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Design Implementation of a Power Electronic Bidirectional DC/DC converter Interface with Dual Battery Energy Storage for Hybrid Electric Vehicle System using Fuzzy Controller

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Abstract: *Power Electronic Interface plays a very important role in clean vehicle technologies. This paper proposes a unique bidirectional dc-dc converter, which can interface main energy storage (ES1) and auxiliary energy storage (ES2), and also dc bus of different voltage levels for numerous applications in hybrid electric vehicle systems. This proposed topology is capable of delivering power from low voltage dual source to dc link i.e Powering mode known as Step Up mode and also delivering power from high voltage dc link to dual source i.e regenerating mode known as Step Down mode. Additionally, the proposed system can control power flow between any two low voltage sources known as buck and boost mode. The proposed topology and its control strategy are designed and analyzed for 1kw prototype system using MATLAB/Simulink. The simulation results related to this are presented and discussed.*

Keywords: *Bidirectional dc/dc converter (BDC), dual battery storage (ES1 & ES2), Fuel Cell Hybrid Electric Vehicle (FCV/HEV).*

I. Introduction

Due to the rising concerns about environmental issues, such as urban pollution and climate change as well as depleting energy resource issues, automobile manufacturers are being forced to shift their attention towards clean vehicle technologies. These days Hybrid Electric Vehicle can be an alternative to internal combustion engine vehicles due to advancement in battery technologies, power electronic interface and control strategies. Hybrid Electric Vehicles can provide better solution to reduce the environmental impact of transports because of low emissions and also reduce energy dependency.

In the literature, limited research work on integrated power electronic interface (IPEI) has been reported to interface a low voltage energy source to electric motor in electric vehicles & plug in hybrid electric vehicle [5]-[9]. Multi-input and multi output dc-dc converters are investigated for hybrid energy storage systems [10]-[12]; however these converters are not able to provide isolation between HV dc-link, HV traction battery & LV loads. In addition, these topologies require more components and have lower efficiency in comparison to stand alone converters. Three port isolated resonant and non resonant dc-dc converters are investigated for potential onboard charging in PEVs [13]-[15]. However, they are not suitable for vehicle to grid application due to their unidirectional operation. Moreover these topologies are not able to provide high voltage gain. Schaltz et al. sufficiently divide the load power among the fuel cell stack, the battery & the ultra capacitors based on two proposed energy management strategies [4]. Thounthong et al. studied the influence of fuel cell (FC) performance and the advantages of hybridization for control strategies [3]. Battery storage devices helps in improving the slow response time for fuel cell stack by supplying peak power during accelerating the vehicle [1]. Ehsani et al. reviewed the vehicle dynamics to achieve optimal torque speed characteristics of electric propulsion system. Super-capacitors which are high power density component reduce peak power transients during accelerating and regenerative braking [16]. It means super-capacitors can store regenerative energy during deceleration & release it during acceleration, & thus supplies an additional power.

A typical schematic diagram for a FCV/HEV is illustrated in fig 1. The fuel cell (LV) stack is used as main power source, and the super capacitors are directly connected in parallel with it. The dc-dc converter is used to convert the fuel cell stack voltage into a sufficient dc bus voltage which goes to inverter & helps in supplying power to propulsion motor. Here the main battery storage device (ES1) is used for supplying peak power and ES2 can be used as an auxiliary battery storage device. The function of bidirectional dc/dc converter (BDC) is to interface dual battery storage with dc bus of the driving inverter. Fuel cell stack and battery storage devices have different voltage levels. These bidirectional DC-DC converters can be of isolated & non-isolated types.

The manuscript proposes a new BDC topology for FCV/HEV power systems. It consist of two operating mode; lower voltage powering mode and a high voltage regenerating mode. Apart from this, the proposed topology can independently control power flow between any two low voltage sources known as buck/boost mode. The proposed system presents a detailed analysis of all f its operation modes with its experimental results. This can operate over a wide range of voltage levels.

