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A High-Gain DC-DC Converter for Fuel-Cell for Submarines

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Abstract

In this research paper, we present a novel high-gain DC-DC converter designed for fuel cell applications in submarines. Fuel cells offer significant advantages for submarine power systems due to their high efficiency, silent operation, and capability to function without atmospheric oxygen. The proposed converter enhances the low voltage output of fuel cells to meet the higher power demands of submarine systems. This paper details the structure of the converter, operational modes, and simulation results. The converter demonstrates substantial improvements in voltage gain and efficiency, making it a suitable solution for advanced submarine power applications.

Keywords: Fuel cell; DC-DC converter; High-gain; Submarine power systems; Power electronics

1. Introduction

In recent years, distributed generation (DG) technologies have garnered considerable interest due to their benefits, such as local production capabilities, enhanced resilience during grid outages, and positive environmental impacts [1]. DG units, including wind turbines, photovoltaic systems, and fuel cells, have become pivotal in modern power systems. Among these, fuel cells are particularly notable for their ability to produce power consistently, regardless of weather conditions, thanks to the steady availability of hydrogen and oxygen. Fuel cells generate electricity, water, and heat through an electrochemical reaction between hydrogen and oxygen, achieving an efficiency of 38% to 52% when producing only electricity, and up to 83%-87% when generating both electricity and heat. This dual efficiency makes fuel cells an optimal, clean, and safe power generation source [2, 4].

The application of fuel cells in submarines highlights their unique advantages in specialized environments. Submarines require a power source that is not only reliable and efficient but also capable of operating silently and without atmospheric oxygen. Fuel cells meet these requirements by providing a quiet power generation method and eliminating the need for regular air intake, which is crucial for underwater operations. The high efficiency and low thermal signature of fuel cells further enhance the stealth capabilities of submarines, making them less detectable by adversaries. Additionally, the ability to produce both electricity and heat enables fuel cells to support various submarine energy demands, from propulsion to onboard systems and crew support [5, 8].

DG technologies also enable network operation in island mode, where the DG unit operates independently from the main utility grid. This mode of operation is supported by power electronics interfaces that manage the flow of active and reactive power, ensuring stable network functionality. Standards provided by IEEE guide the monitoring and implementation of DG systems, emphasizing the importance of power electronic circuits in controlling power delivery [9, 10].

In medium and low voltage electrical systems, inverters are essential for power control, but traditional inverters face limitations in handling varying current and voltage ranges. Voltage source inverters typically reduce voltage, while

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current source inverters manage current reduction or voltage increase under constant power delivery. To address these limitations, DC-DC converters are used before inverters to modulate voltage levels. However, this combination can increase system complexity and reduce efficiency [11, 15].

The rising demand for renewable energy sources, particularly those with low output voltages, necessitates the use of voltage-boosting converters. Boost converters enhance voltage and serve as power factor modifiers, achieving high voltage gains by maximizing the duty cycle. Despite theoretical gains, practical limitations such as leakage inductance can restrict performance [16, 20].

Boost converters are classified into isolated and non-isolated types. Isolated converters, using transformers, separate the input source from the load, preventing load-side issues from affecting the input. These converters include full-bridge [21], half-bridge [22], forward [23], and flyback [24] types, mainly used as buck-boost converters. Non-isolated converters, which do not separate the input from the load, typically achieve higher efficiency and voltage gains due to lower conduction losses. They encompass various types, such as multilevel, coupled inductor, switched capacitor, switched inductor, multiphase, and integrated boost series converters [25, 30].

This research paper proposes a novel high-gain DC-DC converter structure tailored for fuel cell applications in submarines. Section 2 analyzes the proposed converter structure, Section 3 presents the simulation results, and the paper concludes with a brief summary in Section 4.

2. Analysis of the Proposed Structure

Figure 1 illustrates how the fuel cell is connected to the DC-DC converter. This converter steps up the low voltage from the fuel cell to supply power to the DC load. The specific DC-DC converter circuit used in this study is shown in Figure 2 and is comprised of four sections.

