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An Isolated High Gain Push Pull Type DC to DC Converter for Fuel Cell Power Generation Systems

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Abstract

Due to their high efficiency and low environmental impact, fuel cell power generation systems have emerged as promising alternatives to traditional energy sources. However, the integration of fuel cells into practical applications necessitates the development of efficient power conversion systems. dc-dc converters play a crucial role in optimizing the power flow between the fuel cell stack and the load. In this paper, a push-pull type high gain dc-dc converter is proposed which consists of a push-pull inverter, a rectifier circuit, and C-filter. The push pull inverter produces high frequency square wave output while the full bridge rectifier and C-filter convert this square wave output into desired dc voltage. The converter boosts the 12V dc input supply to 326 V, representing a gain factor of more than 27. The isolated coupling inductor used in push pull inverter produces high gain and provides electrical isolation. Besides, the proposed topology eliminates the use of bulky grid-connected power transformers that decreases the system size and cost. To evaluate the performance of the proposed topology, a number of simulations under varying loads were carried out in the MATLAB Simulink framework. Further-more, a scaled-down prototype of 160W at 12/326 V was developed to confirm the simulation results. The findings indicate that the suggested converter can be a viable option for the hydrogen fuel cell-based power conversion system.

Keywords: renewable sources, dc microgrid, coupling inductor, power transformer, electrical isolation.

Highlights

- Proposed converter achieves 27x voltage gain from 12V supply, outperforming existing topologies.
- Efficiency remains stable despite fuel flow rate variations, ensuring consistent system performance.
- Minimal switching devices reduce losses, enhancing overall efficiency of the power conversion system.

Acknowledgements

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1 Introduction

Fuel cell power generation systems have gained considerable attention as clean and efficient sources of energy. It offers sustainable alternative for electricity generation by converting chemical energy directly into electrical energy. Fuel cells are preferred source for applications like electric vehicles and emergency power systems due to their small size, lightweight, and lack of pollution [1]. A fuel cell's versatility makes it an attractive alternative to other forms of renewable energy generation like solar and wind energy [2].

The most common types of fuel cells include – proton exchange membrane (PEMFCs), alkaline fuel cells (AFCs), and solid oxide fuel cells (SOFCs). Each type has its advantages and limitations concerning efficiency, operating temperature, and electrolyte material. PEMFC stands out among the many other kinds of fuel cells because of its high efficiency, quick starting, and capability to function at low temperatures [3]. PEMFC is preferred for EVs because of lifespan (5000 h). However, a PEMFC cell generates only about 1 V of direct current when there is no load. To elevate their voltage, although most PEMFCs have many cells attached in series, still not enough to fulfil the criteria of heavy loads [4]. To make fuel cell systems more practical and efficient, power electronics converters are essential. DC-DC converters play a crucial role in managing voltage levels, facilitating voltage regulation, power conditioning, isolation, and improving the overall efficiency of fuel cell power generation systems. Various converter topologies such as buck, boost, buck-boost, and push-pull are employed based on the specific requirements of the applications [5]. Achieving high gain in DC-DC converters is essential for maximizing power transfer efficiency.

Isolation in power converters is critical for ensuring system safety and reliability. The push-pull topology is known for its ability to provide isolation between input and output, making it suitable for applications where safety and reliability are paramount importance. For achieving isolation in push-pull converters both transformer-based and transformer less based solutions are proposed [6].

In [4] a DC-DC boost converter is utilized to raise the PEMFC voltage level to meet the needs of the load and minimizing overloading. Several high gain dc to dc converters (isolated and non-isolated) have been proposed for the fuel cell applications. Non-isolated low-power DC-DC converter topologies yield high output gain for solar photovoltaic system applications [7]. The major challenges of high-gain DC-DC boost converters are high-voltage stress on the switch, extreme duty ratio operation, diode reverse-recovery time, and converter low efficiency. Furthermore, the non-isolated dc to dc converter-based system faces galvanic isolation problems. Figure 1 shows the conventional fuel cell power generation setup.

It is seen from this figure that a low gain dc to dc converter initially elevates fuel cell generated dc voltage before converting to ac voltage by the inverter. As the ac voltage remains rather low, a low frequency bulky power transformer is employed to elevate the voltage level. This power transformer accounts for an approximate 70% increase in system size. An auxiliary cooling system is employed to mitigate the thermal conditions of the power transformer [8]. Thus, the conventional topology with power converter increases system dimension as well as expenses associated with maintenance. To solve this problem, an isolated high gain dc-dc converter has been proposed. The paper [9] presents a study on the optimization of transformer design and circuit layout in order to achieve an isolated full-bridge boost converter with minimal levels of parasitic circuit inductances. These converters have higher efficiency in the medium-to-high input voltage range but decrease dramatically at low input voltage and high power. In FC applications, isolated boost topologies have advantages including reduced ripple current, transformer design, and cost, where unbalanced input might cause transformer saturation and losses [10]. Half-bridge isolated converter, full bridge converter, push–pull converter, multiphase interleaved boost dc-dc converters, Cuk converter are most common isolated dc-dc converter. The disadvantages of these isolated dc-dc converter are highlighted in Table-1.

For high-power applications, a high static gain DC-DC converter with electrical isolation has been proposed in ref. [11]. However, this gain is insufficient for grid-integration, also uses a large number of components. A DC-DC converter with high gain is suggested in ref. [12] for microgrid and nano grids integrated solar systems. To ensure the maximum power point tracking with acceptable power quality, the proposed topology aims to achieve minimal ripple current properties at the converter's input and output. Nevertheless, this particular topology employs larger number of components and intricate control methods, augmenting the overall system complexity.

This research presents a high gain push pull type dc to dc converter for fuel cell application. This converter produces 326V from 12V power supply yielding the voltage gain around 27. Besides, this converter can provide electrical isolation from high voltage side to low voltage side. Incorporation of lower number of switching devices produces low switching losses as compared to full H-bridge type converter, which increases the efficiency. Furthermore, as each switch subjects to the supply voltage, the voltage stress across the switching device is low. A comprehensive simulation is carried out in the MATLAB Simulink