The main objectives of this proposed converter are as follows:

1) Controls power flow between dc bus & the two low voltage sources
2) It also independently controls power between the two low voltage sources.
3) Interfaces more than two dc sources for different voltage levels.
4) It produces a voltage difference that is desired between its high & low side within reasonable duty cycle.
5) The reduced switch voltage stress is due to the increased voltage gain.
6) Oscillations can be reduced using fuzzy controller.

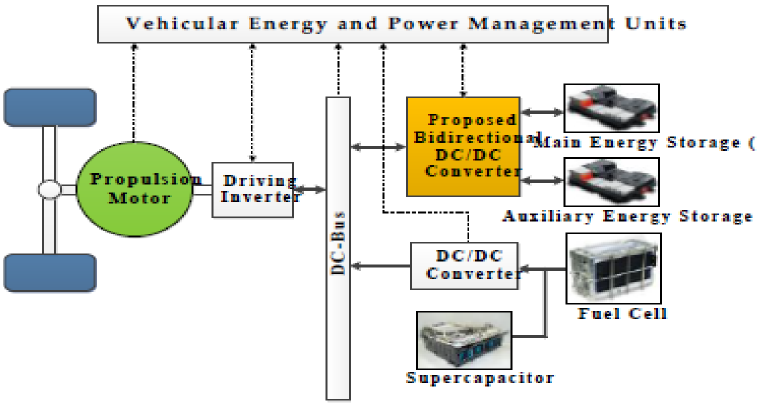


Fig 1: Typical schematic diagram for a FCV/HEV power system.

This manuscript is organized as follows:

Converter topology and operating modes are presented in section II. Section III presents the converter control scheme using fuzzy controller. The simulation & experimental results are presented in section IV. Section V gives the conclusion of this study.

II. Topology And Operation Mode

The proposed bidirectional DC-DC topology with dual-battery energy storage is shown in Fig. 2, where VH, VES1, and VES2 represent the high-voltage dc-bus voltage, the main energy storage (ES1), and the auxiliary energy storage (ES2) of the system, respectively. A charge-pump capacitor (CB) is used as a voltage divider with four active switches (Q1, Q2, Q3, Q4) and two phase inductors (L1, L2) to improve the static voltage gain between the two low-voltage dual sources (VES1, VES2) and the high-voltage dc bus (VH) in the proposed converter. Two bidirectional power switches (SES1 and SES2) in the converter structure, are used to switch on or switch off the current loops of ES1 and ES2, respectively. Here, CB reduces the switch voltage stress of active switches and hence no need to operate at an extreme duty ratio. Three bidirectional power switches (S, SES1, SES2) in Fig. 2 control the power flow between two low-voltage dual sources (VES1, VES2) and to block either positive or negative voltage. This bidirectional power switch is implemented via two metal-oxide-semiconductor field-effect transistors (MOSFETs), pointing in opposite directions, in series connection.

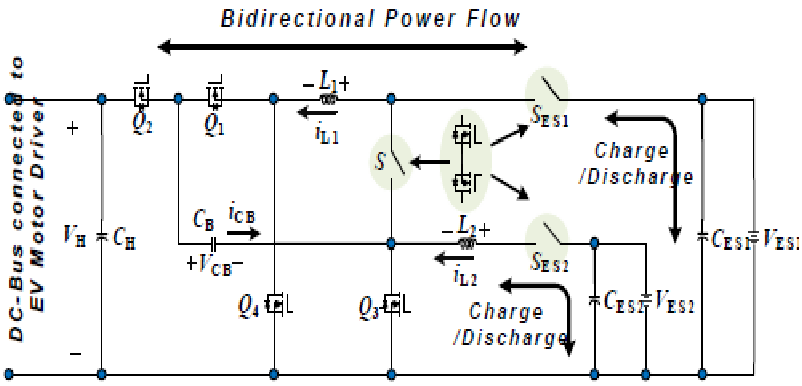


Fig. 2. Proposed BDC topology with dual-battery energy storage.

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	--	--

Table1: Conduction status of devices for different operating modes.