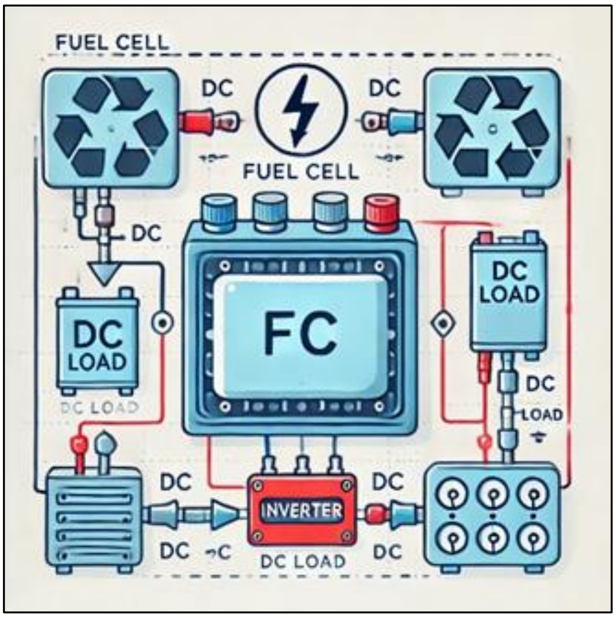


Figure 1 Block diagram of DC-DC converter for cell applications

The first section is the ASL network, which includes two switches (S1 and S2) and two inductors (L1 and L2). The second section is the ASC network, which uses the common switch S1 (shared with the ASL network), a diode (D1), and a capacitor (C1). The third section is the PSC network, consisting of two capacitors (C2 and C3) and two diodes (D2 and D3). The final section is the LC filter, containing an inductor (Lo) and a capacitor (Co). The converter operates in continuous conduction mode (CCM), which is divided into two operational modes.

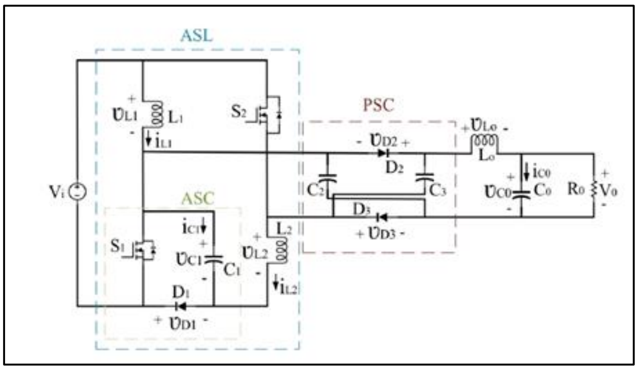


Figure 2 The equivalent circuit of the proposed structure

2.1. First Mode Operation

Switches S1 and S2 are activated simultaneously, causing diode D1 to be reverse biased. Consequently, inductor L1 gets charged via the input source, while inductor L2 is charged through a parallel arrangement of the source and capacitor C1. The PSC diodes, D2 and D3, remain non-conductive and are reverse biased during this phase. Capacitors C2, C3, and CO discharge their energy into inductor Lo. The equivalent circuit for this phase is illustrated in Figure 3.

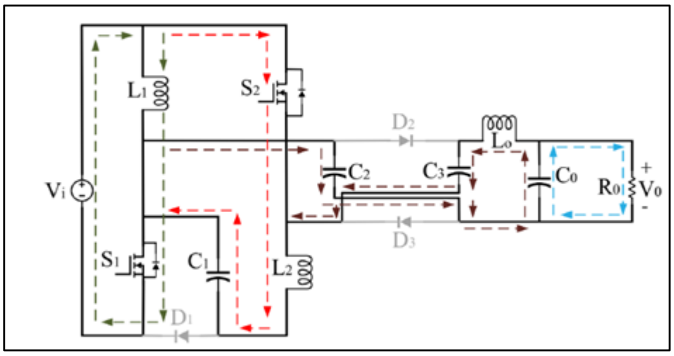


Figure 3 The equivalent circuit for first operation mode

2.2. Second Mode Operation

In this operational mode, switches S1 and S2 are turned off simultaneously, while diode D1 becomes forward biased and conducts. As a result, capacitor C1 is charged through inductor L1 and the DC source. Inductor L2 transfers its energy to capacitors C1, C2, and C3. Additionally, diodes D2 and D3 in the PSC network become conductive. Inductor Lo also discharges through capacitors C2, C3, and Co. The equivalent circuit for this mode is depicted in Figure 4. A summary of the proposed structure is presented in Table 1.

