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Hybrid quadratic DC-DC boost converter for fuel cell-powered electric vehicle with wide voltage gain and low voltage stress

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ABSTRACT

The need to cut carbon emissions and the worry about global warming will be two of the major issues of the twenty-first century. Globally, academics are researching renewable energy sources, with the majority of their efforts focused on the converter side, which is critical to contemporary society. For energy conversion, fuel cells provide an alternative to internal combustion engines. Despite the fact that typical DC-to-DC converters experience high stress and minimal voltage rise, the bulk of research focuses on voltage lift. Researchers from all around the globe use DC-DC converters to control the voltage of fuel cells. If the targets are fulfilled, more switches will be placed, resulting in higher losses. The boost-cuk converter in this research has a high voltage gain and low switching strain. Initially, this contributed to the development of self-control. Switching losses are reduced when just one switch is used. A DC-DC converter is employed in this research to transform the electricity provided by fuel cells. The alternating supply is then sent to the brushless direct current (BLDC) motor by the PWM inverter. The work starts by building MATLAB simulation blocks. Finally, Simulink is used to display the simulated output waveforms of the intended converter.

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1. INTRODUCTION

Today, transportation has become important. It is often impossible to eliminate the utilization of hydrocarbon in any form (gas, liquid and solid) and are utilized in the great majority of transportation techniques [1]. As well as contributing to environmental degradation, these fuels are becoming scarcer [2]. Many professionals in the car industry are engaged in the research and development of automobiles that use less fossil fuel and produce less pollution [3]. To reduce its environmental effect and reliance on fossil fuels, the car industry is investigating renewable energy solutions [4].

Fuel cells, a kind of renewable energy, are one option [5]. This is a clean way to get energy because it uses hydrogen and oxygen to make water as a byproduct [6]. Due to its great flammability and explosive potential, hydrogen use necessitates a number of safety precautions [7]. High-voltage output must be generated via a stack of unpredictable, low-voltage, current-intensive power sources since high-power fuel cells are very costly [8].

With each fuel cell, the fuel cell generates 1.16 volts. The quantity of stacked fuel cells used to increase output voltage [9]. As a safety precaution and to extend its lifespan, the maximum output voltage of a fuel cell is set at 100 volts. The DC bus of a fuel cell electric car cannot be powered by the generated voltage, which is why this converter was created. Depending on the demands of the vehicle, this converter allows the fuel cell voltage to be raised from 100 V to 250 V or even more. The typical input voltage range for electric cars is between 250 V and 400 V.

Scientists have created a broad range of boosting topologies, including the three-level boosting converter, hybrid, multilevel, switched inductor, switched capacitor, cascaded converter, linked inductor, Z source network, Quazi "Z" source network, and parallel resonant converter [10]. A DC-DC converter is offered since some of these topologies do not match all of the requirements (reliability, low current ripple, low voltage stress across the switches, and high voltage gain) [11].

Bringing together the boost and cuk converters, the suggested converter is a hybrid quadratic boost converter Type I and Type II [12]. In this section, we compare the suggested converter to the standard hybrid boost converter and characterize the performance differences across a range of metrics [13]. Using the MATLAB program, we simulate the suggested converter and get the steady-state output voltage and current [14].

2. CIRCUIT CONFIGURATION

To take advantage of the voltage increase offered by a DC to DC standard quadratic boost converter as illustrated in Figure 1, it has been the subject of research and practical application [15]. Since it only requires one switch, it is simple to implement, but parasitic resistances and on-state voltage dips reduce the gain it produces [16]. Converter's power topology, which was the first to be suggested to solve this problem, it is suggested that the Type 1 hybrid quadratic boost converter (HQBC Type I) shown in Figure.2 that combines the boost converter with the cuk converter [17]. This suggested converter, which also has a switch, has a lower voltage stress across the switch than the converter's output voltage, which could lead to a large voltage gain [18]. Similar to the first kind of hybrid quadratic boost converter (HQBC), this second type depicted in Figure 3 employs a switch to reduce voltage stress and has the potential to provide a greater voltage gain over a broader input range than the first type [19]. Since continuous conduction mode (CCM) operation offers a constant current for fuel cell applications, it was proven to be the most efficient mode of operation for hybrid quadratic boost converter Type I (HQBC Type 1) and hybrid quadratic boost converter Type II (HQBC Type 2) [20].

