FUZZY LOGIC-ENABLED BIDIRECTIONAL DC-DC CONVERTER WITH HIGH VOLTAGE GAIN FOR EV BATTERY CHARGING AND REGENERATIVE BRAKING

PATLOLLA SWATHI, Dr. P. DURAIPANDY
M.Tech Student, Associate Professor
DEPT OF EEE Department of Electrical & Electronics Engineering
J.B. Institute of Engineering & Technology, R.R. District, Telangana

ABSTRACT
This research presents a novel non-isolated high gain bidirectional DC-DC converter (BDC) and its application in integrating an energy storage system with an electric vehicle (EV). The proposed converter achieves high voltage gain through dual-duty cycle operation while employing fewer components, eliminating the need for voltage multiplier cells or hybrid switched-capacitor approaches. A fuzzy logic controller (FLC) is introduced to enhance the system's dynamic response and efficiency under varying driving conditions. The converter powers the motor during forward motoring mode and facilitates regenerative braking, transferring energy back to the battery. Simulation and performance analysis are conducted using MATLAB/Simulink. Results demonstrate improved voltage regulation, reduced current ripple, and higher efficiency compared to conventional PID-controlled systems. The fuzzy logic controller optimizes power flow, ensuring seamless transitions between motoring and braking modes while maximizing energy recovery. The proposed system is validated for its viability in EV applications, offering a compact, efficient, and robust solution for bidirectional power conversion.

INDEX TERMS: bidirectional DC–DC converter, high voltage gains, electric vehicle, regenerative braking, battery charging, fuzzy logic control.

I.INTRODUCTION

Governmental bodies and organizations are enforcing stricter limits for fuel consumption and emissions due to the rising rate of oil consumption in the transportation sector, as well as growing concerns over the impact of global warming and the depletion of energy resources. By 2040, it is predicted that the yearly sales of EVs and Hybrid Electric Vehicles (HEVs) would surpass those of petrol and diesel vehicles, with sales of over 48 million [1]. The automobile industry is concentrating on the development of new technologies for the power train, battery, and charging infrastructure in response to the rising demand for vehicles with better fuel efficiency and less impact on the environment. The installation of a high-energy battery pack and regenerative braking aid in extending the driving range and battery life of electric vehicles.

Power electronic converters find its application in drivetrain to modulate the power flow from battery to the propulsion motors and to facilitate regenerative braking in the reverse direction. To increase efficiency and power density, the drivetrain motor and propulsion inverter are made to operate at higher voltage [2]. To raise the battery voltage to the desired level, a boost converter is used. It also enhances the overall performance of the drivetrain by delinking the battery voltage and the inverter dc link voltage [3]. The DC-DC converter must be bidirectional because the forward mode will face transient and overload conditions during which power gets transferred from the battery to load and during the reverse mode, the battery pack has to get charged. Some of the benefits derived by providing a BDC between the battery and the inverter [4], [5] are: a) It reduces the stress on the inverter with an additional DC stage b) It adjusts the inverter supply voltage to increase the motor output, c) The cost and size of the battery can be reduced because of lower cell count requirement and d) The system voltage and battery can be individually designed by the manufacturers. This architecture thus enables versatile system designs for vehicles with various output characteristics. For instance, the battery nominal voltage in the 2010 Toyota Prius is about 200 V, while the DC-DC converter raises the voltage of the dc bus to about 650 V [2].

The most common BDC is the one with an isolated framework [2], [6] to [11]. These isolated converters employ the high frequency transformer throughout the operation, increasing its losses and volume. Transformer core saturation [25] is another issue with this kind of converter. Additionally, many isolated converter configurations, such as LLC converters, CLLC converters and dual-active-bridge (DAB) converters, which are the most prevalent kind of isolated BDCs, call for a significant number of active switches [10], [11]. Therefore, no isolated BDCs are typically preferred when isolation is not mandatory. This is as a result of its simple structure and low component count, which draw the attention of several researchers. They are suitable for some applications, such as the drive train of an electric vehicle, where size and weight are crucial considerations.

To attain high conversion ratios, non-isolated BDCs employ many circuit principles, including SEPIC/Cuk/Zeta, voltage multiplier cells, switching capacitors, and linked inductors. Due to their cascaded construction, SEPIC/Cuk/Zeta converters have a low efficiency and higher voltage stress. BDCs can be designed using voltage multiplier cells; however, this is restricted by the high voltage across switches. BDCs [12] to [14] utilize switched capacitors that perform better, have a simpler construction, and require less control complexity. However, for high-gain applications, the circuit becomes progressively complex and is susceptible to losses with the growing number of switches and capacitors.

