

Intelligent Power Conversion Architecture with Fuzzy-Controlled Single-Phase AC-DC, Dual Active Bridge, and Interleaved Boost Converter for Efficient and Adaptive Electric Vehicle Battery Charging

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Abstract - proposed single-phase grid-connected interleaved boost converter with power factor correction is designed for efficient charging of electric vehicles. It improves the power factor, ensuring optimal use of electrical energy from the grid. The interleaved boost converter reduces losses and increases power transfer capability, ensuring a stable and reliable charging experience. A high-frequency transformer-based dual active bridge converter enhances efficiency and power density, allowing power flow from the grid to the vehicle's battery with minimal losses. This converter is suitable for compact electric vehicle charging stations and accommodates multiple DC loads, ensuring efficient power distribution.

1. Introduction

Electric vehicles are becoming more popular among customers owing to their environmental advantages and long-term cost reductions. Electric vehicles have gotten more efficient as technology has advanced, providing greater range and quicker charging periods [1], [2]. Furthermore, governments throughout the globe are adopting incentives and infrastructure improvements to encourage the wider use of electric vehicles, which is adding to their appeal. The electric vehicle is evolving, and the key challenge is charging the battery [3]. While electric vehicles have made tremendous advances in terms of range and charging speed, charging station availability and accessibility remain an issue. This has raised worries about range anxiety and limited charging choices, particularly in rural places [4], [5]. By using a single-phase grid-connected high-frequency dual active bridge converter, the suggested converter intends to overcome the problem of restricted charging alternatives. This revolutionary design enables electric vehicles to be charged efficiently and quickly regardless of their location or proximity to regular charging stations [6]. Furthermore, the use of an interleaved boost converter offers a constant and dependable power supply, lowering the possibility of power fluctuations while charging. This converter employs power electronics

The high-frequency operation minimizes electromagnetic interference, ensuring a clean and reliable power transfer process. MATLAB/Simulation can analyze grid and electric vehicle charging system performance results, providing valuable insights for optimization and further development. It also allows for easy modification and testing of control strategies, ensuring converter compatibility with various grid and electric vehicle scenarios.

Keywords - dc fast charger, dc-dc power converters, dual active bridge (DAB), energy storage, fast charging station, DC link, Fuzzy Controller.

switching devices such as insulated gate bipolar transistors (IGBTs) or silicon carbide (SiC) MOSFETs. These devices are very efficient and provide exact control over power flow [7]. Advanced components allow converters to effectively convert alternating current (AC) electricity from the grid into direct current (DC) power for charging electric vehicles, easing energy transfer during grid-to-vehicle operations. When compared to conventional power conversion systems, power electronics systems are lighter and smaller in size, making them perfect for incorporation into electric vehicle charging infrastructure [8]. Furthermore, the use of modern power electronics switches reduces energy losses and improves overall system performance, resulting in a more sustainable and efficient charging procedure for electric vehicles. This dual capability of electric vehicle batteries not only improves charging efficiency, but also allows for grid stabilisation and optimisation. Electric vehicle charging infrastructure may contribute to a more stable and dependable electrical grid by using the associated batteries for load-demand management and reactive power compensation, hence boosting the wider use of electric automobiles. A single-phase AC-DC converter transforms alternating current (AC) from the electrical grid to direct current (DC) for charging the electric vehicle's battery in this proposed system [9]. The

