor current. The voltages across inductors L1 and L2 can be denoted as

$$L_1 \frac{di_{L1}}{dt} = V_{ES2} - V_{CB} \quad (1)$$

$$L_2 \frac{di_{L2}}{dt} = V_{ES2} \quad (2)$$

State 2 [t1 < t < t2]: During this state, the interval time is (Du-0.5)Tsw; switches Q3 and Q4 are turned on; and switches Q1 and Q2 are turned

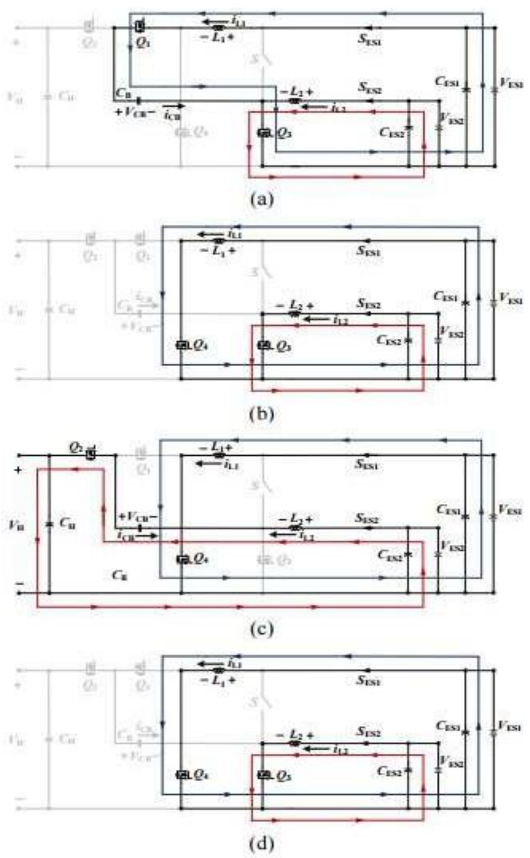

Fig. 2.3 Circuit states of the proposed BDC for the low-voltage dual-source-powering mode. (a) State 1. (b) State 2. (c) State 3. (d) State 4.

a) off. The low-side voltages VES1 and VES2 are located between inductors L1 and L2, respectively, thereby linearly increasing the inductor currents, and initiating energy to storage. The voltages across inductors L1 and L2 under state 2 can be denoted as

$$L_1 \frac{di_{L1}}{dt} = V_{ES1} \qquad (3)$$

$$L_2 \frac{di_{L2}}{dt} = V_{ES2} \qquad (4)$$

b) State 3 [t2 < t < t3]: During this state, the interval time is (1-Du)Tsw; switches Q1 and Q3 are turned on, whereas switches Q2 and Q4 are turned off. The voltages across inductors L1 and L2 can be denoted as

$$L_1 \frac{di_{L1}}{dt} = V_{ES1} \qquad (5)$$

$$L_2 \frac{di_{L2}}{dt} = V_{CB} + V_{ES2} - V_H \qquad (6)$$

c) State 4 [t3< t <t4]: During this state, the interval time is (Du-0.5)Tsw; switches Q3 and Q4 are turned on, and switches Q1 and Q2 are turned off. The voltages across inductors L1 and L2 can be denoted as

$$L_1 \frac{di_{L1}}{dt} = V_{ES1}$$

$$L_2 \frac{di_{L2}}{dt} = V_{ES2}$$

2.2. High-Voltage DC-Bus Energy-Regenerating Mode :

In the High-Voltage DC-Bus Energy-Regenerating mode, during regenerative braking operation, the kinetic energy stored in the motor drive is fed back to the source. The absorbed power of the battery is lower than the regenerative power. Consequently, the excess energy is utilized to charge the energy storage device. The high-voltage dc bus energy-regenerating mode circuit diagram and the steady-state waveforms of the BDC are found in Fig.4.4.

In that, the switches Q1 and Q2 is utilized to control the current in the inductors, which have a phase-shift angle of 180°. The current in the inductor directly flow away from the dc-bus and toward the dual energy storage devices. To improve the conversion efficiency, the switches Q3 and Q4 worked as the SR. Based on the steady-state waveforms appeared in Fig. 4.4(b), when the duty ratio is below 50%, four different circuit states are possible, as found in Fig. 4.5. The operating principle and the ON-OFF status of the switches of the BDC in high-voltage dc-bus energy-regenerating mode, the operation can be explained briefly as follows.