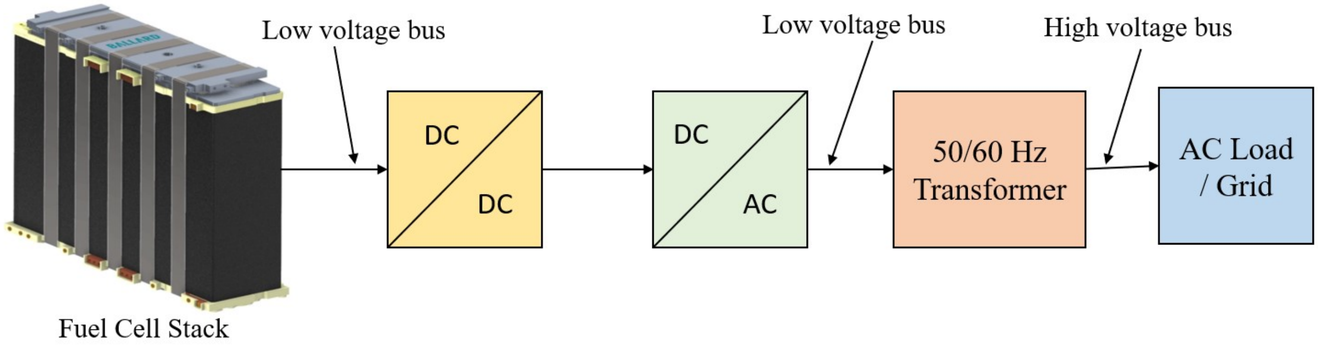


Fig 1. Schematic diagram of a typical fuel cell power generation system

environment to evaluate the performance of the proposed dc-dc converter. A hardware prototype has also been developed to prove the validity of the proposed system.

2 Isolated Push Pull type DC to DC Converter

This section provides a comprehensive description of an isolated dc-dc converter with high gain feature tailored for fuel cell power system. Figure 2 depicts the considered dc-dc converter that is capable of generating an output voltage of around 326V from an input of 12V. It has three parts: (1) a push pull inverter (2) a full bridge rectifier and (3) a C-filter. The push-pull inverter employs a pair of power MOSFETs and a high frequency (HF) coupling transformer, to produces high frequency square wave from the fuel cell (FC) generated dc voltage. High frequency operation of transformer drastically reduces transformer core size and weight. Besides, the HF transformer ensures electrical isolation between input and output thus guaranteeing the safety of the equipment from high voltage. The full bridge rectifier converts this ac square wave output into unidirectional output. C-filter reduces harmonics content in the rectified signal and a high value of dc voltage is obtained at the output side. The operating principle of this push pull type dc to dc converter can be explained through two distinct stages as is given below.

Stage 1: During this mode, when PEMFC starts up, the power flow circulates from the PEMFC to the load via switching device (S1), high frequency multi-winding transformer, diodes (D2) and (D3). Specifics of this mode of operation are depicted in Figure 3 [marked red].

Stage 2: In this mode, when (S2), (D4), and (D1) are turned on, the power flow circulates from the PEMFC to the load via high-frequency transformer. Specifics of this mode of operation are described in Figure 4.

The operational response of the converter under consideration is shown in Figure 5.

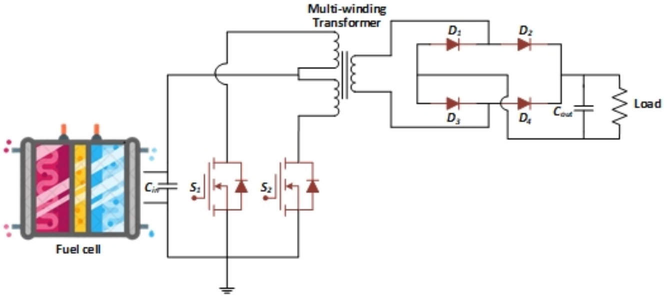


Fig 2. Isolated push pull type DC to DC converter

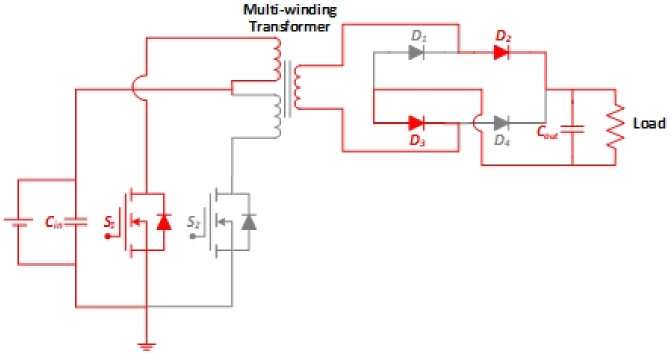


Fig 3. Current flow diagram of stage-1.

2.1 Proton Exchange Membrane Fuel Cell

Fuel cells are electrochemical devices that converters that convert chemical energy directly into electrical energy through the reaction between hydrogen and oxygen.

In contrast to batteries, they may generate electricity constantly so long as fuel and oxidant are present. A proton exchange membrane (PEM) fuel cell comprises cathode

Table 1. Disadvantages of some isolated dc to dc converters

Topologies	References	Limitations
Half-bridge Isolated Converter	[13], [14], and [15]	• Hard-switching operation • turnoff voltage spikes • Use four switching devices that increases converter losses and heat • To guarantee reliable switching and reduce unwanted shoot-through currents, specialized gate driver circuits are often required.
Full-bridge Isolated Converter	[16], [17], and, [18]	• Hard-switching operation • Use five switching devices that increases converter losses • Low voltage conversion ratio. • Power switches get full input voltage. This high voltage stress can reduce component reliability and longevity.
Current-fed push–pull converter	[19], [20]	• high voltage stress of the switches • low voltage conversion ratio
Multiphase interleaved boost DC-DC converters	[21], [22]	• Require complex control algorithm • Imbalances between the phases can lead to current and voltage mismatches, reducing the converter's efficiency. • Due to phase mismatches, multiphase • Interleaved converter switching devices may incur differential voltage stress. This can stress components and shorten their lifespan. • Due to more components and uneven current sharing, multiphase converters generate higher heat. To prevent overheating and component failure requires thermal management.
Cuk converter	[23], [24], and [25]	• Require complex control algorithm • It requires careful component and control parameter selection to operate properly. • Efficient gate driving and control strategies are needed to minimize switching losses.
Resonant Isolated Boost converter	[26], [27]	• High current rating of switches • Unable to flow low power

and anode electrodes with a separator in-between made from Nafion coated solid polymer electrolyte membrane as shown in Fig. 6.

Pure hydrogen (H_2) from a pressurized tank is continuously supplied into the anode electrode. On the anode, the hydrogen gas gets oxidized and transformed into hydrogen ions (H^+) and electrons (e^-). The PEM allows only positive charged particles (H^+) to pass through it. On

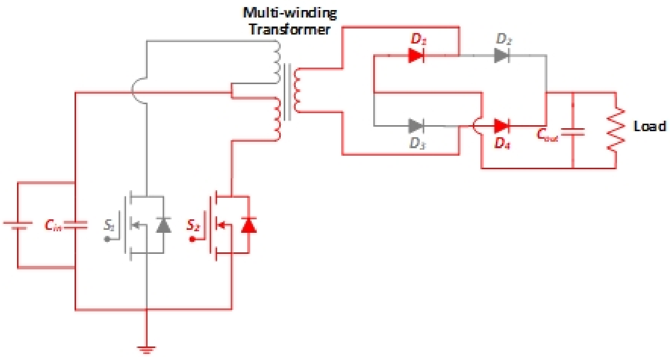


Fig 4. Current flow diagram of stage-2.