interleaved boost converter raises the DC power voltage to a level suited for quick charging, while the dual active bridge converter provides efficient power transmission between the grid and the electric vehicle [10]. This unique charging technique not only allows charging electric vehicles faster and easier, but it also contributes to grid stability and efficiency by allowing power flow. In G2V mode, the rectifier is utilised for power factor correction (PFC), ensuring that the electric vehicle pulls electricity from the grid more efficiently and evenly [11]. The full-bridge topology is the most used PFC architecture because it has a basic construction and is straightforward to operate, allowing for PF operation unity. Harmonic distortion of the current waveform, on the other hand, might be a big worry, and alternative control mechanisms must be devised to solve this issue. The interleaved boost converter is in charge of increasing the voltage from the grid in order to charge the electric vehicle's battery pack. This converter is very efficient and minimises losses throughout the charging process. Furthermore, the interleaved boost converter aids in the uniform distribution of power across several charging stations, providing for a more stable and scalable charging infrastructure. The interleaved boost converter is made up of two inductors and two switches that regulate the current flow [12]. These components work together to effectively convert the incoming grid electricity into a higher voltage suited for charging the battery pack of an electric vehicle. The converter can handle larger power levels while minimising losses and enhancing overall performance by interleaving the action of the two switches and inductors. Dual DC-AC bridge converters with high frequencies are often utilised in electric vehicle charging systems [13], [14]. When compared to typical converters, these high-frequency converters can achieve better power density and efficiency. Furthermore, the high-frequency operation allows for quicker charging times while also reducing the charging system's size and weight, making it more comfortable for electric vehicle users [15], [16]. These converters can effectively convert high-frequency alternating current (AC) power from the grid to direct current (DC) power for charging the vehicle's battery pack. Furthermore, a bus capacitor with a larger capacitance is required by the full-bridge converter to store energy between stages. This increases the system's cost and takes up more space. It also reduces the system's reliability and ability to manage higher power. Scientists are looking at new converter topologies, such as the dual active bridge (DAB) converter, to make the converter more dependable, enhance its power density, and make the bus capacitor smaller [17]. The DAB converter uses a transformer to create galvanic isolation and enables power to flow without requiring a big bus capacitor [18], [19]. This not only lowers the system's cost and space, but also increases its reliability and power density capabilities, making it a potential choice for high-performance energy storage applications. Electrical vehicles have varying power converter ratings and needs. A high-performance electric

vehicle, for example, may need a power converter with greater voltage and current ratings to satisfy its demanding power requirements [20]. A smaller electric vehicle meant for urban commuting, on the other hand, may have lesser power needs and may use a power converter with lower ratings. To provide best performance and efficiency, the power converter topology must be carefully selected and designed based on the unique needs of the electrical vehicle [21]. Different power ranges' will be acquired from converters depending on the rating of the electric vehicle charging. Disturbances with varying ranges of electric vehicle charging circumstances may arise with this converter. These disruptions may have an impact on the power converter's overall performance and efficiency, as well as the charging process of an electric vehicle. This transient and dynamic disturbance may be solved by the fuzzy logic controller, which can minimise transient and dynamic disturbances and enable steady and effective charging of electric vehicles [22]. The fuzzy logic controller may efficiently limit the effects of disturbances by assessing real-time data and modifying the converter's settings, resulting in a smoother charging process and enhanced overall performance of the power converter. Furthermore, the use of a fuzzy logic controller enables adaptive control, which allows the system to adapt to changing charging circumstances and optimise energy transfer between the converter and the electric vehicle. Using memory functions and a rule basis, the fuzzy logic controller precisely controls the converter's output voltage and current, providing safe and efficient charging of the electric vehicle [23]. Furthermore, the fuzzy logic controller can manage system non-linearity and uncertainties, making it a reliable option for power converter control in electric vehicle charging applications [24]. The outcomes of various control techniques and their influence on the charging process, such as quick charging or delayed charging, may be shown using MATLAB simulation. This enables engineers to optimise the control algorithm and increase the charging system's overall performance. Furthermore, the simulation may give insights into the behaviour of the converter under various operating settings, assisting in the identification of any possible faults or restrictions that may develop during real-world use. The following are the benefits of the suggested system.

- A high-frequency dual active bridge converter optimizes energy transfer from the grid to the electric vehicle by permitting power flow. This efficiency is required for quick, reliable charging.
- High-frequency operating speeds charging, meeting electric vehicle consumers' key issue. High-power converters minimize charging times.
- The fuzzy logic controller's rule-based method precisely controls converter output voltage and

current. This ensures safe and effective charging, especially when responding to electric vehicle power needs.

2. System Layout

The electric vehicle (EV) battery charging system is a multi-stage architecture designed to improve efficiency, adaptability, and performance. It starts with a single-phase AC to DC conversion, ensuring compatibility between the grid power source and the EV charging infrastructure as shown in Fig .1. An interleaved boost converter is then employed to increase DC power, enhancing power density and reducing ripple. The heart of the system is a dual active bridge (DAB) converter and a high-frequency transformer, which facilitate power flow and enable energy transfer to

the grid EV during charging periods. The high-frequency transformer reduces size and weight while maintaining efficient power transfer. A fuzzy logic controller is integrated to optimize control and adaptability, analyzing real-time data and dynamically adjusting converter parameters to mitigate disturbances and varying charging conditions. Power electronics switching devices like IGBTs or SiC MOSFETs are crucial for precise control over power flow, enhancing system efficiency and grid stability. The system addresses challenges such as limited charging options, range anxiety, and infrastructure accessibility, promoting the widespread adoption of electric vehicles in a sustainable and environmentally conscious transportation landscape.