The four operating modes are as follows:

1] Low Voltage Dual Source Powering Mode:

Fig 3(a) & 3(b) shows the circuit and waveforms for this mode respectively. Here the switch S is turned off and the switches SES1, SES2 are turned on and the low voltage dual sources are supplying energy to dc bus and load. This mode can be explained in four states as follows:

a) State 1 [t0 < t < t1]: In this state Q1 & Q3 are turned on & Q2 & Q4 are turned off. In this state inductor current iL1 decreases linearly from its initial value whereas iL2 increases.

b) State 2 [t1 < t < t2]: In this state Q3 & Q4 are turned on & Q1 & Q2 are turned off. In this state inductor current iL1 and iL2 increases.

c) State 3 [t2 < t < t3]: In this state Q2 & Q4 are turned on & Q1& Q3 are turned off. In this state inductor current iL1 increases linearly from its initial value whereas iL2 decreases.

d) State 4 [t3< t <t4]: In this state Q3 & Q4 are turned on & Q1 & Q2 are turned off. In this state inductor current iL1 and iL2 increases.

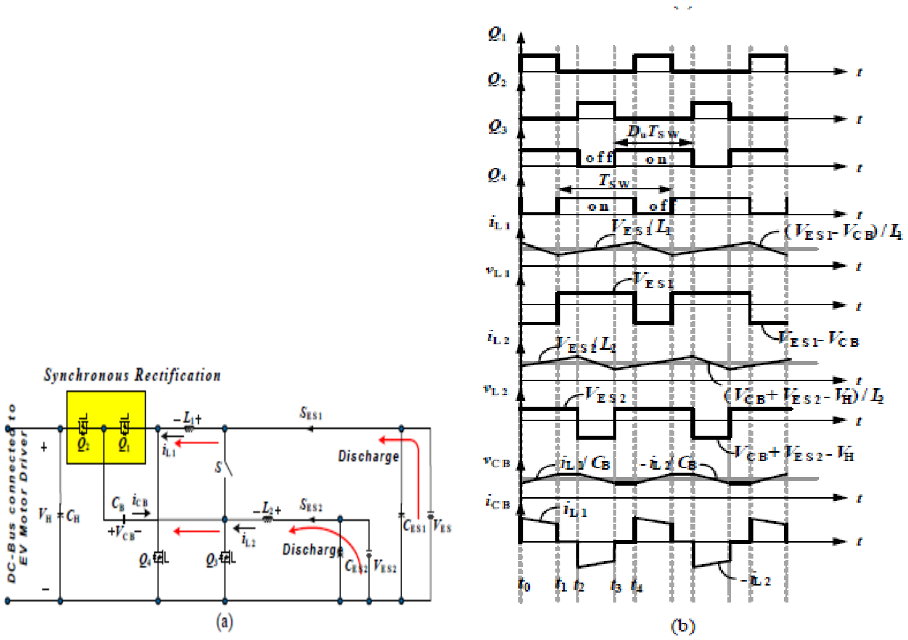


Fig 3: Low voltage dual source powering mode (a) Circuit diagram (b) Waveforms

2] High Voltage DC Bus Energy Regenerating Mode:

Fig 4(a) & 4(b) shows the circuit and waveforms for this mode respectively. Here the switch S is turned off and the switches SES1, SES2 are turned on and the kinetic energy stored in motor drive during braking operation is feedback to the low voltage dual source. This mode can be explained in four states as follows:

a) State 1 [t0 < t < t1]: In this state Q1 & Q3 are turned on & Q2 & Q4 are turned off. In this state inductor current iL1 decreases linearly from its initial value whereas iL2 increases.

b) State 2 [t1 < t < t2]: In this state Q3 & Q4 are turned on & Q1 & Q2 are turned off. In this state inductor current iL1 and iL2 increases.

c) State 3 [t2 < t < t3]: In this state Q2 & Q4 are turned on & Q1& Q3 are turned off. In this state inductor current iL1 increases linearly from its initial value whereas iL2 decreases.

d) State 4 [t3< t <t4]: In this state Q3 & Q4 are turned on & Q1 & Q2 are turned off. In this state inductor current iL1 and iL2 increases.