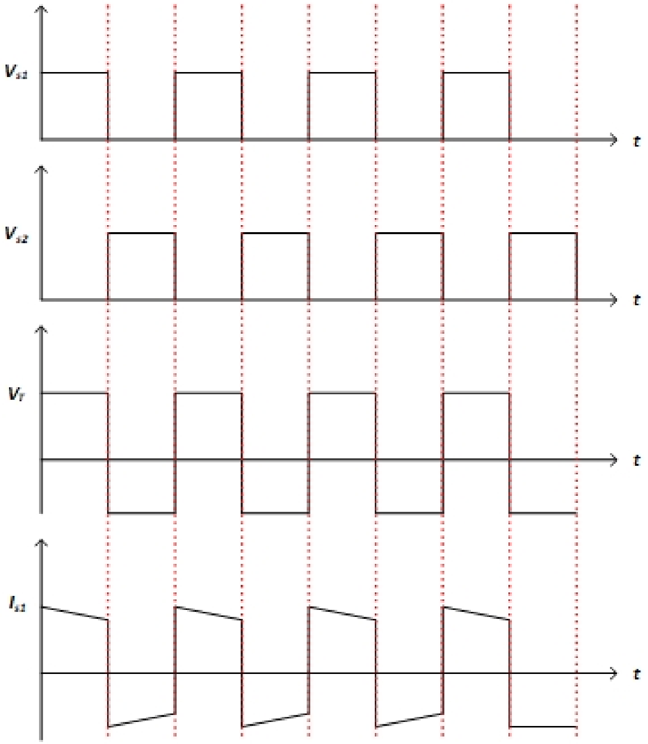


Fig 5. Operating waveforms of the chosen dc to dc converter

reaching the cathode, these ions (H^+) combine with oxygen (O_2) to produce water. Freed electrons are then transferred towards the cathode part via the outside load, thus producing electrical energy. The overall electrochemical reactions can be summarized as [28]–[30]:
Reaction at anode:

$$2H_2 \rightarrow 4H^+ + 4e^- \qquad (1)$$

Reaction at cathode:

$$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \qquad (2)$$

Overall reaction:

$$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O + \text{electrical energy} + \text{heat} \qquad (3)$$

The thermodynamic potential generated by the overall reaction is given by Nernst's equation:

$$E_{Nernst} = E_o + \frac{RT}{2F} \ln \left[P_{h2} \sqrt{P_{o2}} \right] \qquad (4)$$

where R is universal gas constant, E_o standard reversible cell potential (1.229 V) at open circuit condition, P_{o2} and P_{h2} are the partial pressure of oxygen and hydrogen gases respectively. Due to internal voltage drops like ohmic voltage drop (V_{ohm}), activation voltage drop (V_{act}), and concentration voltage drop (V_{conc}), the electric potential appearing across a single fuel cell is given by:

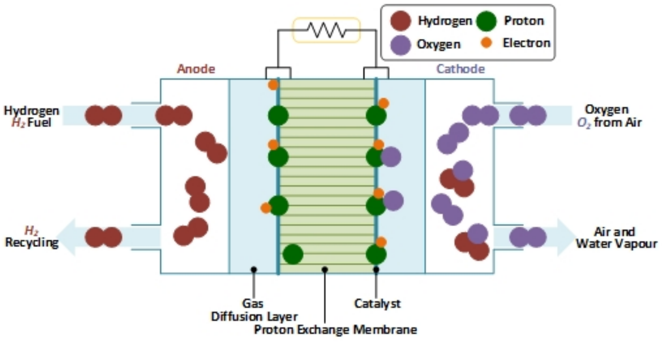


Fig 6. Schematic representation of PEM fuel cells

$$V_{FC} = E_{Nernst} - V_{ohm} - V_{act} - V_{conc} \qquad (5)$$

All these three voltages drop $V_{ohm}, V_{act}, \text{and} V_{conc}$, depend on fuel cell stack currenti_{FC}, temperature T, as well as physical parameters of fuel cell like - membrane area A_{cell}, its thickness l, concentration and consumption of reactants [31] [32].
By series-connecting N cells, the stack voltage rises to

$$V_{stack} = NV_{FC} \qquad (6)$$

When the external load is connected, this voltage reduces significantly due to load current and stack temperature [29].

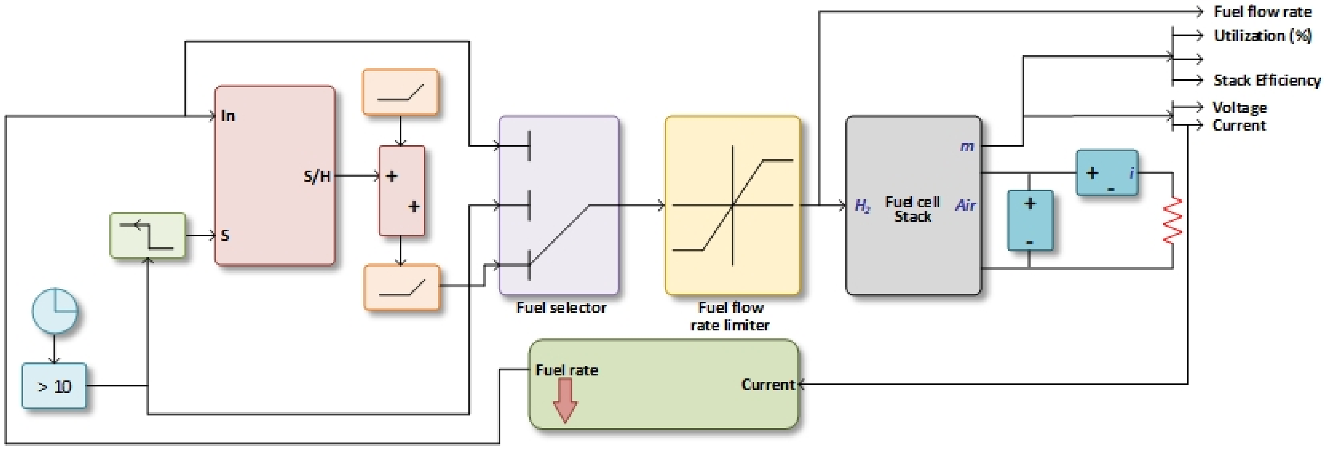


Fig 7. Fuel flow rate controlling of PEM fuel cells

2.2 Fuel Rate Control Mechanism

Figure 7 depicts the proposed system's mechanism for regulating the volume of fuel flowing through the system. The amount of current is directly proportional to the fuel flow rate. The fuel selector establishes connection with the relevant switch so that the appropriate action could be taken. A total of three switches controls the fuel selection. In situations of excessive fuel flow, the fuel flow limiter effectively limits the flow of gasoline. Thus, fuel cell current and voltage can be regulated by regulating the amount of fuel that is flowing through the cell.