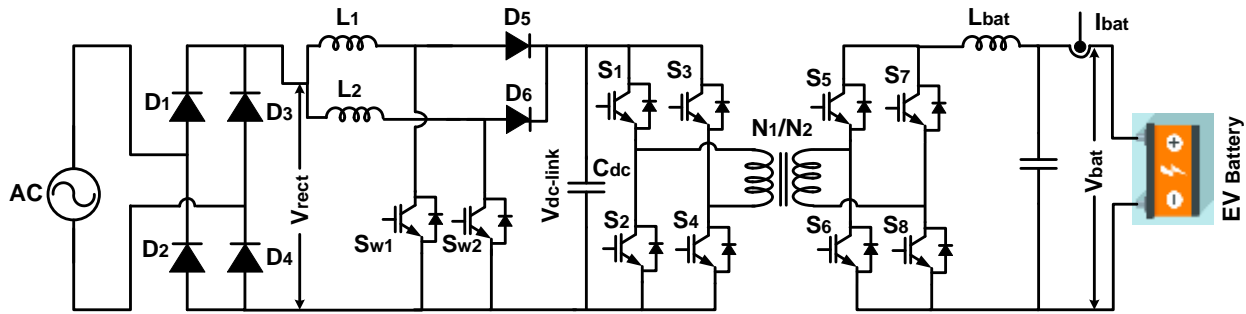


Fig .1 Dual active bridge converter electric vehicle charging infrastructure.

3. Brief Detail and Parameter Design

3.1. Full-Bridge Diode Rectifier:

This proposed system full bridge diode rectifier converts the ac to dc by utilizing four diodes arranged in a bridge configuration. This rectification process allows for efficient power conversion and is commonly used in various electronic devices and power supplies. The first stage involves rectifying the single-phase AC input from the grid to obtain a DC voltage. The rectifier is typically a diode bridge rectifier and the average DC voltage (V_{dc}) can be calculated using the following equation (1):

$$V_{dc} = \frac{2\sqrt{2} \cdot V_{rms}}{\pi} \quad (1)$$

3.2. Interleaved Boost Converter:

The duty cycle is a crucial parameter in interleaved boost converters, determining the time the switch is on and the total switching period. It directly impacts the converter's efficiency and performance, allowing for precise voltage regulation. Adjusting the duty cycle allows for higher output voltage, while a lower cycle reduces it. Therefore, the duty cycle is essential for optimizing the converter's performance. The output voltage (V_{boost}) and current ripple ($I_{L_{ripple}}$) influences the stability of the interleaved boost converter can be determined using the equation (2), (3).

Table 1. System specifications for G2V mode.

G2V/Charging Mode	
V_g and f	230 V and 50 Hz
$V_{DC-link}$	400 V
P_{rat}	7.7 kW
f_{sw}	50 kHz
ΔI_{ripple}	20%
$\Delta V_{DC-link}$	5%
η target	>95%
PF target	>98%

$$V_{boost} = \frac{D \times V_{dc}}{1-D} \quad (2)$$

$$I_{L_{ripple}} = \frac{V_{dc} \cdot D \cdot V_{dc}}{f_{sw} \cdot L} \quad (3)$$

The power factor correction of grid to vehicle charging mode given by equation (4)

Fig. 3 dual active bridge converter control for battery charging process.