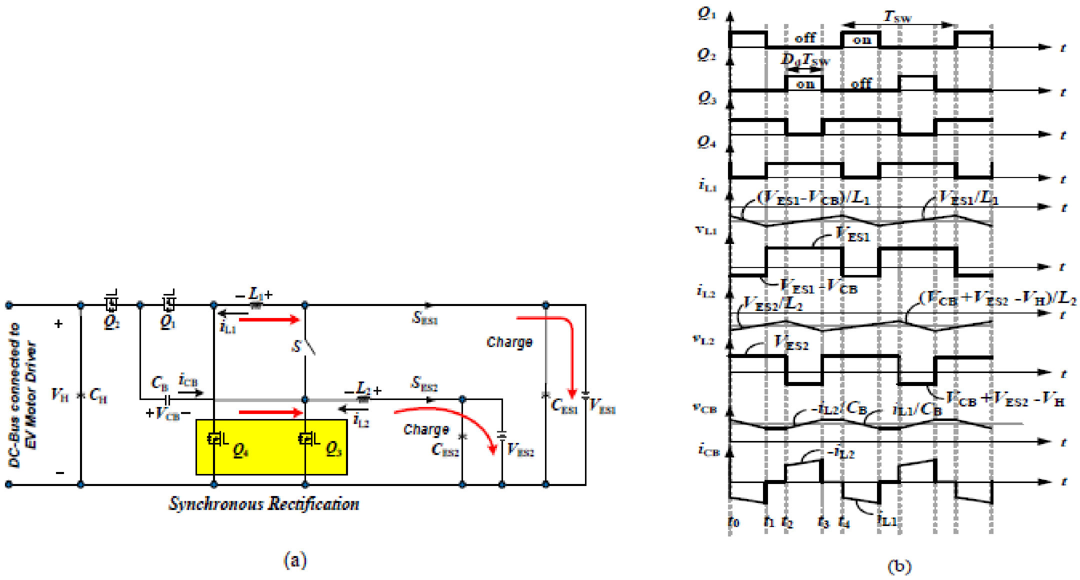


Fig 4: High voltage dc bus regenerating mode (a) Circuit diagram (b) Waveforms

3] Low Voltage Dual Source Buck/Boost Mode:

Fig 5(a) shows the circuit and 5(b) & 5(c) shows waveforms for buck and boost mode respectively. In this state the energy transfer between main energy storage and auxiliary energy storage is observed and vice-versa. When duty cycle of S is controlled then power transfer from main to auxiliary storage takes place indicating converter in buck mode and when duty cycle of Q3 is controlled then vice-versa happens indicating converter in boost mode.

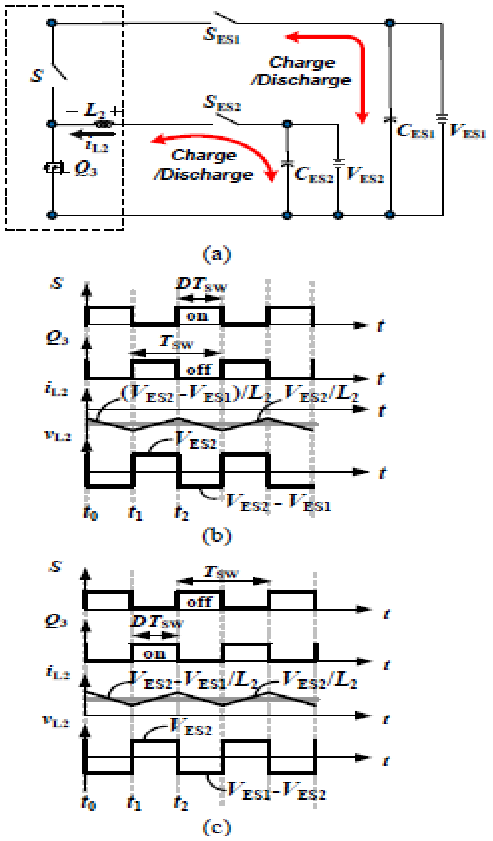


Fig 5: Low voltage dual source Buck/Boost mode (a) Circuit diagram (b) Waveforms for Buck mode (c) Waveforms for boost mode