The system efficiency can be increased with hybrid topologies, but there is insufficient voltage gain and a greater ripple current [15] associated with few of these topologies. However, high conversion factors can be attained using hybrid architectures like SEPIC/quasi-Z source with switched capacitors [16], [17]. Conversion efficiency is nonetheless limited by a high component count and its inability to provide soft switching. Large ripple current at the LV side is a prevalent issue with all high gain non-isolated BDC circuits as it shortens the life and degrade the performance of the battery. Large capacitors can control input ripple current [18], but this is not preferred as the capacitor adds bulk and expense to the system. Interleaved DC-DC converter is a better option to reduce the input current ripple, but it has a lower voltage gain and more components [19].

The transportation sector is undergoing a significant transformation driven by stringent environmental regulations, rising fuel costs, and the global push toward sustainable energy solutions. Electric vehicles (EVs) have emerged as a key technology to reduce greenhouse gas emissions and dependence on fossil fuels. However, the widespread adoption of EVs depends on improving their energy efficiency, driving range, and battery management systems. A critical component in achieving these goals is the bidirectional DC-DC converter, which facilitates efficient power flow between the battery, motor, and regenerative braking system.

Traditional bidirectional DC-DC converters face challenges such as limited voltage gain, high component count, and control complexity, particularly in applications requiring high efficiency and dynamic response. While conventional controllers like Proportional-Integral-Derivative (PID) have been widely used, they often struggle with nonlinearities, parameter variations, and transient conditions inherent in EV power systems. To address these limitations, intelligent control strategies such as fuzzy logic control (FLC) have gained attention due to their ability to handle uncertainty, adapt to varying operating conditions, and improve system robustness.

This paper presents a high-gain bidirectional DC-DC converter (HGBDC) with an advanced fuzzy logic controller for EV applications. The proposed converter achieves superior voltage gain with minimal components, eliminating the need for complex voltage multiplier circuits or coupled inductors. The integration of FLC enhances dynamic performance, ensuring smooth transitions between motoring and regenerative braking modes while optimizing energy recovery. Key contributions of this work include:

A novel non-isolated HGBDC topology that achieves high voltage gain using dual-duty cycle operation, reducing component count and improving efficiency.

Implementation of a fuzzy logic controller to replace conventional PID control, offering better adaptability to load variations and transient conditions.

Comprehensive analysis of converter performance under different driving scenarios, including acceleration, deceleration, and

regenerative braking, using MATLAB/Simulink.
Validation of energy recovery efficiency, demonstrating the converter's ability to recharge the battery during braking while maintaining stable voltage regulation.
This work bridges the gap between high-performance power electronics and intelligent control, offering a scalable solution for next-generation EV powertrains. The proposed fuzzy-controlled HGBDC not only enhances energy efficiency but also extends battery life, contributing to the broader adoption of sustainable transportation technologies.

II.DC-DC CONVERTERS

A DC-DC converter with a high step-up voltage, which can be used in various applications like automobile headlights, fuel cell energy conversion systems, solar-cell energy conversion systems and battery backup systems for uninterruptable power supplies. Theoretically, a dc-dc boost converter can attain a high step-up voltage with a high effective duty ratio. But, in practical, the step-up voltage gain is restricted by the effect of power switches and the equivalent series resistance(ESR) of inductors and capacitors.

Generally, a conventional boost converter is used to get a high-step-up voltage gain with a large duty ratio. But the efficiency and the voltage gain are restricted due to the losses of power switches and diodes, the equivalent series resistance of inductors and capacitors and the reverse recovery problem of diodes. Due to the leakage inductance of the transformer, high voltage stress and power dissipation effected by the active switch of these converters. To reduce the Voltage spike, a resistor-capacitor –diode snubbed can be employed to limit the voltage stress on the active switch. But, these results in reduction of efficiency. Based on the coupled inductor; converters with low input ripple current are developed. The low input current ripple of these converters is realized by using an additional LC circuit with a coupled inductor.

III.ELECTRIC VEHICLE

An **electric vehicle**, also called an **EV**, uses one or more electric motors or traction motors for propulsion. An electric vehicle may be powered through a collector system by electricity from off-vehicle sources, or may be self-contained with a battery, solar panels or an electric generator to convert fuel to electricity.[1] EVs include, but are not limited to, road and rail vehicles, surface and underwater vessels, electric aircraft and electric spacecraft.

EVs first came into existence in the mid-19th century, when electricity was among the preferred methods for motor vehicle propulsion, providing a level of comfort and ease of operation that could not be achieved by the gasoline cars of the time. Modern internal combustion engines have been the dominant propulsion method for motor vehicles for almost 100 years, but electric power has remained commonplace in other vehicle types, such as trains and smaller vehicles of all types.