5. Fuzzy Logic Controller Design

Fuzzy logic controllers are predicated on rules that specify the ultimate control response. Each rule contains information about the control action to be executed in response to a specific set of circumstances. As shown in Figure 3, a simple fuzzy controller system's block design. To prepare the input parameters for processing by means of fuzzy logic, a procedure known as fuzzification is carried out. It is straightforward to learn and easy to maintain a rule-based controller. Decisions are made by referring to a suitable set of fuzzy rules. Finally, the necessary output control parameter is obtained by doing the inverse of fuzzification, also known as defuzzification. A fuzzy logic controller with just one output and two inputs is developed for this system. Figure 4 depicts the developed fuzzy logic controller being utilised to control the boost converter's gate pulses. A fuzzy logic controller, pulse width modulator (PWM), and boost converter make up the circuit. A single-phase rectifier's DC input serves as the input source. A fuzzy logic controller is maintained in the feedback route of an interleaved boost converter to regulate the switching duty cycle and hence the input current waveform. The reaction of the interleaved boost converter relies heavily on the current flowing through the inductor. It also tells us how much energy the converter can store. Therefore, the output voltage may be affected by changes to the inductance. To keep the output voltage constant regardless of changes in the inductor, the fuzzy logic controller makes continual adjustments to the switch's duty cycle depending on the required input current waveform. The output voltage is kept stable by the controller, which monitors the inductor current and adjusts it accordingly in response to variations in the inductor's properties.

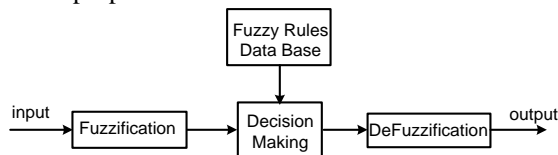


Fig 4. Typical Fuzzy Logic Controller Block Diagram

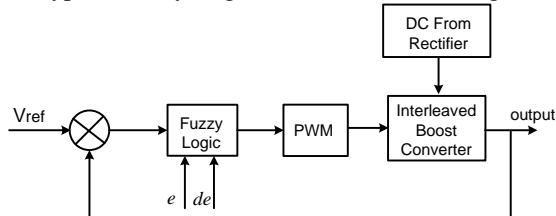


Fig 5. Block diagram of Fuzzy controlled Boost converter

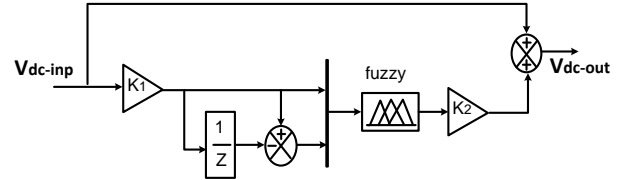


Fig 6. Fuzzy logic controller block

The fuzzy controller takes in the error voltage (e) and the differential (de) as inputs. The voltage delta between (V_{out}) and (V_{ref}) is known as the error voltage. The error voltage change is calculated by subtracting the current error voltage from the prior error voltage. The error and its rate of change are used by the fuzzy controller as inputs to identify the best course of action. The controller can efficiently modify the system's output voltage to match the required reference voltage by taking into account both the present error voltage and its change over time. Here are the formulas for the error voltage and the error voltage rate of change.

$$e = V_{dc-ref} - V_{dc} \tag{6}$$

$$\Delta e = e(k) - e(k-1) \tag{7}$$

5.1 Results Membership Function

The FIS editor in MATLAB's fuzzy logic toolbox is used to set up the controller's membership functions for the input and output voltages of the fuzzy logic system. Input and output membership functions, as well as the FIS editor, are shown in the following images: Users may set up the fuzzy logic controller's input and output membership functions using the FIS editor included in MATLAB's fuzzy logic toolbox. The controller's behaviour can be designed and fine-tuned with much less effort thanks to this graphical interface. Input and output voltage membership functions, as well as the FIS editor, are shown in the pictures to provide a visual illustration of the controller's operation.

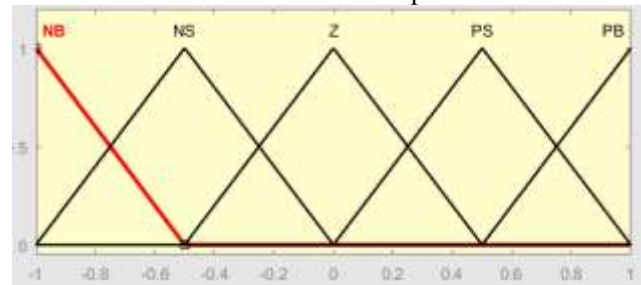


Fig 7: Input error Membership Function (e)