III. Converter Control

Fig 6 shows the converter control model which indicates vehicular strategic management level and the proposed BDC controller. The strategic management level consists of an electrical power demand estimation and vehicular power and voltage management unit. The inductor current $iL1$ or $iL2$ is detected and compared with the reference current to control the power flow. In the converter control structure, the vehicular energy and power and voltage management unit selects the bidirectional DC/DC converter mode according to the operating conditions of the vehicle, such as power demand of different driving state ($Pdem$) and the dual-source voltages ($VES1$, $VES2$). It then selects the appropriate current references $iL1,ref$ or $iL2,ref$ that can control the active switches (S, $Q1$ to $Q4$) with fuzzy controller. The pulse-width-modulation (PWM) switching scheme converts the duty cycle determined by different switch selectors into gate control signals for the power switches.

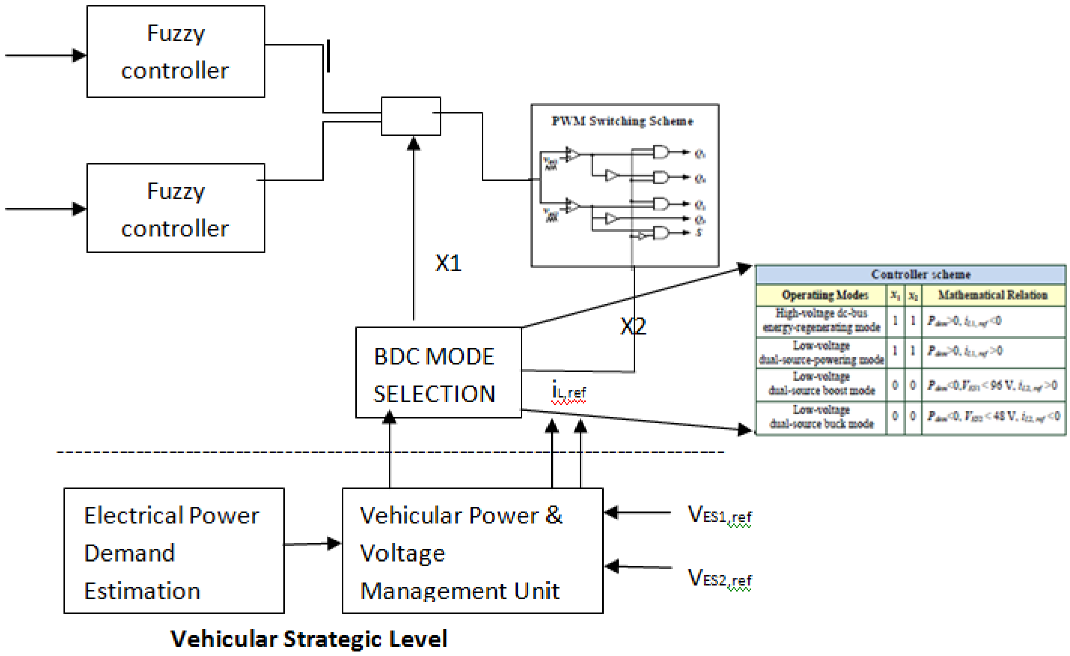


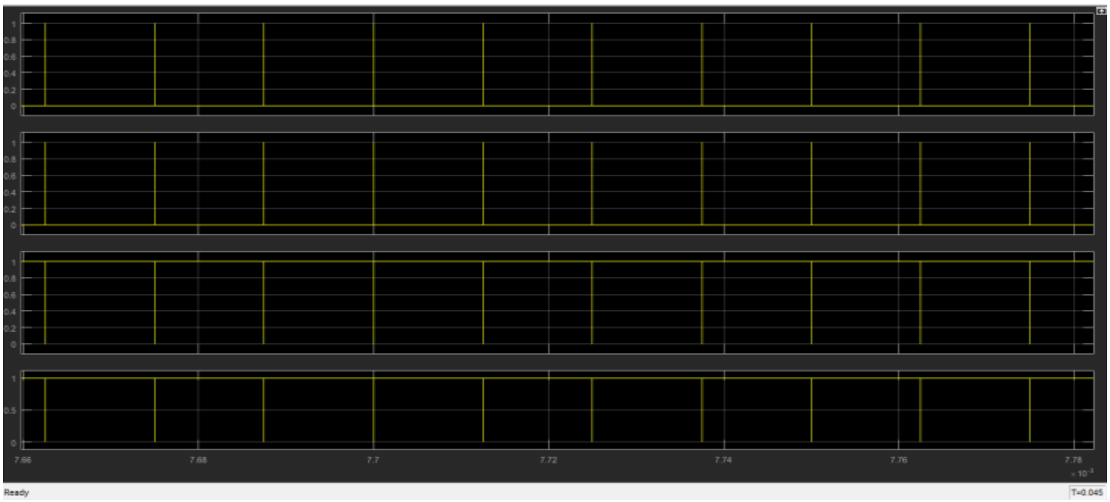
Fig. 6: Block diagram of the closed-loop control scheme