2.3 Multi-Winding Transformer

The method for determining the required number of turns in multi-winding transformer is described here.
The Faraday's law

$$v(t) = N\frac{d\emptyset}{dt} \tag{7}$$

Shows that,

$$\emptyset(t) = \frac{1}{N}\int_0^t v(t)\ dt \tag{8}$$

Thus, the square-wave output voltage of the push-pull inverter while applied at the multi-winding transformer input, produces a triangular-wave flux in the transformer core as shown in Figure 8.
In $0 \leqslant t \leqslant \frac{T}{2}$:

$$V_{max} = N\frac{\Delta\emptyset}{\Delta t} = N\frac{(\emptyset_{max} - 0)}{\left(\frac{T}{2} - \frac{T}{4}\right)} \tag{9}$$

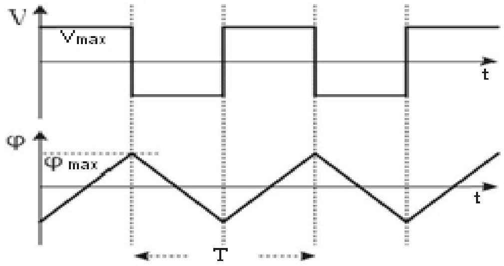


Fig 8. High-frequency transformer voltage and magnetic flux [31]

As for the square-wave voltage, $V_{rms} = V_{max}$, equation (9) reduces to

$$V_{rms} = \frac{4N\emptyset_{max}}{T} = 4fNAB_{max} \tag{10}$$

The voltage gain of this converter is given by

$$A_V = \frac{N_s}{N_p} \times D \tag{11}$$

Where,
N_s = no. of secondary turns,
N_p = no. of primary turns and
D = duty cycle

3 Grid Integrated Fuel Cell Power Generation System

Figure 9 shows schematic diagram of a typical grid integrated fuel cell power generation system. The utilization

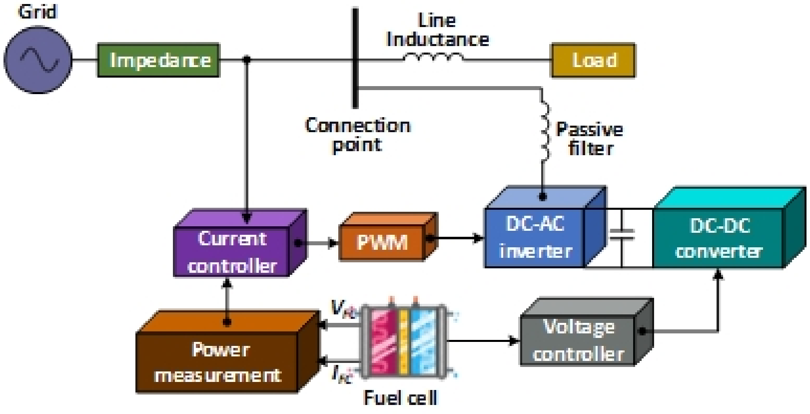


Fig 9. Schematic diagram of a conventional fuel cell power generation system.

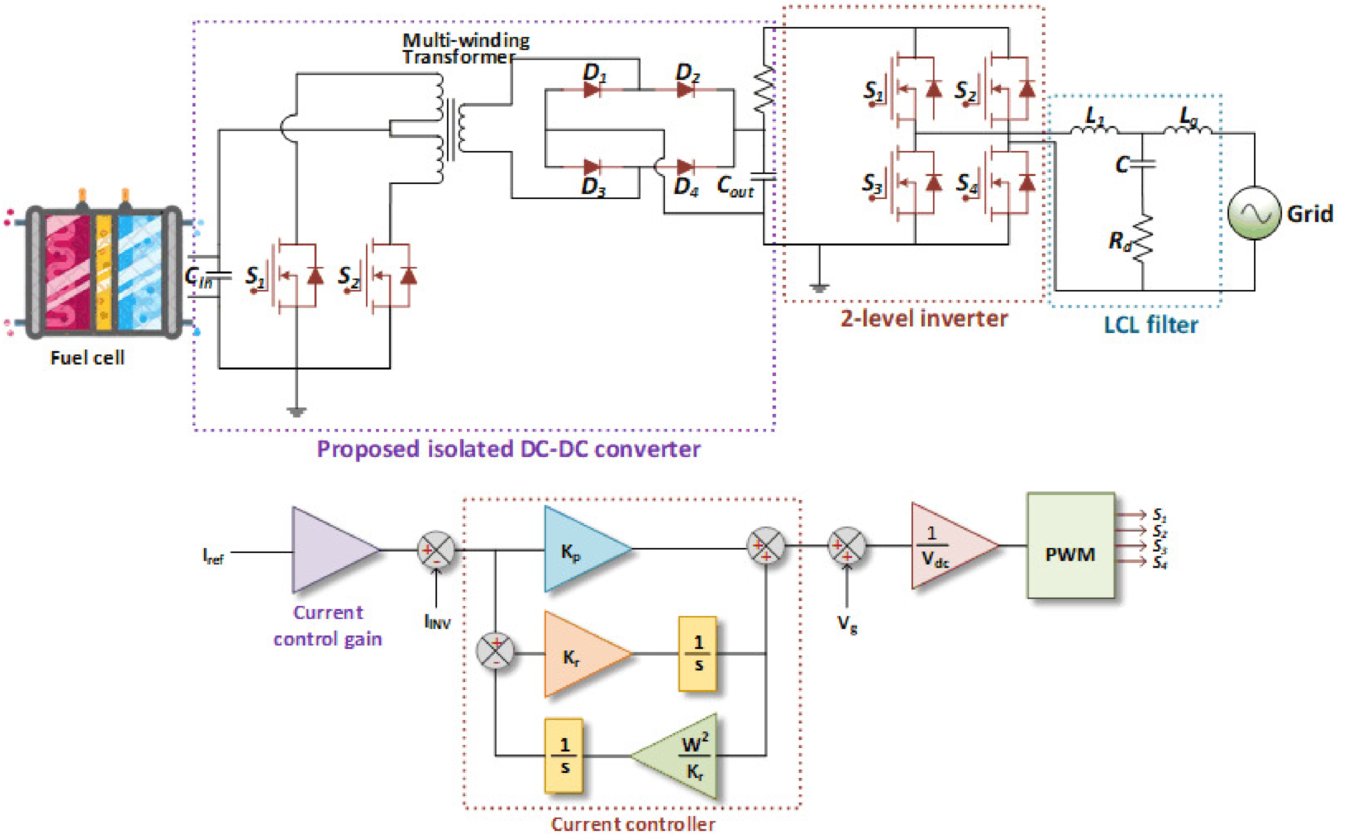
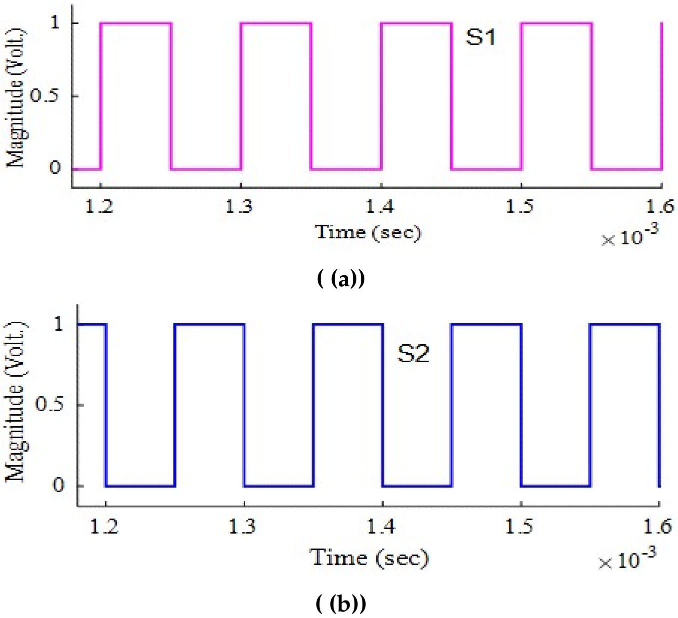