In the 21st century, EVs saw a resurgence due to technological developments, and an increased focus on renewable energy. A great deal of demand for electric vehicles developed and a small core of do-it-yourself (DIY) engineers began sharing technical details for doing electric vehicle conversions. Government incentives to increase adoptions were introduced, including in the United States and the European Union

IV.FUZZY LOGIC

In recent years, the number and variety of applications of fuzzy logic have increased significantly. The applications range from consumer products such as cameras, camcorders, washing machines, and microwave ovens to industrial process control, medical instrumentation, decision-support systems, and portfolio selection.

To understand why use of fuzzy logic has grown, you must first understand what is meant by fuzzy logic.

Fuzzy logic has two different meanings. In a narrow sense, fuzzy logic is a logical system, which is an extension of multivalve logic. However, in a wider sense fuzzy logic (FL) is almost synonymous with the theory of fuzzy sets, a theory which relates to classes of objects with unsharp boundaries in which membership is a matter of degree. In this perspective, fuzzy logic in its narrow sense is a branch of fl. Even in its narrower definition, fuzzy logic differs both in concept and substance from traditional multivalve logical systems.

In fuzzy Logic Toolbox software, fuzzy logic should be interpreted as FL, that is, fuzzy logic in its wide sense. The basic ideas underlying FL are explained very clearly and insightfully in Foundations of Fuzzy Logic. What might be added is that the basic concept underlying FL is that of a linguistic variable, that is, a variable whose values are words rather than numbers. In effect, much of FL may be viewed as a methodology for computing with words rather than numbers. Although words are inherently less precise than numbers, their use is closer to human intuition. Furthermore, computing with words exploits the tolerance for imprecision and thereby lowers the cost of solution.

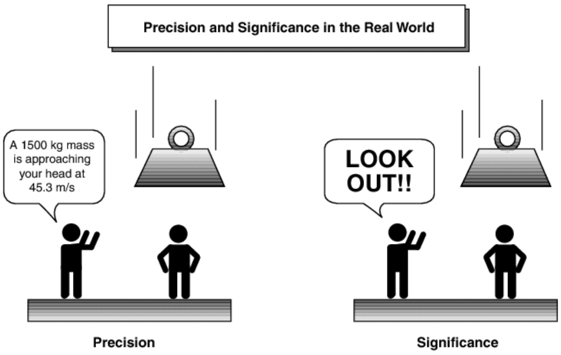

Fig. 1 Fuzzy Description

V.PROPOSED HIGH GAIN BIDIRECTIONAL DC-DC CONVERTER (HGBDC)

The proposed HGBDC shown in figure 2 has four active power switches (S1, S2, S3, and S4), two identical inductors (L1 and L2), a diode (D1), and a capacitor (CH) at the high voltage side. Diode D1 helps in blocking the reverse voltage VL appearing across the MOSFET while the switches S1 and S2 are conducting in boost mode. A switching frequency of fs is used by the switches S1, S2, S3, and S4. During boost mode, switches S1 and S2 have a duty ratio of d1, and switch S3 has a duty ratio of d2. The duty ratio of the switch S4 is (1- d1-d2) during boost mode and it is db during buck mode of operation of the converter.

6.1. OPERATION OF THE HGBDC IN BOOST MODE

The boost operation of the converter is explained in three different phases namely, Mode I, Mode II and Mode III. The current flow path of the proposed HGBDC operating in boost mode is depicted in figure 2. During this mode, the energy is transferred from the low voltage side to the high voltage side of the converter with the help of controlled switches S1, S2, S3 and S4. The switches S1, S2 and S3 are operated through the PWM control. Typical waveforms of the proposed HGBDC in boost mode for continuous conduction are shown in figure 3.

1) MODE I

The switches S1 and S2 are turned on in this mode (t0, t1), while the switches S3 and S4 are turned off for the duration of d1Ts. Energy flow is from the battery to the inductors L1, L2 which are connected in parallel, as shown in figure 2(a). The energy stored in the capacitor; CH is released to the load. The voltage across the inductors is expressed in (1) to (3).

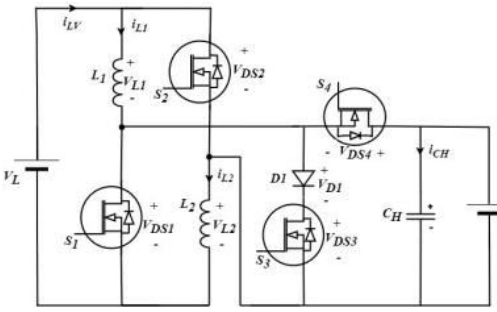

Fig 2. Proposed High Gain Bidirectional DC - DC Converter (HGBDC)

$$v_{L1} = v_{L2} = V_L \quad (1)$$

$$L_1 \frac{di_{L1}}{dt} = L_2 \frac{di_{L2}}{dt} = L \frac{di_L}{dt} = V_L \quad (2)$$

$$\frac{di_L}{dt} = \frac{V_L}{L} \quad (3)$$

where vL1 and vL2 are the voltages across inductors L1 and L2 respectively.