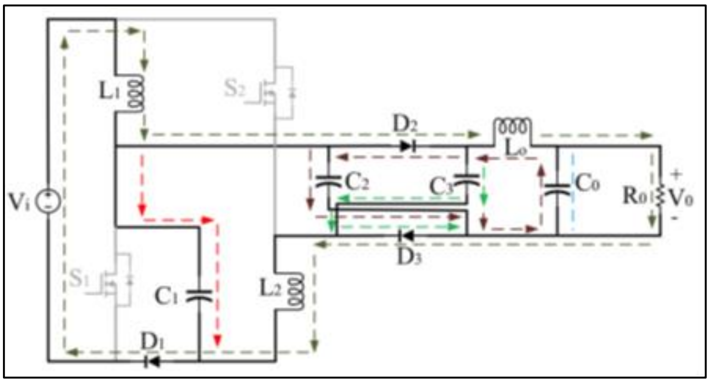


Figure 4 The equivalent circuit for second operation mode

Table 1 The number of components for the converter

Components	Specification
Switches	2
Capacitor	4
Inductors	3
Diodes	3

The voltage gain of proposed converter is obtained by (1):

$$M = \frac{V_o}{V_i} = \frac{1+3D-2D^2}{(1-D)^2} \quad \text{.................} \ (1)$$

Also, the voltage stress on switches is given by (2) and (3):

$$S_1 = \frac{V_{s1}}{V_i} = \frac{2M+4}{1+\sqrt{11+8M}} \quad \text{............} \ (2)$$

$$S_2 = \frac{V_{s2}}{V_i} = \frac{(2M+4)^2}{12+8M+2\sqrt{11+8M}} \quad \text{.....................} \ (3)$$

A PI controller is required to regulate the proposed converter and set the fuel cell voltage to the desired level. The voltage reference is compared to the actual voltage of the fuel cell, and the resulting error is fed into the PI controller. Figure 5 illustrates a basic block diagram of this PI controller.

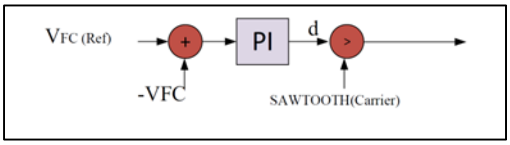


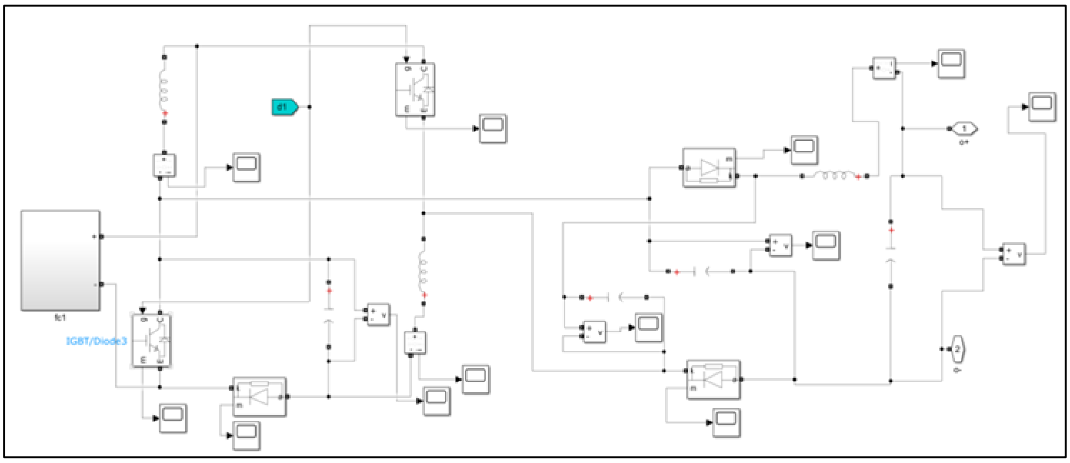
Figure 5 The PI controller for controlling the duty cycle