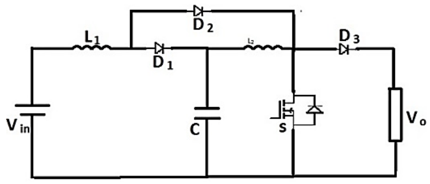

Figure 1. QBC converter with conventional quadratic DC-DC boost

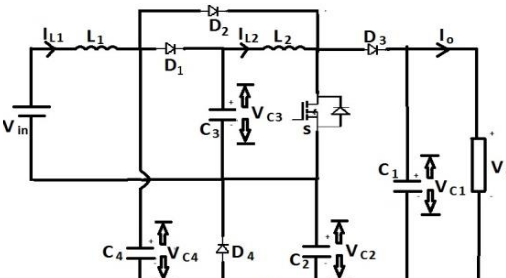

Figure 2. Type-I proposed hybrid quadratic boost converter

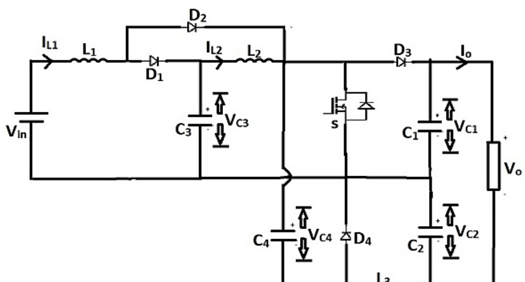

Figure 3. Type-II proposed hybrid quadratic boost converter

3. CIRCUIT OPERATION

Since the two suggested converters work on similar principles, the HQBC Type I will be analyzed here and its key wave forms are shown in Figure 4, the suggested converter operates in CCM mode, which maximizes the efficiency [21].

i) Mode 1: [t_1- t_2]

The operational diagram for this mode is shown in Figure 5. The transition from the intermediate state to the first phase occurs at this particular moment, as switch 'S' is toggled ON. When a DC power supply is plugged in, energy from capacitors C_3 and C_4 begins charging inductors L_1, L_2, and L_3, while diodes D_1, D_3, and D_4 are switched off due to their reversed bias. C_1 capacitor is used to charge up the appliance [22].

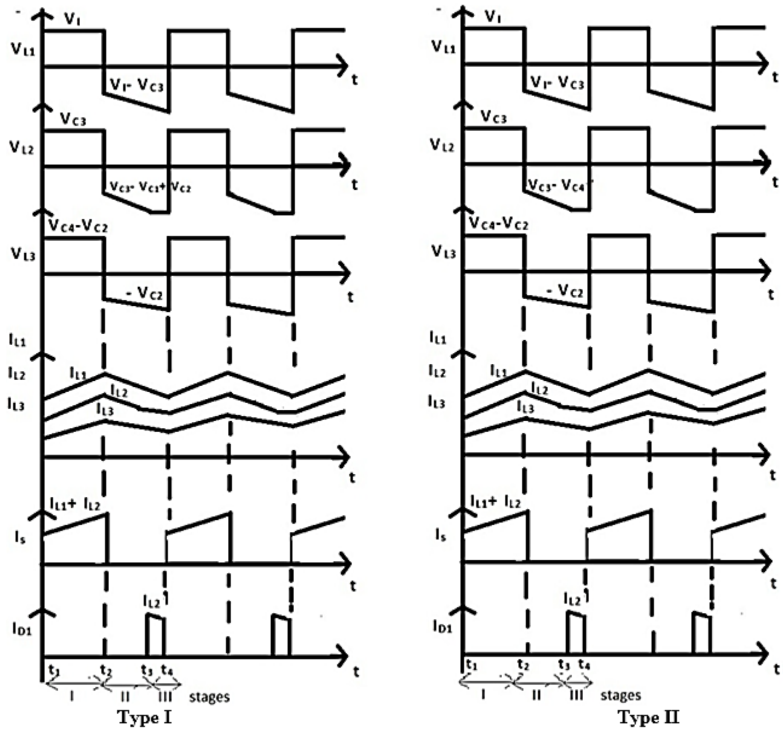

Figure 4. Important waveforms associated with the operational phases of power converters