2) MODE II

Switch S3 is active for the duration of d2Ts, while switches S1 and S2 are turned off in Mode II (t1, t2). As displayed in figure 2(b), current flow is through L1, D1, S3 and L2. The energy from the source is delivered to the inductors. The load receives the energy that is stored in the capacitor. Source is in series with the inductors in this mode. Equations (4) and (5) represent the currents flowing through and the voltages across the inductors.

$$i_{L1} = i_{L2} \quad (4)$$

where iL1 and iL2 are the current through inductors L1 and L2 respectively.

$$v_{L1} + v_{L2} = V_L \quad (5)$$

$$v_{L1} = v_{L2} = L \frac{di_L}{dt} \quad (6)$$

$$\frac{di_L}{dt} = \frac{V_L}{2L} \tag{7}$$

3) MODE III

The MOSFET switches S1, S2 and S3 are turned off in this mode (t2, t3), whereas the body diode of the MOSFET S4 conducts during (1-d1-d2) TS. Diode D1 is reverse biased. The load is supplied by both the source and the inductors as depicted in figure 3(c). The capacitor CH is in charging mode as the body diode of S4 is forward biased. The inductors are connected in series to the source. The current through and the voltage across the inductors are given in (8) to (10).

$$i_{L1} = i_{L2} \tag{8}$$

$$v_{L1} + v_{L2} = V_L - V_H \tag{9}$$

$$v_{L1} = v_{L2} = L\frac{di_L}{dt} \tag{10}$$

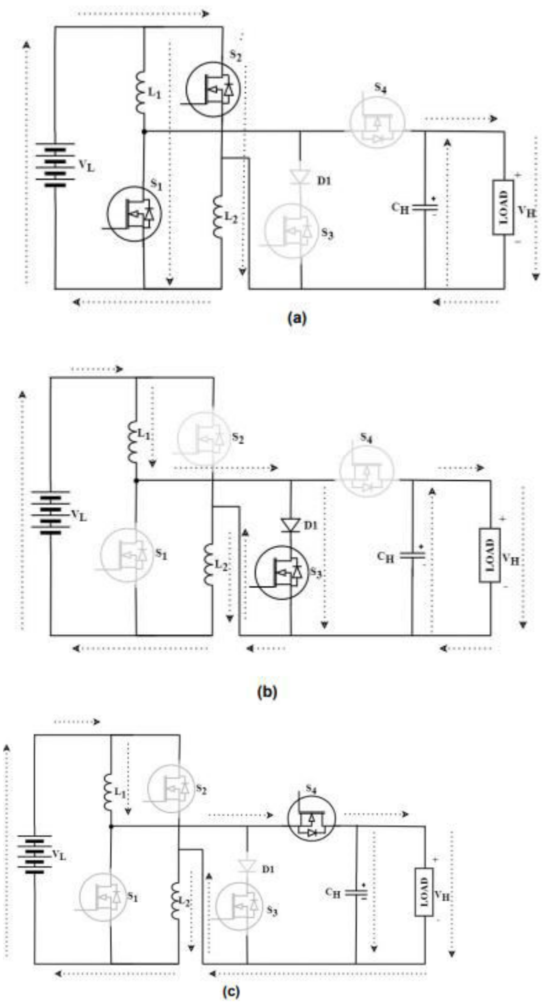

Fig 3. HGBDC in boost mode (a) Mode I (b) Mode II (c) Mode III

6.5. CONVERTER DESIGN AND MOTOR CONTROL

The proposed HGBDC may be used to test its viability for applications like electric automobiles by integrating it into a simple DC motor drive. In this work, the converter is operated in continuous conduction mode to drive the dc motor in forward motoring and regenerative braking modes. The HGBDC is connected to a battery and a dc motor load as shown in figure 4. The light electric vehicle industry makes extensive use of DC motors, which are chosen for their simplicity and to check the viability of the converter operation in the proposed scheme. A 5 HP separately excited DC motor model rated at 240 V and 1750 rpm is utilized as the load to analyse the performance of the HGBDC in both MATLAB/Simulink and the OP4500 real-time simulation mode. The converter specifications are given in Table III. The simulation makes use of the lithium ion (Li-ion) battery, whose specifications are listed in Table IV. The lithium-ion battery has a strong possibility of replacing other batteries as the foreseeable future of electric vehicle batteries. This is due to its fascinating properties including large power density, high energy density, extended life cycle, absence of memory effect, and superior energy efficiency. During regenerative braking, the proposed BDC transfers power from the motor back to the battery, and when the vehicle is moving, it delivers power from the battery to the DC motor.