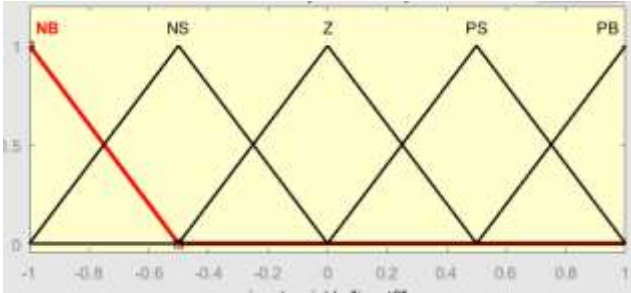


Fig 8. Change in error input Membership Function (de)

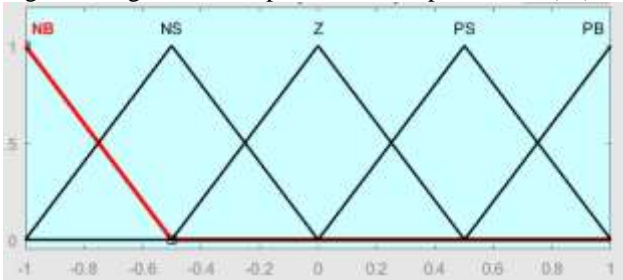


Fig 9. Output duty cycle Membership Function

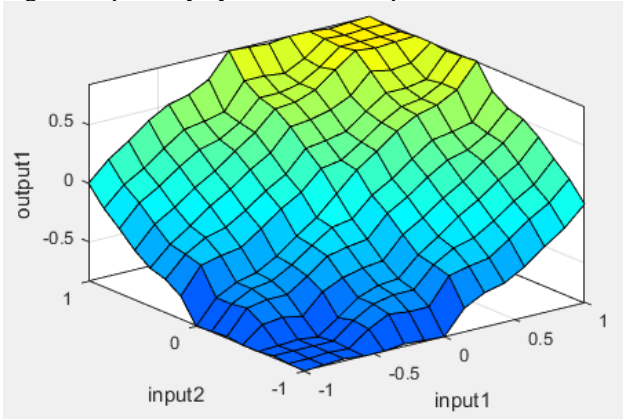


Fig 10. Surface viewer

5.2 Fuzzy Rules

The fuzzy rules are developed with prior system information in mind. The PWM duty cycle is regulated by the controller's rule base in response to changing input. The fuzzy rules take into account various factors, such as input variables, output variables, and the desired system behavior. These rules help determine the appropriate PWM duty cycle that will optimise the system's performance. Additionally, the rule base is continuously updated and refined to adapt to any changes or improvements in the system's working conditions. The look-up table for the designed rule set is given in figure 10.

$de \ e$	NB	NS	ZE	PS	PB
NB	NB	NB	NB	NS	ZE
NS	NB	NB	NS	ZE	PS
ZE	NB	NS	ZE	PS	PB
PS	NS	ZE	PS	PB	PB
PB	ZE	PS	PB	PB	PB

Fig 10: Look-up table for fuzzy rule set

6. Result and Discussion

To rectify power factor, a boost converter circuit has been implemented with gate pulse control using a fuzzy control technique. The algorithm uses fuzzy logic to dynamically adjust gate pulse timing based on input voltage and current waveforms, ensuring efficient power transfer and improved power factor. Tests have shown that the algorithm works well for accurate and responsive gate pulse switching. The interleaved boost converter improves DC voltage from the rectifier supply by reducing ripple voltage and increasing overall efficiency. Fuzzy logic control minimizes transient and dynamic disturbances from electric vehicle variation, ensuring smooth and stable operation. It also optimizes battery energy utilization, enhancing efficiency and performance. Fuzzy logic control can overcome supply disturbances such as voltage fluctuations and power surges, ensuring reliable operation in challenging electrical environments. The converter adapts to different driving conditions and load demands, providing a versatile solution for electric vehicles. As shown in Fig.11 and 12 MATLAB simulations can show variations in converter performance under various battery charging conditions and consumer demands, allowing engineers to optimize converter design and ensure efficiency in real-world scenarios. Simulation results can identify potential issues or weaknesses in the converter's operation, allowing for further improvements. The simulation results provide a visual representation of converter performance, aiding in making informed decisions regarding design and implementation in electric vehicles.