IV. Simulation And Experimental Results

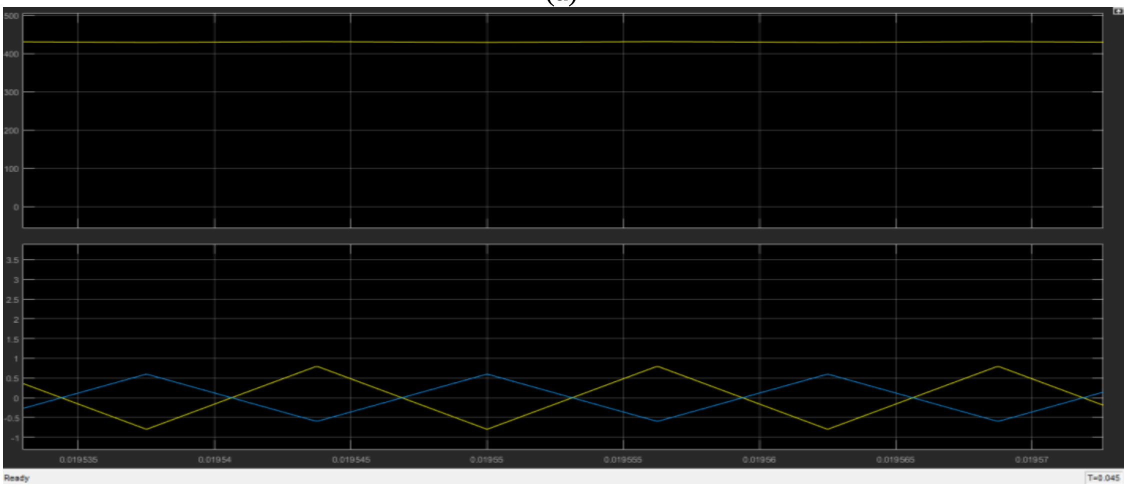
Simulation was conducted for 1kw prototype and the performance can be viewed from the results. Table II shows the parameters and specification of the proposed system. Both the sources give dc bus voltage of 430 V.

TABLE II.
SPECIFICATIONS AND PARAMETERS OF THE PROTOTYPE SYSTEM

Specifications	
ES1 voltage	V_{ES1}: 96 V
ES2 voltage	V_{ES2}: 48 V
DC-bus voltage	V_H: 430 V
Output power	P_o: 1 kW
Switching frequency	f_{SW}: 40 kHz
Parameters	
Inductors	L_1, L_2: CH330060, 250 uH
High-side capacitor	C_H: aluminum capacitor, 1880 µF
Low-side capacitor	C_{ES1}: aluminum capacitor, 400 µF C_{ES2}: aluminum capacitor, 400 µF
Charge-pump capacitor	C_B: film capacitor, 10 µF
Switches	S, S_{ES1}, S_{ES2}: IXFK360N15T2 Q_1, Q_4, Q_2, Q_3: W45NM60