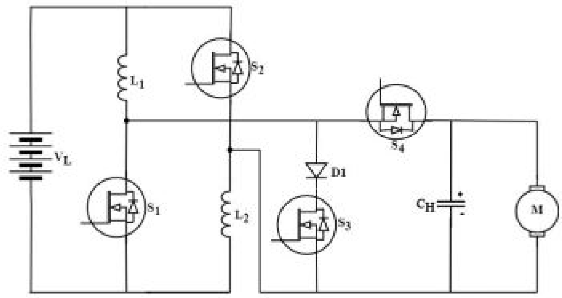

Fig 4. HGBDC connected to battery source and a dc motor load.

TABLE 6.3 CONVERTER SPECIFICATIONS

Parameter	MATLAB/Simulink	RT-LAB
Input Voltage	48V	48V
Output Voltage	240V	240V
Switching Frequenc	50 kHz	5 kHz
Inductor L_1, L_2	200 µH	1000 µH
Capacitor C_H	300 µF	1000 µF
Load (DC motor)	5 HP, 240 V, 1750rpm	5 HP, 240 V, 1750 rpm

TABLE 6.4 BATTERY PARAMETERS

Parameter	Value/Specifications
Type	Li-ion
Nominal Voltage	48 V
Initial %SoC	80
Battery Capacity	140 Ah
Nominal Discharge Current	60.87 A

6.5.4. CONTROL TECHNIQUE

A practical technique for adjusting the speed of the drive is to control the output voltage of the BDC. A Fuzzy controller is used to ensure that the vehicle reaches the target speed and reacts quickly to rapid changes in speed without oscillations. Figure depicts the control circuitry for the HGBDC. It senses the motor speed $\omega motor$ and compares it to the reference speed ωref. The error signal is processed by the fuzzy controller and compared to a high frequency sawtooth signal to generate the PWM control signals.

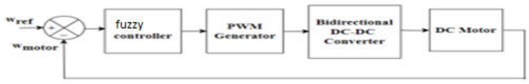

Fig 5. Block diagram of closed loop control scheme

VI.SIMULATION RESULTS

The HGBDC fed DC motor drive is modelled and simulated using MATLAB/Simulink for a duration of 10 seconds. The steady-state inductor current and the gate drive pulses of the MOSFET switches for both boost and buck mode of operations of the converter are shown in figure 10 and figure 11 respectively. In boost (forward motoring) mode, the inductor current increases when the first three switches S1, S2 and S3 are turned on, whereas the current through the inductor decreases when the switch S4 is turned on. As shown in figure 10, the average value of the inductor current in steady state is 32 A. During buck (regenerative braking) mode, the steady-state inductor current is -13.5A. Negative value of the inductor current shows the reversal of current flow from the load to source; hence the power flow. Battery is charged from the regenerative power during this braking mode. For a rated speed of 1750 rpm in forward motoring mode, the duty ratio of the PWM pulses generated by the PWM controller, d1 and d2 for the switches S1/S2 and S3 respectively are 0.455 and 0.245 for a voltage gain of 4.85. During regenerative braking mode, the switch S4 operates with a duty ratio db which is 0.5 and the corresponding voltage gain is 1/3 for a speed of 1150 rpm.

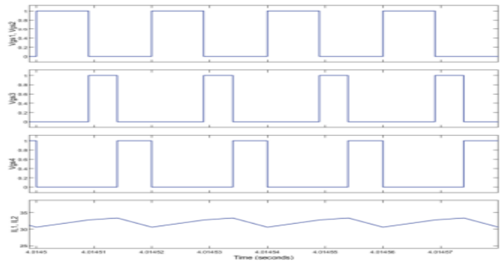

Fig 6. Switching signals for S1, S2, S3, S4 and inductor currents in boost mode of operation.

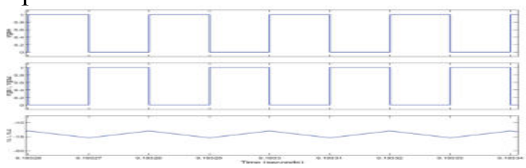

Fig 7. Switching signals for S1, S2, S3, S4 and inductor currents in boost mode of operation.

Two different cases are considered for analysing the dynamics of the system:

(i) transition of the motor operation from forward motoring to regenerative braking.

(ii) a step change in speed during forward motoring.