Fig 10. Detailed circuit diagram of grid-integrated fuel cell power plant.

of hydrogen gas (H^2) in combination with oxygen to produce direct current (dc) power of low magnitude. The produced voltage of the PEMFC is boosted using the proposed dc-to-dc converter. This boosted voltage is then passed through the inverter to produce appropriate ac voltage for grid integration. Besides, the proposed converter acts as isolation medium from high voltage side to low voltage side. To integrate with the grid, a current-controlled inverter is employed via an LCL filter.

This current controller makes the inverter ac output voltage in phase with the utility grid. This synchronization is crucial for maintaining a reliable power system and maximizing the effectiveness of energy transmission. The modern control system makes use of a PI and PR controller. The PR controller is employed here as it can ensure excellent reference tracking with zero steady-state error over a wide frequency range. The optimal values for the controller's parameters, namely $K_p = 1600, K_r = 100$, and $W_2/K_r = 986.83$, are determined using the trial-and-error approach. V_{ref} is calculated by adding the output of the PR converter to the grid voltage, followed by the division of the resulting voltage by V_{dc}. The firing pulses for the proposed inverter circuit are obtained by comparing the V_{ref} voltage with multiple carrier signals generated by the phase disposition (PD) technique. The LCL filter, here, acts as an isolator and it also eliminates the ripple of inverter voltage and current so that the THD of the system remains within the IEEE acceptable range. The detailed control circuit diagram of grid integrated fuel cell power plant is presented in Figure 10.



((a))

((b))

Fig 11. Switching pulses of semiconductor devices.

4 Simulation Results

The performance of the proposed push pull type high gain dc to dc converter is evaluated through simulation in Matlab/Simulink environment. For clarity, entire simulation result is divided into two parts. (i) dc to dc converter with 12 volts input supply and (ii) simulation of the proposed grid integrated fuel cell power generation system.

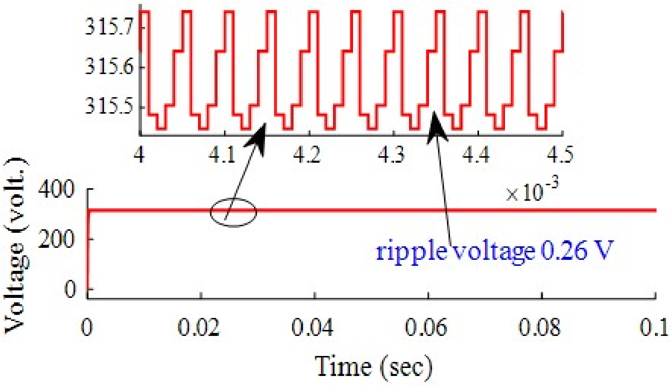


Fig 12. Output voltage of the proposed dc to dc converter

Table 2. Simulation Parameters of DC-to-DC converter

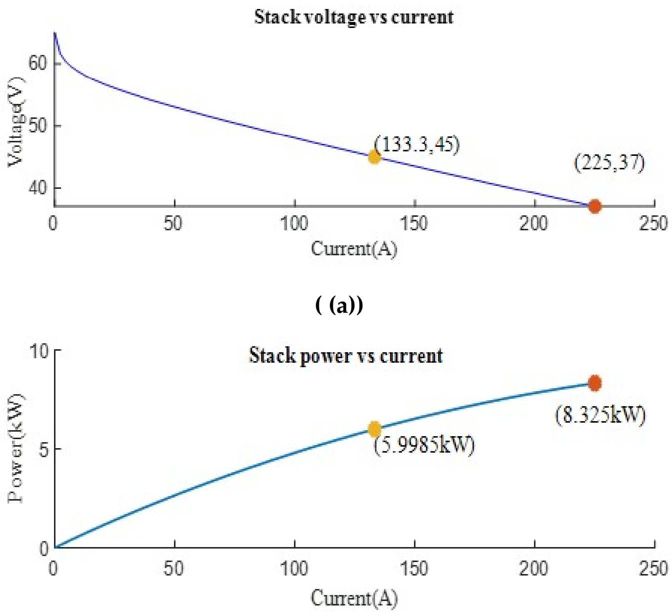
Parameter	Value
DC supply voltage	12 volts
Capacitors	2200µF, 64 µF
Multi-winding Transformer ratio	12:12:320
IGBTs	Internal Resistance=1e-3 Ω, Snubber resistance=1e5 Ω
Diodes	R_{on}=0.001, forward voltage=0 Snubber resistance=500 ohms, Snubber capacitance=250e-9 F
Load	100 ohms

Table 3. Electrical properties of a PEMFC

Parameter	Value
Stack rating voltage (V)	45
Stack rating Current (A)	133.3
Power (kW)	6
Maximum voltage (V)	65
Maximum current (A)	225
Time constant	1ms
Nominal stack Efficiency	55%
Number of cells	65

Table 4. Technical specifications for the proposed converter

Parameters	Rating(units)
PWM generator	TL494
DC Power Supply	PL-3003T (30V, 3A)
Transistor	BC547, BC557
Resistor	100, 1k, 10
Voltage Regulator	LM 7812
Input capacitor	1000µF (16V), 2200µF (25V)
Diodes	1N4007
Output Capacitor	33µF (2pics)



((a))

((b))

Fig 13. Switching pulses of semiconductor devices.