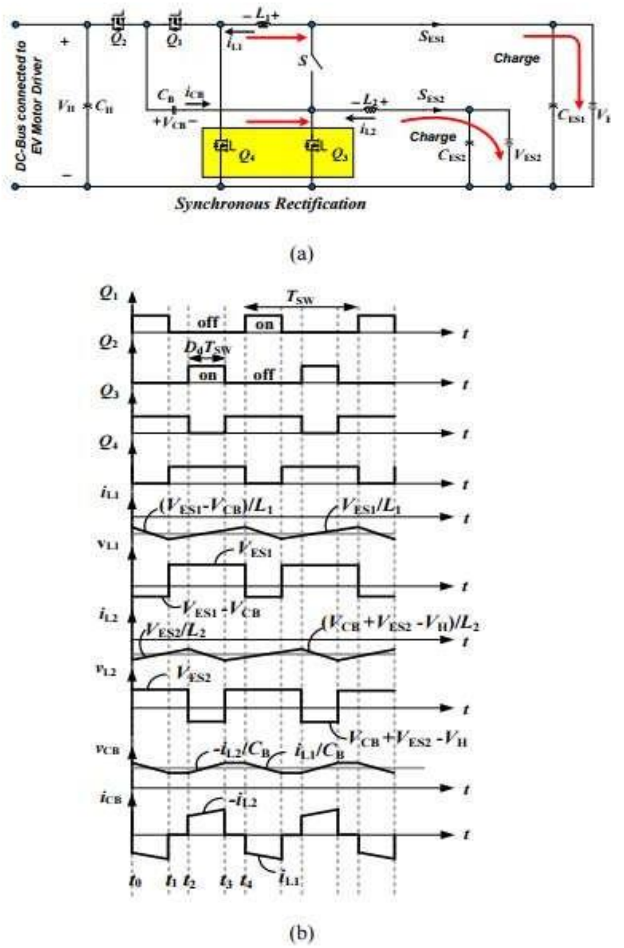

Fig.2.4. High-voltage dc-bus energy-regenerating mode of the proposed BDC: (a) circuit schematic and (b) steady-state waveforms.

3. FUZZY CONTROLLER:

The word Fuzzy means vagueness. Fuzziness occurs when the boundary of piece of information is not clear-cut. In 1965 Lotfi A. Zahed propounded the fuzzy set theory. Fuzzy set theory exhibits immense potential for effective solving of the uncertainty in the problem. Fuzzy set theory is an excellent mathematical tool to handle the uncertainty arising due to vagueness. Understanding human speech and recognizing handwritten characters are some common instances where fuzziness manifests.

Fuzzy set theory is an extension of classical set theory where elements have varying degrees of membership. Fuzzy logic uses the whole interval

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between 0 and 1 to describe human reasoning. In FLC the input variables are mapped by sets of membership functions and these are called as "FUZZY SETS".

Fuzzy set comprises from a membership function which could be defines by parameters. The value between 0 and 1 reveals a degree of membership to the fuzzy set. The process of converting the crisp input to a fuzzy value is called as "fuzzificaton." The output of the Fuzzier module is interfaced with the rules. The basic operation of FLC is constructed from fuzzy control rules utilizing the values of fuzzy sets in general for the error and the change of error and control action. Basic fuzzy module is shown in fig.5

The results are combined to give a crisp output controlling the output variable and this process is called as "DEFUZZIFICATION."