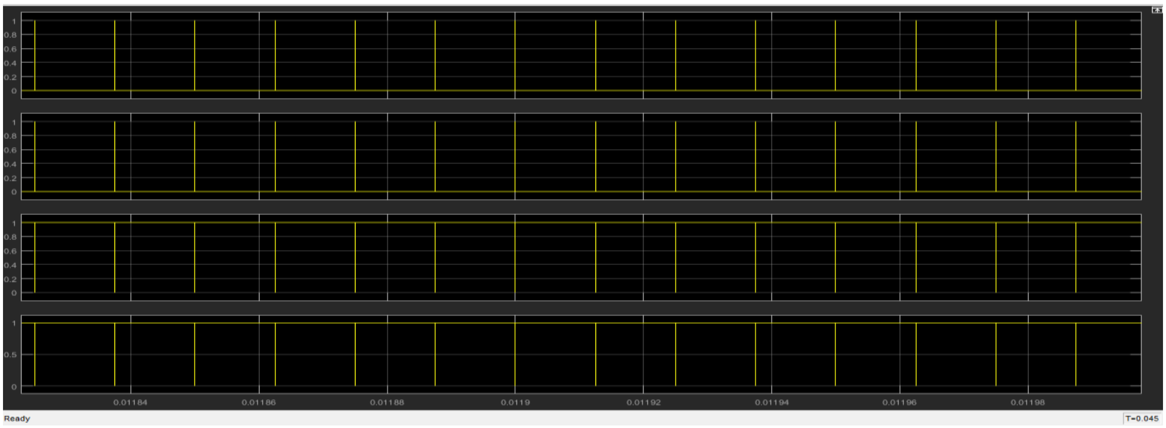


(a)

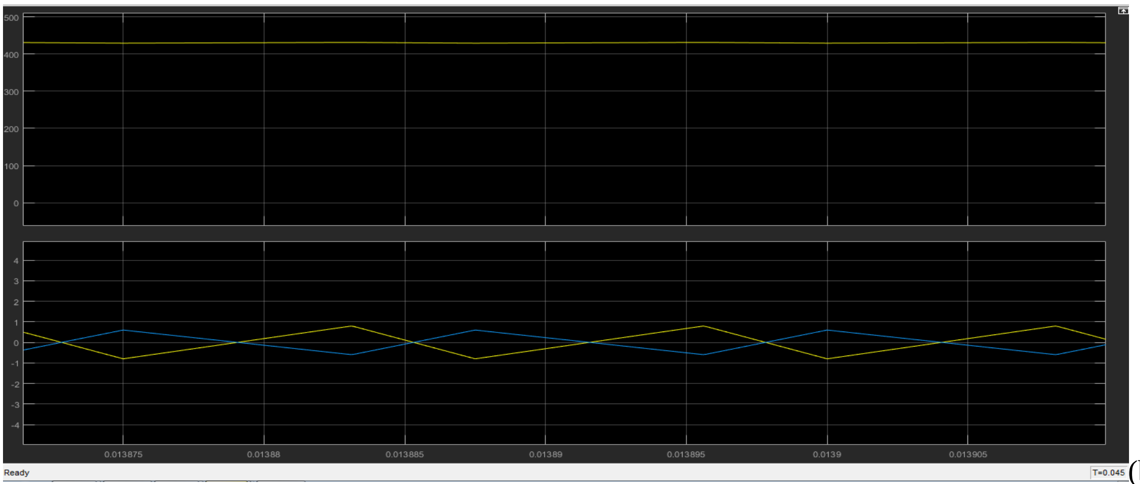


(b)

Fig. 7.Measured waveforms for low-voltage dual-source-powering mode: (a) gate signals; (b) output voltage and inductor currents.