3. Simulation Results

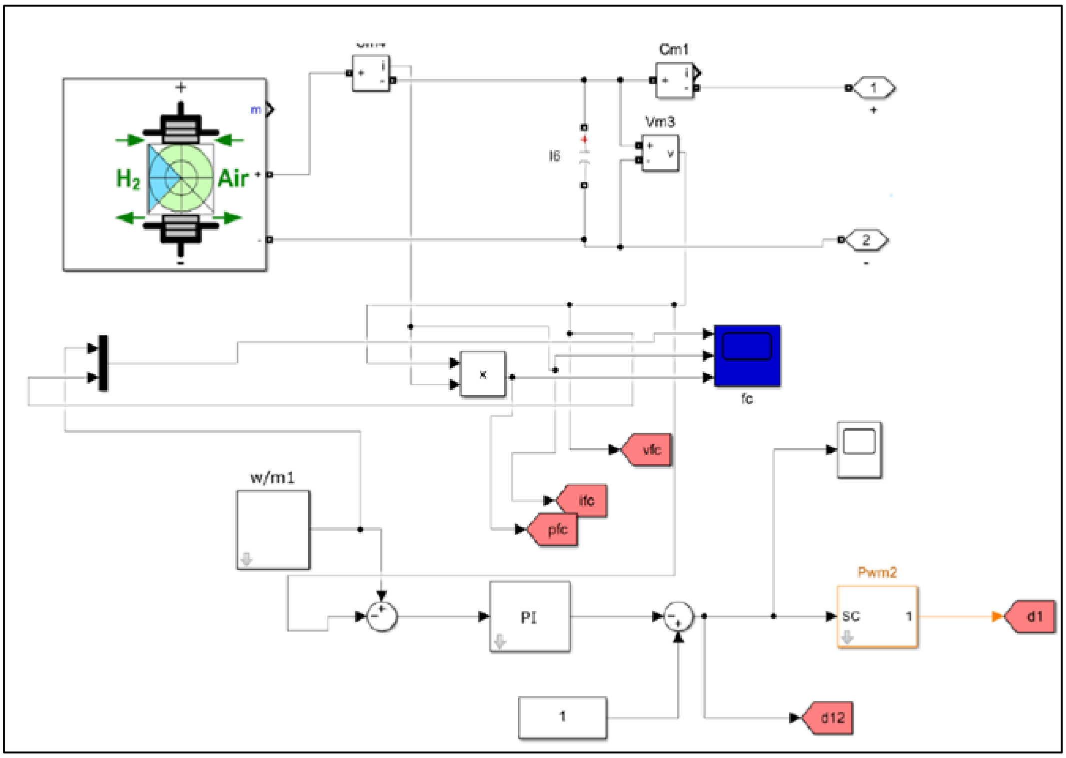
In this section, the performance of the DC-DC converter for fuel cell applications is evaluated using MATLAB/Simulink software. The converter's role is to adjust the fuel cell voltage to achieve the desired power output. The parameters used in the simulation are listed in Table 2. Figure 6 shows the implementation of the proposed system in MATLAB.

Table 2 The simulation parameters of proposed converter

Parameter	Value
Input capacitor of fuel cell	3100 µF
Capacitor C_1	400 µF
Capacitor C_2, C_3	120 µF
Capacitor Co	220 µF
Inductor L_1, L_2	3800 µH
Switching frequency	20 kHz
Proportional gain constant of PI controller	0.02
Integral gain constant of PI controller	0.32



(a)



(b)

Figure 6 Block diagram of MATLAB/Simulink; (a) proposed converter, (b) fuel cell implementation

The fuel cell operates within a voltage range of 244 to 254 volts. At 244 volts, it generates a current of 40 amps, resulting in an output power of 8 kilowatts. The simulation uses data points at 224 and 265 volts for validation purposes. During the simulation, the reference voltage of the fuel cell is adjusted at t=0.15 seconds to assess system performance. A DC-DC converter is used to step up the voltage from 224 or 265 volts to approximately 1544 volts. Figure 7 illustrates the output voltage of the fuel cell, showcasing the control system's ability to accurately track the reference voltage and exhibit a suitable dynamic response.