A. TRANSITION OF THE MOTOR OPERATION FROM FORWARD MOTORING TO REGENERATIVE BRAKING

The converter is made to operate in boost (forward motoring) mode from 0-5 seconds and in buck (regenerative braking) mode from 5–10 seconds. Figure 12 shows the motor speed, armature torque, armature current, armature voltage (output voltage VH) of the converter, battery SoC and battery voltage for this case. Simulations are carried out for the braking action with a speed change from 1750 rpm to 1150 rpm when the motor current and current exhibit a reversal characteristic as shown in figure. The change in directions of current and torque during the transition from motoring mode to regenerative braking mode indicates the reversal of power flow. As seen in figure armature voltage decreases in proportion to the decrease in speed. There is a dip in battery voltage and reduction in SOC of the battery during forward motoring (0 to 5 seconds). But the battery voltage and SoC of the battery increases during regenerative braking as observed in figure 12(e) and 12(f). The SoC of the battery increases by 0.02% from 79.95 to 79.97 during a short span of 5s in regenerative braking mode.

B. A STEP CHANGE IN SPEED DURING FORWARD MOTORING.

A step change in motor speed from 1250 RPM to 1750 RPM at constant torque constitutes the second instance of transient operation. Figure depicts the speed waveform for a duration of 10 seconds. It is observed that the system settles down at the new speed within 0.5 seconds. The momentary change in armature torque caused by a sudden alteration in the speed is seen in Figure.The characteristics of current that is identical to that of torque is shown in figure. The change in armature voltage with respect to the change in motor speed is depicted in figure. As seen in figure, when the speed increases, the motor draws more energy from the source, resulting in a fall in the SoC of the battery by 0.08%. The battery voltage and current during this phase are depicted in figures. The battery and motor energy characteristics are shown in figure. The theoretical efficiency of the of the proposed HGBDC is calculated for rated power and resistive load and is found to be 94.12% in boost mode and 95.51% in buck mode as discussed in section II.D. The results are in good agreement with the simulation results which are 94.57% and 95.05% respectively.

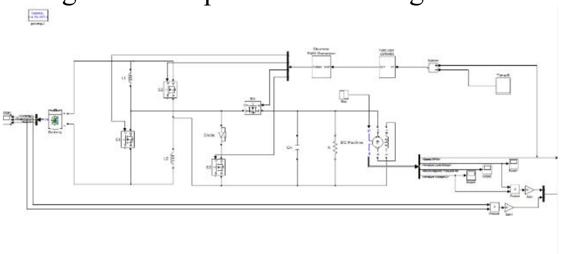

Fig 8 : Simulation results for case 2- step change in speed during forward motoring using Fuzzy logic control