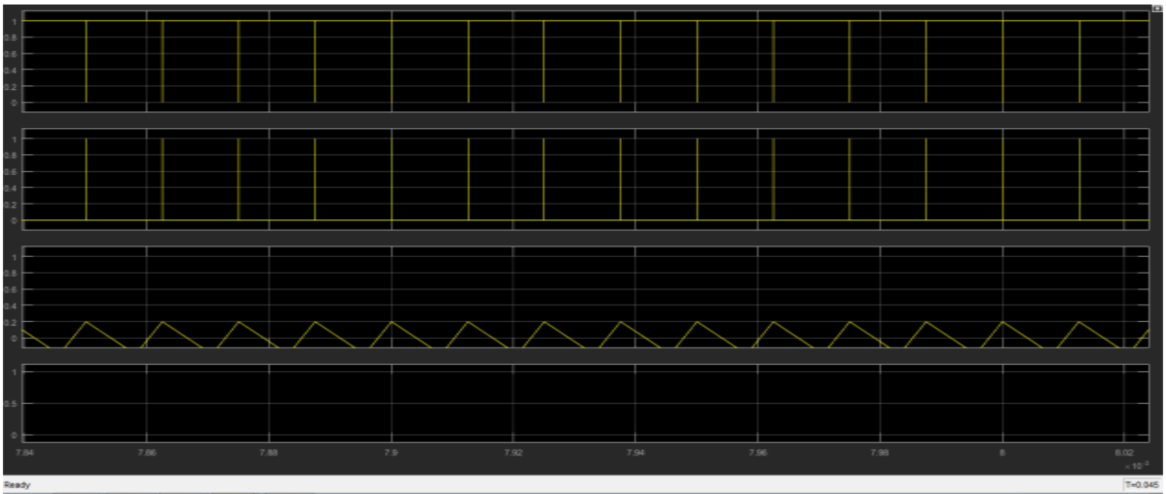


(a)

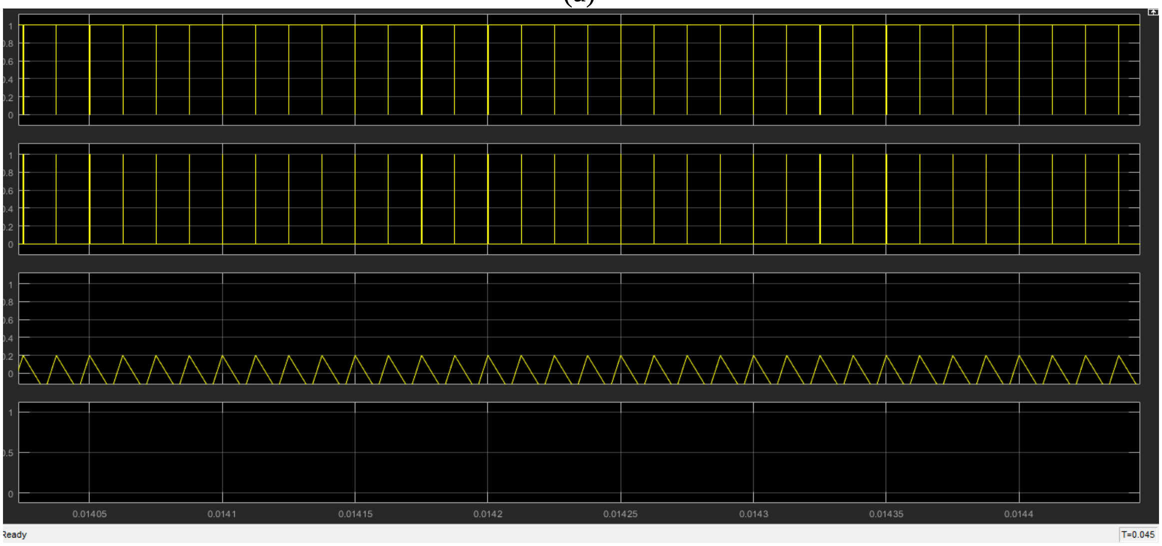


(b)

Fig.8. Measured waveforms for high-voltage dc-bus energy-regenerating mode: (a) gate signals; (b) output voltage and inductor currents.



(a)



(b)

Fig. 9. Measured waveforms of gate signals, output voltage and inductor currents for the low-voltage dual-source buck/boost mode: (a) buck mode; (b) boost mode.

V. Conclusion

A Bidirectional DC-DC converter has been developed which interfaces low voltage dual energy storage and high voltage dc bus and also permits energy transfer between low voltage dual sources. The circuit diagram and its various operating modes are studied and explained in detail along with its simulation results using fuzzy controller and it can be observed that oscillations are reduced using this controller. Higher efficiencies can be achieved using this proposed model and can be applied in Hybrid Electric Vehicle System.

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