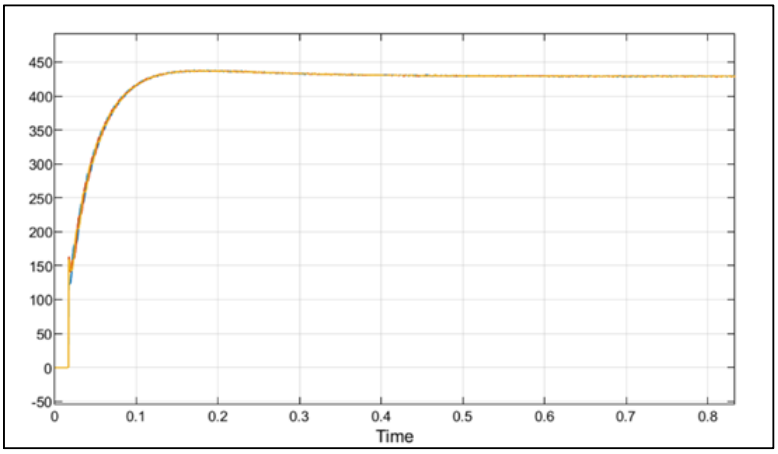


Figure 7 The output voltage of fuel cell

Figure 8 displays the current of the fuel cell, which exhibits minimal current ripple.

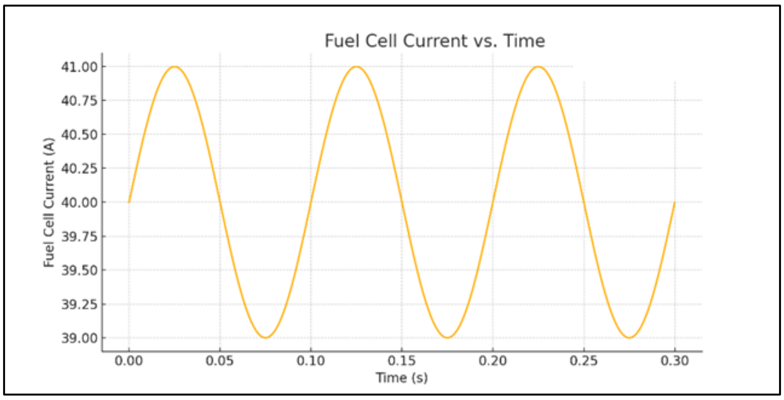


Figure 8 The current profile of fuel cell

The power output from the fuel cell, derived from its voltage and current, is 4300 watts until t = 0.15 seconds and increases to 7200 watts thereafter.

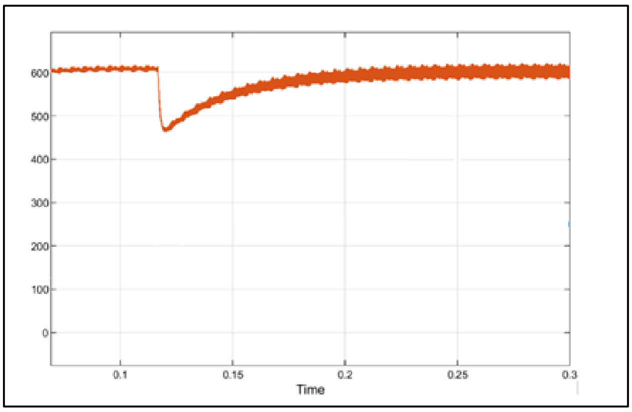


Figure 9 The output power of fuel cell

Given that the value of D is determined through impedance matching, for a fuel cell voltage of 265 volts, D is equal to 0.3. According to the voltage gain of the proposed converter in Equation (1), the output voltage is 1100 volts. Figure 10 shows the output voltage of the proposed converter. Ideally, the output voltage should be 1200 volts when the fuel cell voltage is 265 volts, but it experiences a slight drop due to losses.