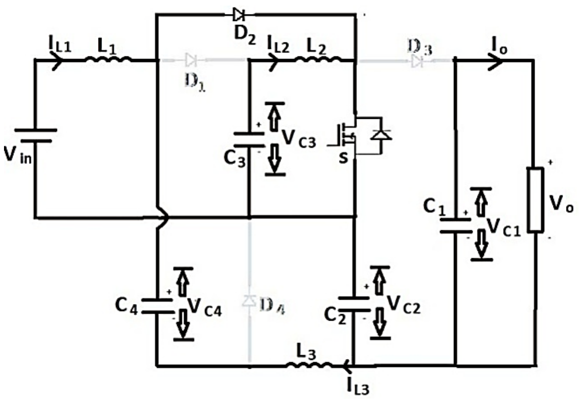

Figure 5. Mode 1 proposed hybrid quadratic boost converter [t_1- t_2]

ii) Mode 2: [t2- t3]

The circuit shown in Figure 6 depicts that at this very moment, the "S" switch is disabled. Through a series of inductors (L_1, L_2, and L_3), energy is stored and then transferred to capacitors (C_1 and C_4), which in turn provide the load when their currents decrease. It's important to remember that this only occurs when the voltage across C_3 (V_{C3}) is higher than the voltage across C_4 (V_{C4}), i.e., $V_{C4}<V_{C3}$. This D_3remains in reverse bias.

iii) Mode 3: [t3- t4]

The schematic representation of this mode is shown in Figure 7. Here and now, switch "S" is off, however V_{C4} is superior than V_{C3} due to the switch's position. While inductors L_2 and L_3 are feeding energy back to capacitor C_1, the charge held in L_1 is being transferred to C_3.

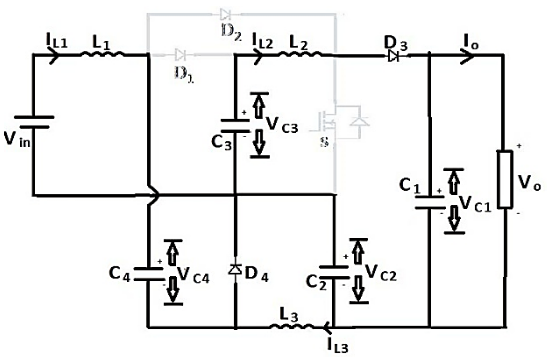

Figure 6. Mode 2 proposed hybrid quadratic boost converter [t_2- t_3]

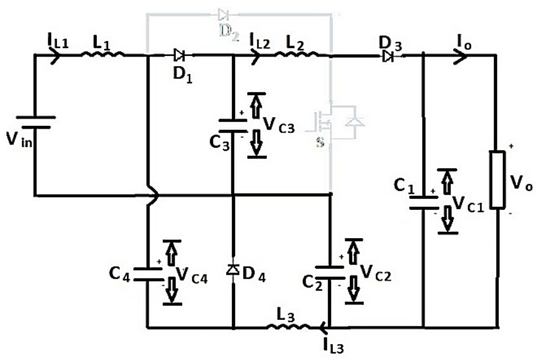

Figure 7. Mode 3 proposed hybrid quadratic boost converter [t3- t4]

The results indicate that the input current is relatively constant and the load is perpetually powered throughout all time intervals. Utilizing a constant current in the load increases efficiency. The proposed Type II Converter displays the same sub-intervals as the proposed Type I converter during CCM operation.