6.1 Steady state condition proposed electric vehicle charging system

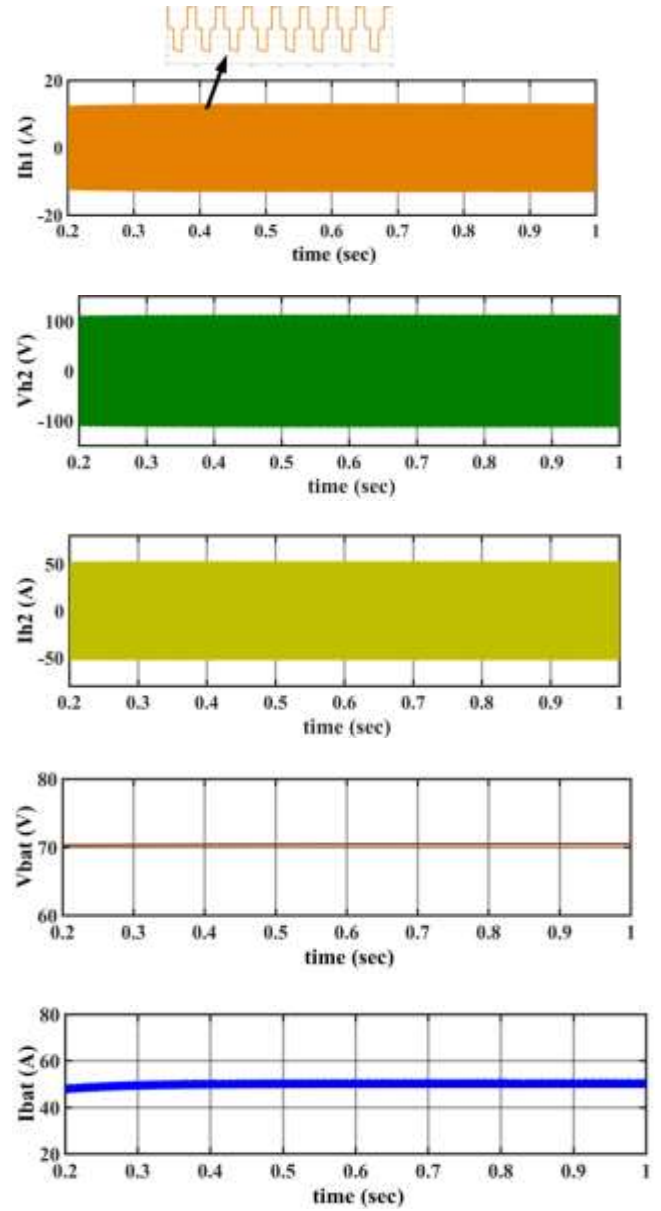
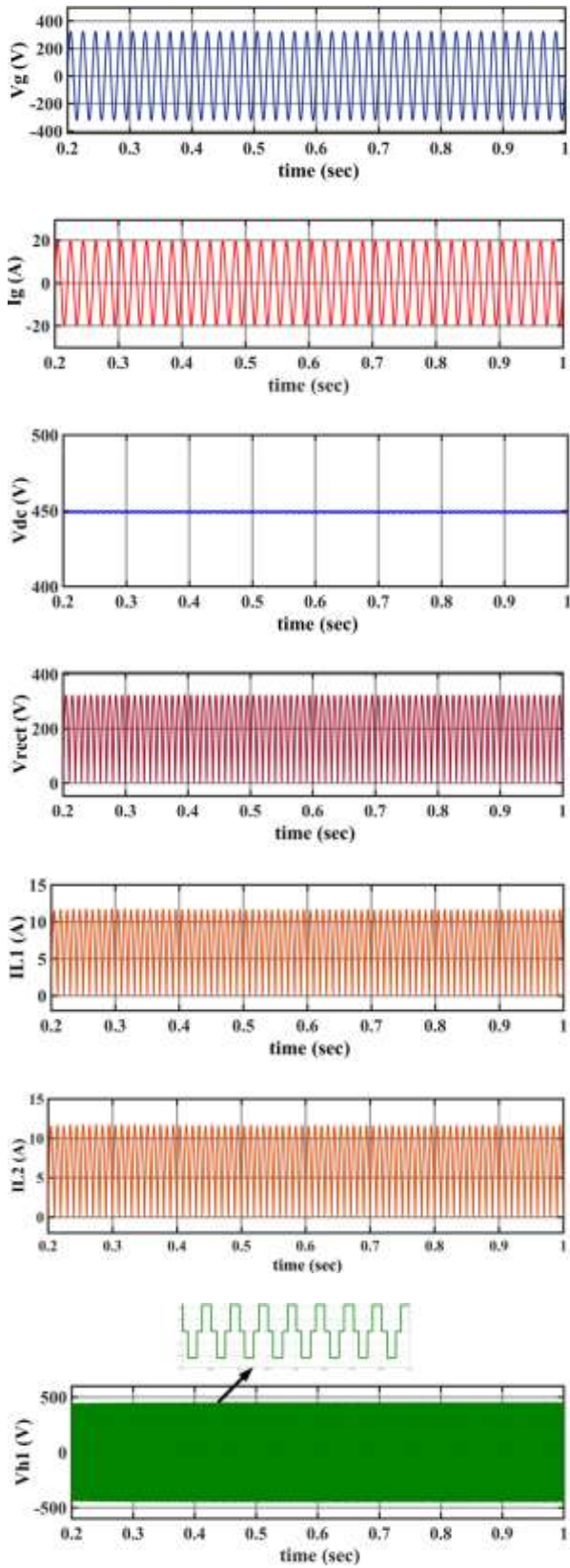
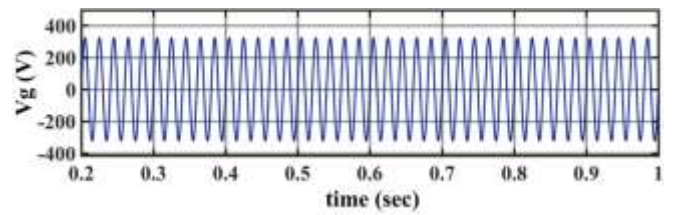