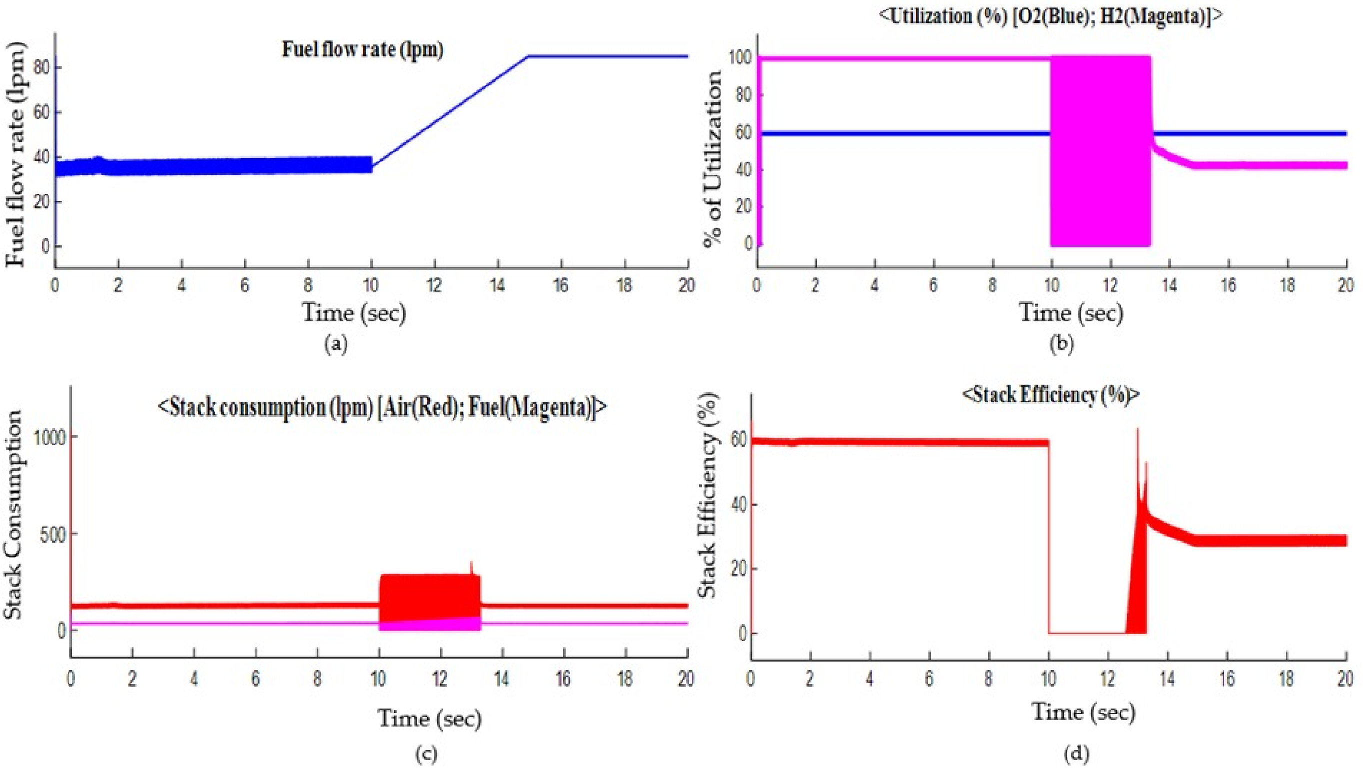
4.1 Simulation of Push Pull type dc to dc Converter

The proposed dc to dc converter is simulated with the parameters shown in Table-2. Figure 11 shows the pulses of two switching devices and the output voltage is shown in Figure 12. From this figure, it is seen that the proposed topology generates 326 V from 12 volts power supply with ripple voltage 0.26 V. Therefore, the proposed dc to dc converter has a voltage gain of 27 (approximate) with minimal ripple voltage.

4.2 Simulation of Fuel Cell Based Power Generation System

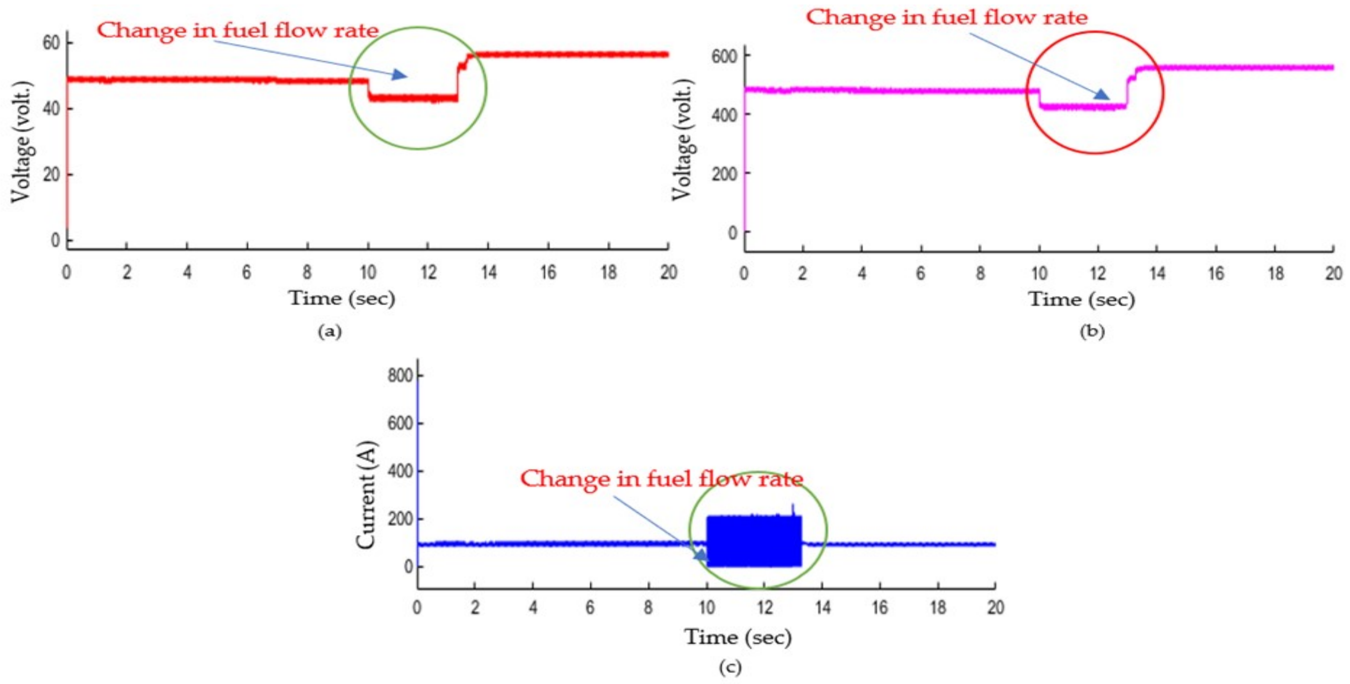
To assess the performance of grid-integrated fuel cell system simulations are carried out in Matlab/Simulink environment. In this study, a 6 kilo-watt (kW) 45 volts (V) proton exchange membrane fuel cell (PEMFC) is employed, and its corresponding parameters are shown in Table 3. Figure 13 (a) and 13 (b) show the variation of stack voltage, and power with current. The fuel cell stack provides dc voltage and current at the output terminals. This dc voltage is supplied to the proposed high-gain boost converter, which amplifies the 45Vdc input to nearly 500Vdc. This amplified voltage is then fed into a five-level inverter to generate ac voltage. To evaluate the impact on fuel consumption and system performance, the fuel flow rate is manipulated within the range of 35 to 85 liters per minute (lpm). The corresponding outcomes are depicted in Figures 14 (a), 14 (b), 14(c), and 14 (d). From Figure 14 (b) and 14 (c), it can be observed that variations in fuel flow rate do not exhibit a significant influence on both fuel consumption and the O_2 utilization factor.