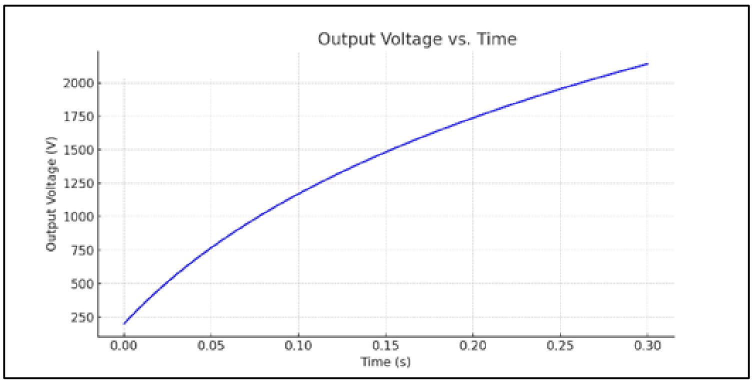


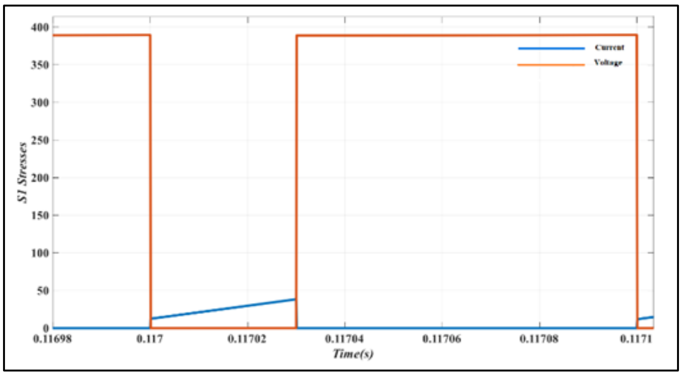
Figure 10 The output voltage of proposed converter

The following equations are used to determine the voltage stress on the S_1 and S_2 switches:

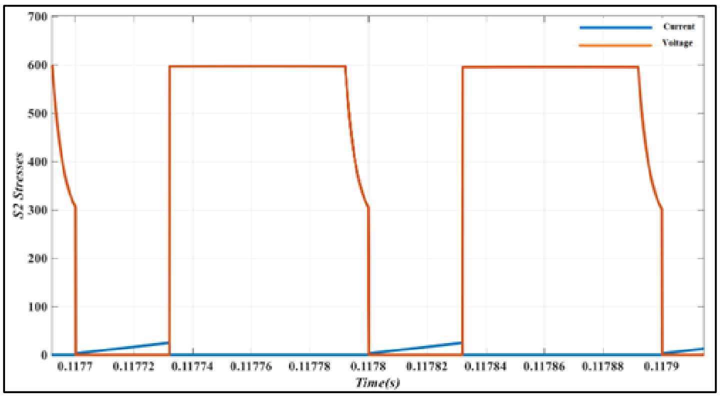
$$V_{S1} = \frac{2M+4}{1+\sqrt{11+8M}} \times V_i \text{ .... (4)}$$

$$V_{s2} = \frac{(2M+4)^2}{12+8M+2\sqrt{11+8M}} \times V_i \text{ ....(5)}$$

Figure 11 illustrates the voltage and current of switches S1 and S2. In Figure 11(a), the current of switch S1 increases up to 40 A due to the charging capacitor. According to Figure 11(b), the current of switch S2 reaches 26 A, which should be limited using snubber or clamp circuits.



(a)



(b)

Figure 11 The voltage and current of switches; (a): switch S_1, (b) switch S_2

4. Conclusion

The study introduces a high-gain DC-DC converter optimized for submarine fuel cell applications, addressing the critical need for efficient, silent, and reliable power sources in underwater environments. The proposed converter's design ensures enhanced voltage gain and operational efficiency, meeting the stringent demands of submarine systems. Simulation results confirm the converter's capability to regulate and step up the fuel cell voltage effectively, providing a robust solution for submarine energy needs. Future work will focus on further optimization and real-world implementation of the converter to validate its practical applicability and performance under actual operating conditions.

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