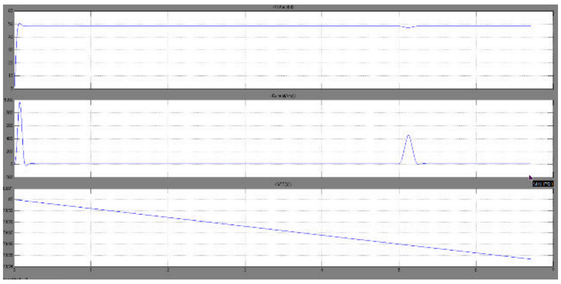

Fig 9 : Battery Voltage, Current & SOC

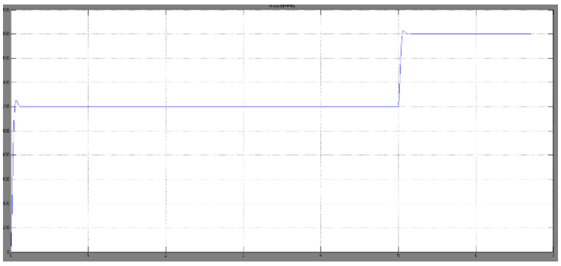

Fig 10: speed

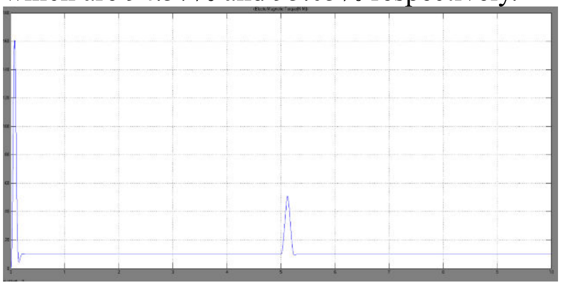

Fig 11: Electro Magnetic torque

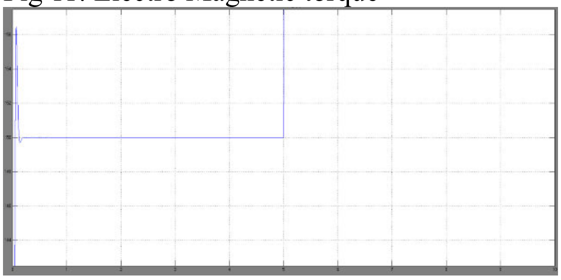

Fig 12: Armature voltage

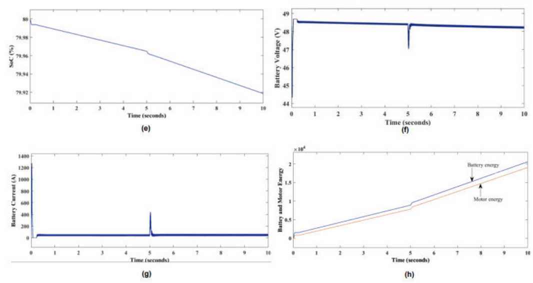

Fig 13. Simulation results for case 2- step change in speed during forward motoring: (e) battery SoC, (f) battery voltage, (g) battery current and (h) battery and motor energy

VII.CONCLUSION

This project presented a **high-gain bidirectional DC-DC converter (HGBDC)** with **fuzzy logic control (FLC)** for electric vehicle (EV) applications, addressing critical challenges in power efficiency, voltage regulation, and regenerative braking energy recovery. The proposed converter topology achieved **high voltage gain** using a dual-duty cycle approach while minimizing component count, eliminating the need for complex voltage multiplier circuits or coupled inductors. By integrating a **fuzzy logic controller**, the system demonstrated superior dynamic performance compared to conventional PID-based control, particularly under transient conditions such as acceleration, deceleration, and regenerative braking.

FUTURE SCOPE

While this study demonstrated significant advancements, further improvements can be explored:

- **Wide-Bandgap Semiconductors (SiC/GaN):** Replacing silicon-based switches with SiC or GaN devices could further reduce losses and enable higher switching frequencies.
- **Adaptive Fuzzy-PID Hybrid Control:** Combining fuzzy logic with adaptive PID tuning may enhance precision in extreme operating conditions.
- **Hardware Prototyping:** Experimental validation with a physical prototype would reinforce simulation findings.
- **Integration with Vehicle-to-Grid (V2G):** Extending the converter's bidirectional capability to support V2G applications for grid stabilization.

REFERENCES

[1] C. H. T. Lee, W. Hua, T. Long, C. Jiang and L. V. Iyer, "A Critical Review of Emerging Technologies for Electric and Hybrid Vehicles," IEEE Open Journal of Vehicular Technology, vol. 2, pp. 471-485, 2021, doi: 10.1109/OJVT.2021.3138894.

[2] V. Rathore, K. Rajashekara, P. Nayak and A. Ray, "A High-Gain Multilevel dc–dc Converter for Interfacing Electric Vehicle Battery and Inverter," IEEE Transactions on Industry Applications, vol. 58, no. 5, pp. 6506-6518, Sept.-Oct. 2022, doi: 10.1109/TIA.2022.3185183.

[3] H. Chen, H. Kim, R. Erickson and D. Maksimović, "Electrified Automotive Powertrain Architecture Using Composite DC–DC Converters," IEEE Transactions on Power Electronics, vol. 32, no. 1, pp. 98-116, Jan. 2017, doi: 10.1109/TPEL.2016.2533347.

[4] A. Gupta, R. Ayyanar and S. Chakraborty, "Novel Electric Vehicle Traction Architecture With 48 V Battery and Multi-Input, High Conversion Ratio Converter for High and Variable DC-Link Voltage," IEEE Open Journal of Vehicular Technology, vol. 2, pp. 448-470, 2021, doi: 10.1109/OJVT.2021.3132281.

[5] J. O. Estima and A. J. Marques Cardoso, "Efficiency Analysis of Drive Train Topologies Applied to Electric/Hybrid Vehicles," IEEE Transactions on Vehicular Technology, vol. 61, no. 3, pp. 1021- 1031, March 2012, doi: 10.1109/TVT.2012.2186993.

[6] D. Sha, D. Chen and J. Zhang, "A Bidirectional Three-Level DC– DC Converter with Reduced Circulating Loss and Fully ZVS Achievement for Battery Charging/Discharging," IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 6, no. 2, pp. 993-1003, June 2018, doi: 10.1109/JESTPE.2017.2778039.

[7] T. Zhu, F. Zhuo, F. Zhao, F. Wang, H. Yi and T. Zhao, "Optimization of Extended Phase-Shift Control for Full-Bridge CLLC Resonant Converter with Improved Light-Load Efficiency," IEEE Transactions on Power Electronics, vol. 35, no. 10, pp. 11129-11142, Oct. 2020, doi: 10.1109/TPEL.2020.2978419.