4.1 MATLAB CIRCUITS:

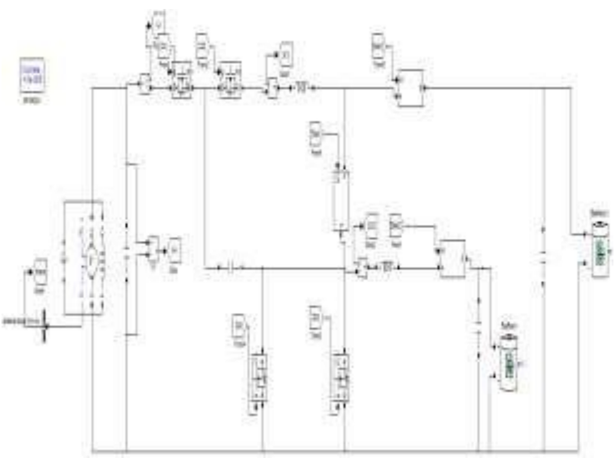


Fig4.1 Simulation Block Diagram

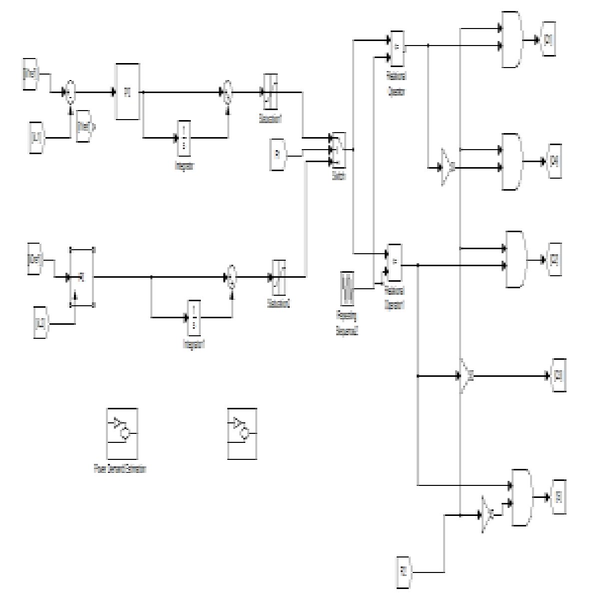


Fig4.2 Simulation Control Diagram

4.2 WAVE FORMS:

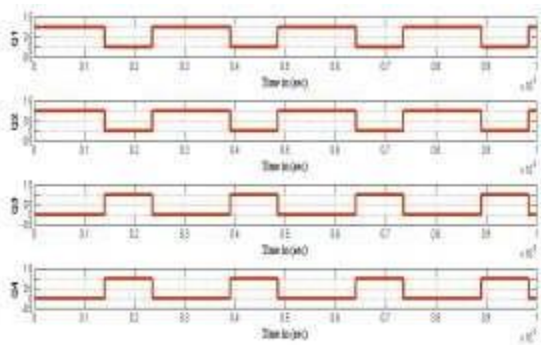
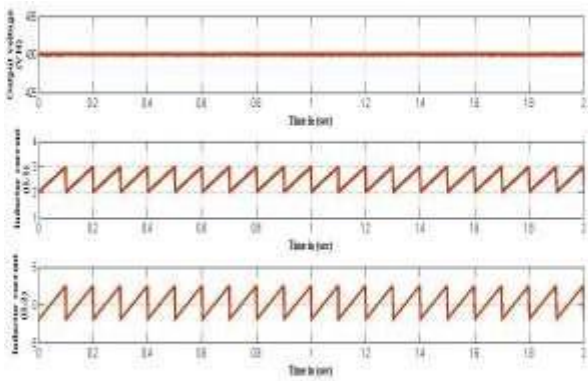


Fig. 4.3. Measured waveforms for low-voltage dual-source-powering mode:(a) gate signals



(b) output voltage and inductor currents.

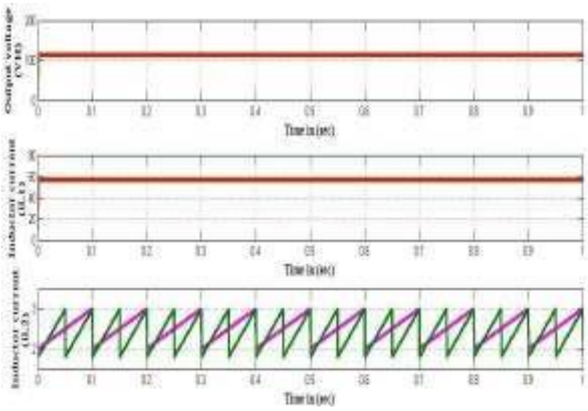


Fig. 4.4. Measured waveforms for high-voltage dc-bus energy-regenerating mode:.

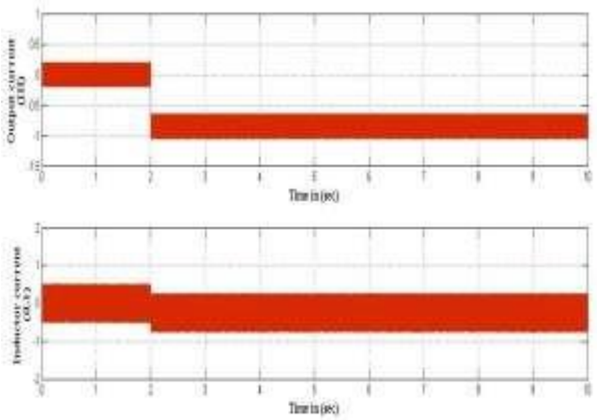


Fig.4.5. Waveforms of controlled current step change in the low-voltage dual-source-powering mode by simulation