Fig.11 Steady state operation of proposed grid connected interleaved dual active bridge converter.

6.2 Dynamic performance of electric vehicle charging condition



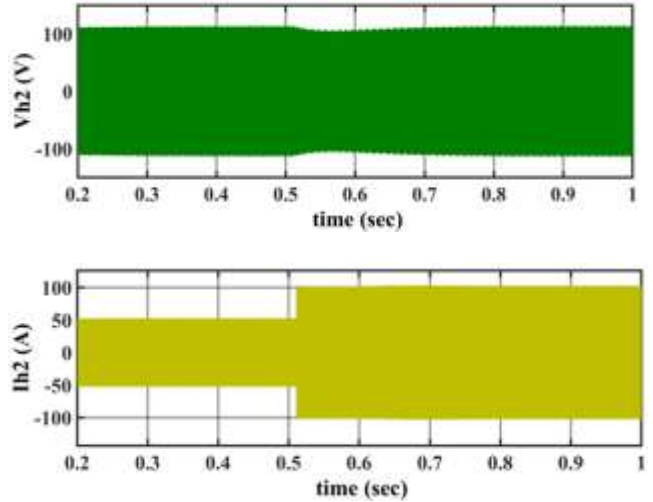
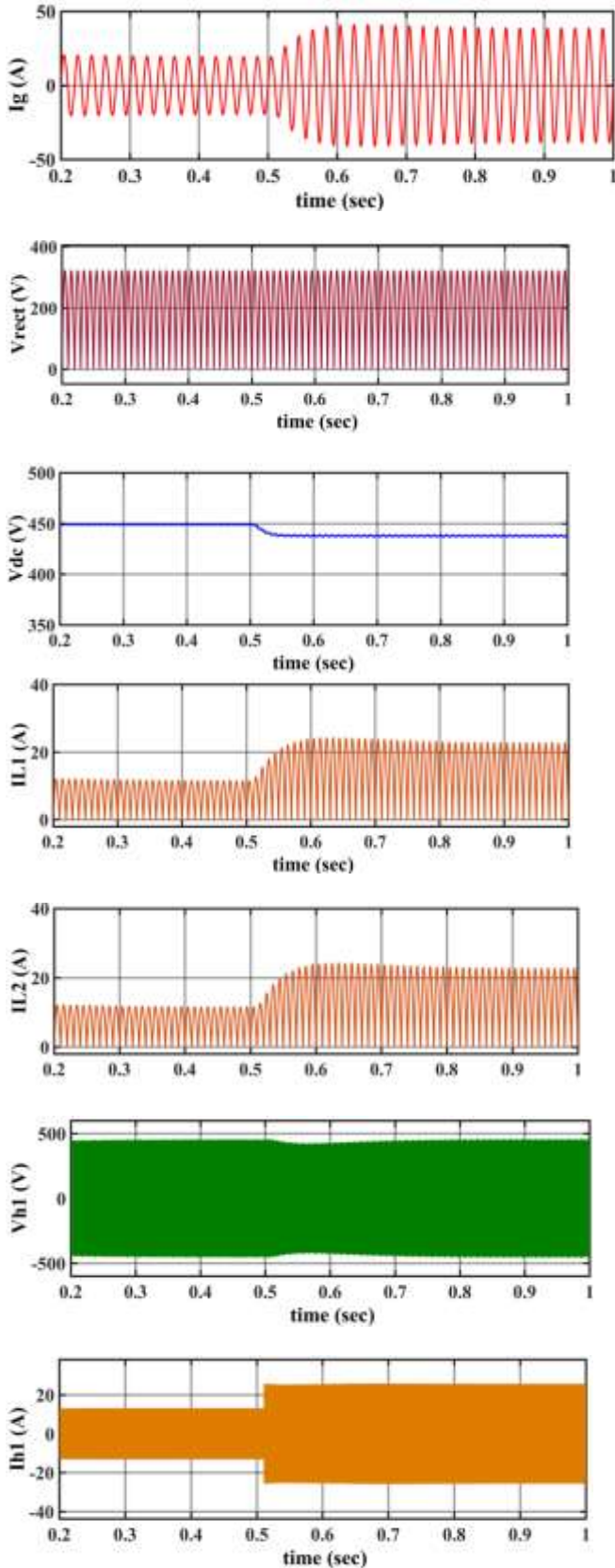
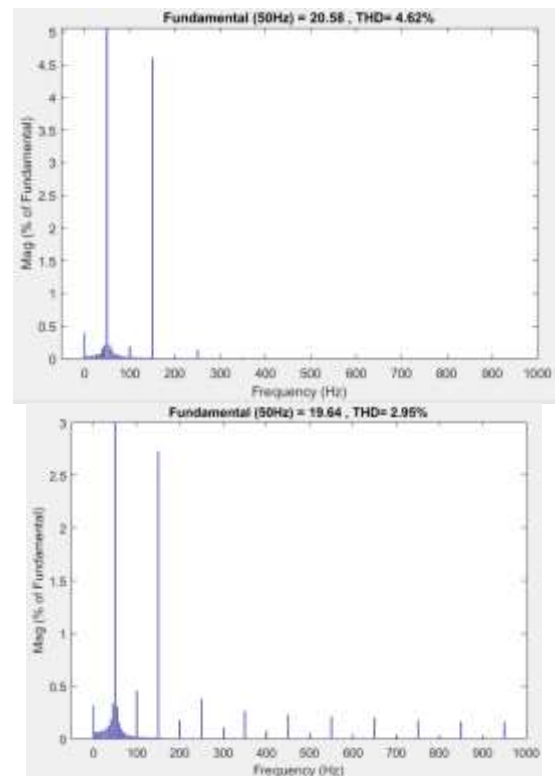


Fig. 12 Dynamic operation of proposed grid connected interleaved dual active bridge converter.



Total Harmonic Distortion (THD) computations may be used to evaluate the proposed grid-connected dual active bridge converter system's harmonic performance in place of a fuzzy logic controller. The FFT analysis shows that the THD is 4.62% due to the harmonics introduced by the grid current. Distortion (THD) estimates with the necessity for a fuzzy logic control the THD of grid current is 2.95%.

7. Conclusion

Charging infrastructure is being developed to support

the grid during peak power demand and compensate for the fuel crisis through electric vehicle (EV) transportation. In charging or G2V mode, a grid connected interleaved DC-DC boost converter is included to operate in rectifier and boost modes. The single phase grid side AC to DC converter provides a stable and efficient power supply to EV charging stations. The interleaved boost converter improves grid DC supply and correction power factor by reducing harmonics and improving efficiency. A fuzzy logic controller improves the performance of the total grid connected dual active bridge for electric vehicle charging

by dynamically adjusting switching frequency and duty cycle, ensuring optimal power transfer and minimizing losses. The high frequency dual active bridge converter converts boosted DC voltage to high frequency AC voltage, enabling power flow from grid to vehicle and features like regenerative braking and vehicle-to-grid capabilities. The MATLAB Simulation platform was used to model and simulate the performance of the converter, achieving high efficiency and fast response time, making it suitable for electric vehicle charging applications.

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