[8] Y. Shen, H. Wang, A. Al-Durra, Z. Qin and F. Blaabjerg, "A Bidirectional Resonant DC–DC Converter Suitable for Wide Voltage Gain Range," IEEE Transactions on Power Electronics, vol. 33, no. 4, pp. 2957-2975, April 2018, doi: 10.1109/TPEL.2017.2710162.

[9] C. Bai, B. Han, B. -H. Kwon and M. Kim, "Highly Efficient Bidirectional Series-Resonant DC/DC Converter Over Wide Range of Battery Voltages," IEEE Transactions on Power Electronics, vol. 35, no. 4, pp. 3636-3650, April 2020, doi: 10.1109/TPEL.2019.2933408.

[10] N. Hou and Y. W. Li, "Overview and Comparison of Modulation and Control Strategies for a Nonresonant Single-Phase DualActive-Bridge DC–DC Converter," IEEE Transactions on Power Electronics, vol. 35, no. 3, pp. 3148-3172, March 2020, doi: 10.1109/TPEL.2019.2927930.

[11] F. Zahin, A. Abasian and S. A. Khajehoddin, "An Alternative Dual Active Bridge Modulation to Minimize RMS Current and Extend ZVS Range," 2020 IEEE Energy Conversion Congress and Exposition (ECCE), Detroit, MI, USA, 2020, pp. 5952-5959, doi: 10.1109/ECCE44975.2020.9235374.

[12] Y. Zhang, W. Zhang, F. Gao, S. Gao and D. J. Rogers, "A SwitchedCapacitor Interleaved Bidirectional Converter with Wide VoltageGain Range for Super Capacitors in EVs," IEEE Transactions on Power Electronics, vol. 35, no. 2, pp. 1536-1547, Feb. 2020, doi: 10.1109/TPEL.2019.2921585.

[13] Y. Zhang, Y. Gao, L. Zhou and M. Sumner, "A Switched-Capacitor Bidirectional DC–DC Converter with Wide Voltage Gain Range for Electric Vehicles with Hybrid Energy Sources," IEEE Transactions on Power Electronics, vol. 33, no. 11, pp. 9459-9469, Nov. 2018, doi: 10.1109/TPEL.2017.2788436.

[14] H. S. H. Chung, W. C. Chow, S. Y. R. Hui and S. T. S. Lee, "Development of a switched-capacitor DC-DC converter with bidirectional power flow," IEEE Transactions on Circuits and Systems I: Fundamental Theory and Applications, vol. 47, no. 9, pp. 1383-1389, Sept. 2000, doi: 10.1109/81.883334.

[15] D. Flores Cortez, G. Waltrich, J. Fraigneaud, H. Miranda and I. Barbi, "DC–DC Converter for Dual-Voltage Automotive Systems Based on Bidirectional Hybrid Switched-Capacitor Architectures," IEEE Transactions on Industrial Electronics, vol. 62, no. 5, pp. 3296-3304, May 2015, doi: 10.1109/TIE.2014.2350454.

[16] Y. Zhang, Q. Liu, Y. Gao, J. Li and M. Sumner, "Hybrid SwitchedCapacitor/Switched-Quasi-Z-Source Bidirectional DC–DC Converter with a Wide Voltage Gain Range for Hybrid Energy Sources EVs," IEEE Trans. on Ind. Electron., vol. 66, no. 4, pp. 2680-2690, April 2019.doi: 10.1109/TIE.2018.2850020.

[17] Avneet Kumar, Xiaogang Xiong, Xuewei Pan and Motiur Reza, "A Wide Voltage Gain Bidirectional DC–DC Converter Based on Quasi Z-Source and Switched Capacitor Network" IEEE Transactions on Circuits and Systems II: Express Briefs, Volume: 68, Issue: 4, April 2021, doi: 10.1109/TCSII.2020.3033048.

[18] Z. Wang, P. Wang, B. Li, X. Ma and P. Wang, "A Bidirectional DC–DC Converter with High Voltage Conversion Ratio and Zero Ripple Current for Battery Energy Storage System," IEEE Transactions on Power Electronics, vol. 36, no. 7, pp. 8012-8027, July 2021, doi: 10.1109/TPEL.2020.3048043.

[19] Y. Zhang, Y. Gao, J. Li and M. Sumner, "Interleaved SwitchedCapacitor Bidirectional DC-DC Converter with Wide Voltage-Gain Range for Energy Storage Systems," IEEE Transactions on Power Electronics, vol. 33, no. 5, pp. 3852-3869, May 2018, doi: 10.1109/TPEL.2017.2719402