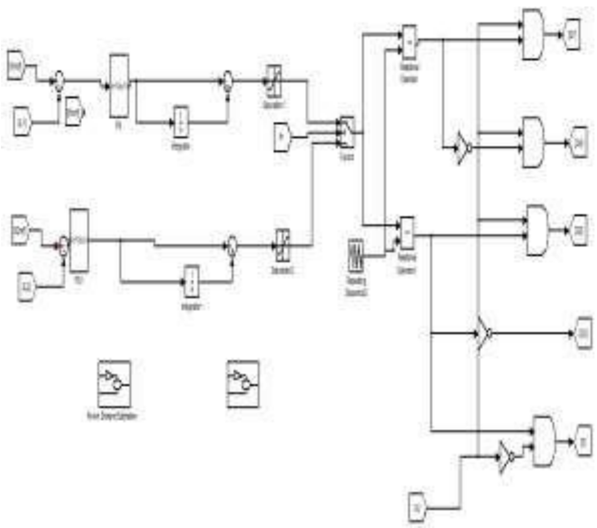


Fig4.6 Simulation of fuzzy logic Control Diagram

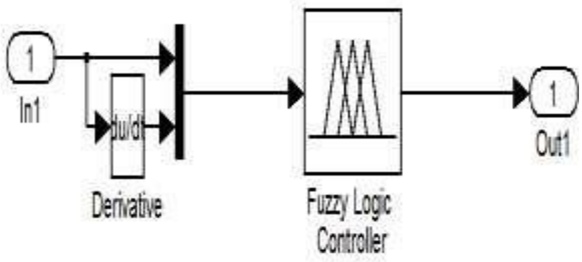


Fig4.7 fuzzy logic Controller

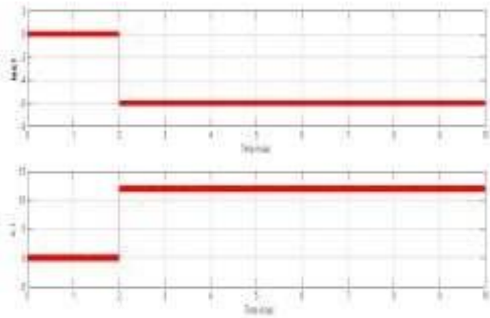


Fig. 4.8 Waveforms of controlled current step change in the low-voltage dual-source boost mode: by simulation;

CONCLUSION

A new bi-directional converter (BDC) topology was introduced to connect dual battery energy sources to a high-voltage DC bus with various voltage levels. The paper discussed the circuit design, operating principles, analyses, and static voltage gains of the proposed BDC, based on different power transfer methods. Simulation waveforms for a 1 kW sample system demonstrated the feasibility of this proposed BDC topology. The converter achieved maximum efficiency of 97.25% for the high-voltage DC-bus energy-regenerative buck mode, 95.32% for the low-voltage dual-source powering mode, 95.76% for the low-voltage dual-source boost mode (from ES2 to ES1), and 92.67% for the low-voltage dual-source buck mode (from ES1 to ES2). The results show that the proposed BDC can be effectively applied in fuel cell/hybrid electric vehicle systems to enable hybrid power architectures.

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AUTHORS:

Dr. Bapayya Naidu Kommula received B.Tech. degree in Electrical and Electronics Engineering from JNTU Hyderabad, India, M.Tech. degree in Advanced Power Systems from JNTU Kakinada and Ph.D. from JNTU Kakinada, India in 2019.His research interests research interests include Power Electronics and Drives, Electric Vehicles, Smart Grid, Renewable Energy Sources. He is an active member of IEEE and IAENG. He has published around 28 papers in International journals and International Conferences.

Name :Kunapureddy Veera Venkata Satya Sai. Course: Btech Electrical & Electronics Engineering.

Intrested subjects: Power Systems, Electric Vehicles, Electrical Machines.
College: Aditya University

Name : Ganja Satish
Course: Btech Electrical & Electronics Engineering.
Intrested subjects:Renewable Energy Systems, Electric Vehicles,Control Systems
College: Aditya University

Name : Yilla Gangadhara Siva Surya
Course: Btech Electrical & Electronics Engineering.
Intrested subjects: Microprocessor and microcontroller, Digital Electronics, Electric Vehicles,
College: Aditya University

Name : Kasibatta Gowtham
Course: Btech Electrical & Electronics Engineering.
Intrested subjects: Power Electronics, Electrical Machines, Electric Vehicles.
College: Aditya University.