The efficiency performance and hydrogen utilization factor of the device are influenced by the fuel flow rate, as depicted in Figure 14 (c) and 14 (d). Output of the fuel cell and boost converter are provided in Figure 15 (a) and Figure 15 (b) respectively. Based on the presented data, it is evident that the voltage produced by the fuel cell and the voltage of the boost converter exhibit a decline when the flow rate of the fuel cell is reduced. After a duration of 14 seconds, the generated voltage and the voltage of the boost converter exhibit an increase in relation to the flow rate. Nevertheless, the fuel current remains constant during the given time frame, as depicted in figure 15 (c). Nevertheless, the performance of the current controlled five-level inverter remains unaffected by variations in fuel flow rate. The fuel flow rate in this suggested system is controlled by applying a ramp signal. Following a duration of 10 seconds, there is an alteration in the fuel flow rate from its initial values, resulting in a further decline that persists until the 13.5-second mark. During this period, there is a decrease in the voltage generated by the fuel, leading to a subsequent fall in the voltage of the boost converter, as seen in figures 15(a) and 15 (b). However, it is noteworthy that this alteration does not have any impact on the efficiency of the power inverter. The constancy of grid voltage and current during the observed period is shown in Figures 16 (a) and 16 (b). It is evident that the fluctuating impact of the fuel flow rate does not affect the overall performance of the system.



(a) (b) (c) (d)

Fig 14. Responses of fuel cell (a) fuel flow rate (b) % of utilization of H_2 and O_2 (c) stack consumption (d) stack efficiency



(a) (b) (c)

Fig 15. Voltage and Current of the fuel cell and boost converter (a) fuel cell output voltage (b) boost converter output voltage (c) generated current in fuel cell

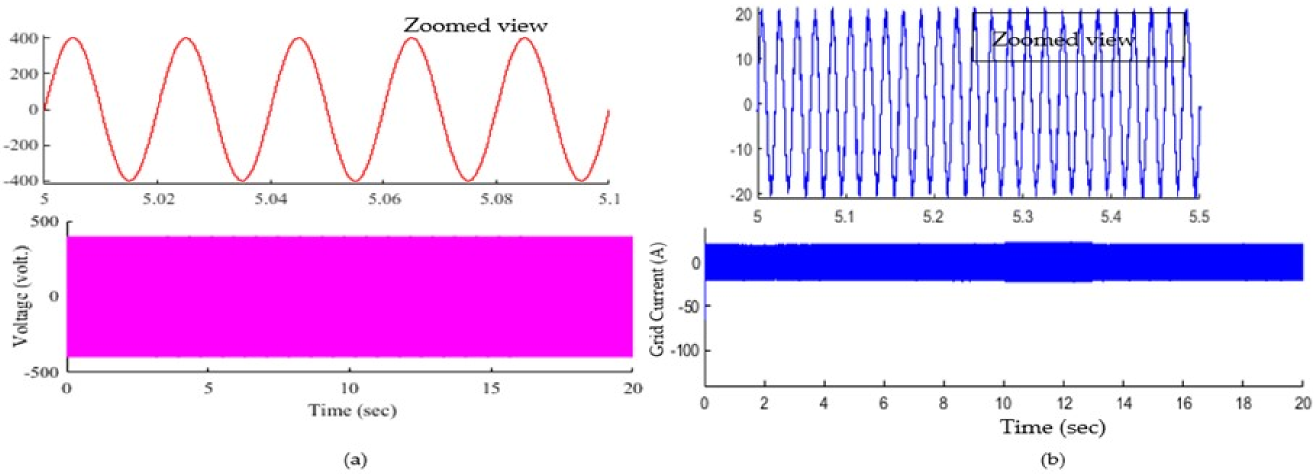


Fig 16. Output responses of power converter (a) grid voltage and (b) grid current

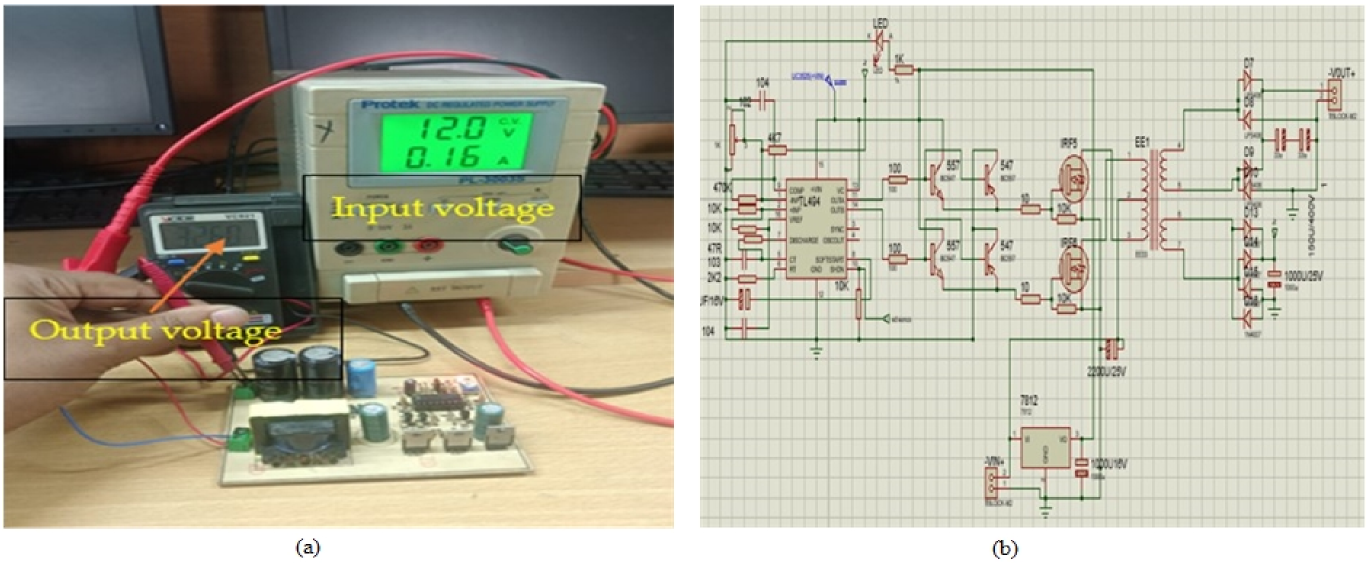


Fig 17. Proposed dc to dc converter (a) input-output arrangement and (b) Circuit diagram in Proteus.

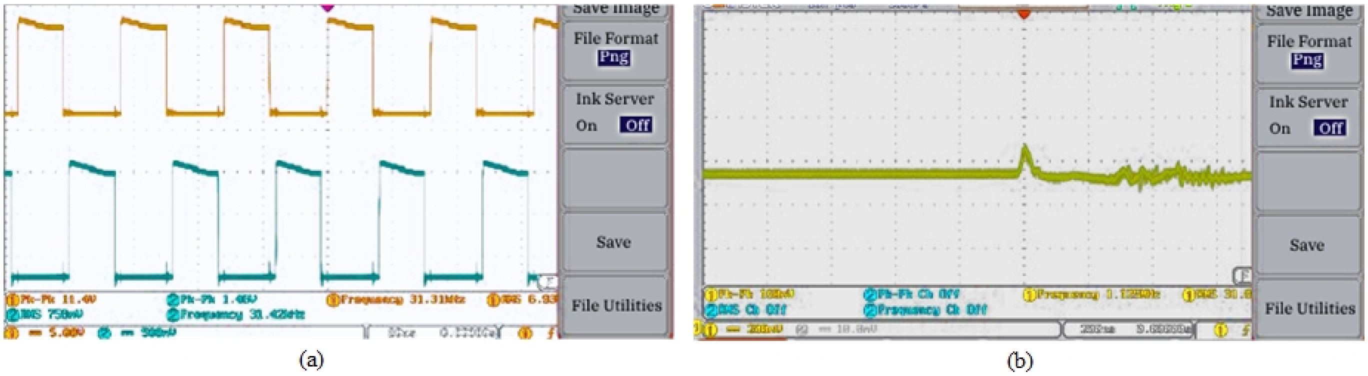


Fig 18. Responses of the proposed DC to DC converter (a) pulses of two switching devices (S_1, and S_2). (b) output voltage.

Table 5. Comparison of the proposed converter against existing converting technologies

Ref.	Frequency	No. of Switching devices	Number of diodes	No. of inductor	No. of coupling Inductor	No. of capacitors	Voltage Gain	Isolation capability
[33]	20 kHz	4	4	0	1	2	2.038	Yes
[34]	50kHz	4	2	1	1	2	12.5	Yes
[35]	-	5	4	1	1	3	2.5	Yes
[36]	50kHz	2	5	2	1	4	8.3	Yes
[37]	-	2	7	2	2	7	25	Yes
[38]	-	3	3	2	-	3	11.11	No
[39]	-	3	2	2	-	2	10	No
[40]	-	3	4	2	-	3	20	No
proposed	**10kHz**	**2**	**4**	**-**	**1**	**2**	**27.083**	**Yes**

5 Experimental Results

The performance of the proposed dc to dc converter has been examined through the construction of a lab prototype as depicted in Figure 17. Table 4 presents the technical details of the hardware. To get the constant dc voltage, the LM 7812 IC is used. Switches are operated at 10 kHz frequency and 50% duty ratio.

Figure 18 (a) shows the switching pulses of the high gain dc-dc converter. In this study, a dc power supply is utilized to represent the fuel cell. The results obtained from the proposed converter are shown in Figure 18 (b). From this figure 17, it is seen that the proposed converter produces 315 volts from 12 volts power supply conforming the simulation results shown in Figure 12. The boost converter exhibits a voltage gain of approximately 27.

6 Comparative Analysis

The contribution of the proposed converter is evaluated through a comparative analysis among similar works reported in the past. The comparison is based on several factors, including switching frequency, number of switching devices, number of diodes, number of inductors, number of coupling inductors, number of capacitors, and voltage gain as shown in Table 5. Both isolated and non-isolated dc-dc converters are considered. From the table it is observed that the proposed converter exhibits the highest voltage gain compared to the other topologies stated, with a value of 27.083. In addition, the proposed topology employs a smaller number of switching devices compared to the references [33]–[35], [38]–[40], while utilizing a higher number of power diodes compared to references [34], [38], [39].

Additionally, the proposed topology utilizes lesser number of capacitors compared to other topologies discussed earlier. It offers electrical isolation between high voltage and low voltage. Moreover, this particular configuration employs a lower switching frequency that would result in reduced switching losses. In summary, the proposed dc to dc converter provides high voltage gain with reduced number of components in comparison to the other topologies discussed.

7 Conclusion

This paper proposes push-pull type high-gain dc-dc converter with reduced number of switching devices and inductors. Operating at 50% duty cycle, it generates 326V from only 12V power supply representing a voltage gain of 27. Its output contains a very small ripple voltage of 0.26 V, and is electrically isolated from the input side, thus ensuring safety and reliability. The theoretical proposition is validated by simulation and small-scale lab prototype. One prospective application of the proposed dc-dc converter is integrating low voltage fuel cell based power source with the grid or other appliances. Grid integration feasibility of fuel cell is examined through simulation. Both standalone and grid connected results show that the proposed topology can be considered as a viable solution for applications involving dc-dc power conversion. In future, to further enhance the efficiency and reliability of the converters, emerging technologies can be explored which include - advanced control strategies, and integration with energy storage systems.

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