4. VOLTAGE GAIN

4.1. Conventional quadratic boost converter

The voltage gain V_O/V_{in} of traditional QBC is dictated by the switching operation, or duty cycle [23]. In this instance, the equation represents the voltage gain of a standard quadratic boost converter.

$$\frac{V_O}{V_{in}} = \frac{1}{(1-\delta)^2} \quad (1)$$

At δ = 0.7, The voltage gain rises from 3.3 to 11.11 for this value of duty cycle.

4.2. Hybrid quadratic boost converter (Type I)

Concerning the constant-current-mode (CCM) operation and voltage gain of this single-switch converter, it is observed that the proposed converter's voltage gain can be expressed as:

$$\frac{V_O}{V_{in}} = \frac{1+\delta(1-\delta)}{(1-\delta)^2} \quad (2)$$

the suggested converter's gain goes from 3.3 to 13.4 if the duty cycle is 0.7. Compared to standard quadratic boost converter, this gain is superior [24].

4.3. Hybrid quadratic boost converter (Type II)

The recommended hybrid quadratic boost converter Type II converter has undergone extensive investigation, and it is possible to draw conclusions about the relationships between the input and output voltages from this data. The following equation gives the estimated voltage gain.

$$\frac{V_O}{V_{in}} = \frac{(1+\delta)}{(1-\delta)^2} \quad (3)$$

If the duty cycle is less than or equal to 0.7, the proposed converter's gain increases from 3.3 to 18.88. This level of gain is preferable over the hybrid quadratic boost converter (Type I). Voltage gain vs duty cycle for a conventional converter, HQBC Type 1, and HQBC Type 2 are shown graphically in Figure 8.

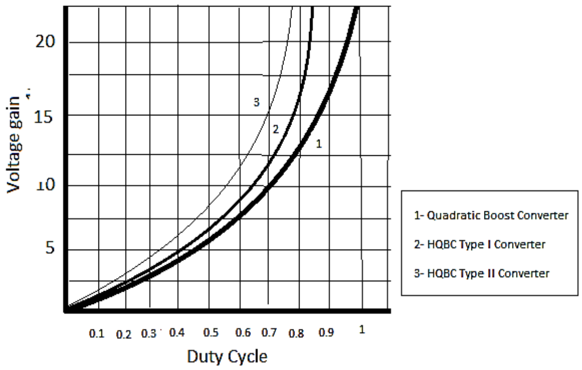

Figure 8. Voltage gain vs duty cycle

5. VOLTAGE AND CURRENT STRESS

5.1. Voltage stress

The Suggested converters be examined in terms of the VI stress they experience [25]. The voltage across the switch in a Type I quadratic boost converter is calculated as follows: voltage across C_1 (Vc_1) minus voltage across C_2 (Vc_2). The voltage across the switch is calculated taking into account the average value while the capacitors are charging and discharging. The voltage across capacitor C_1 in a Type II hybrid quadratic boost converter is the voltage stress across the switches. An equation for voltage stress is

$$Voltage\ stress\ For\ HQBC\ Type\ I, V_{Smax} = V_{C1} + \frac{\Delta V_{C1}}{2} - V_{C2} - \frac{\Delta V_{C2}}{2} \tag{4}$$

$$Voltage\ stress\ For\ HQBC\ Type\ II,\ V_{Smax} = V_{C1} + \frac{\Delta V_{C1}}{2} \tag{5}$$

5.2. Current stress

Under steady-state circumstances, the functioning of both proposed circuits is equivalent, and current flows to the load continuously during all the subintervals [26]. The equation for the present stress is (6).

$$\text{current stress For HQBC Type I \& II, } I_{Smax} = \frac{(2\delta+\delta^2+\delta^3)I_o}{(1-\delta)^2} \tag{6}$$

According to the aforementioned study, the switch is under less voltage stress than the power converter output voltage (Vo). It does, however, need a higher current stress than a typical quadratic boost converter [27]. Figure 9 depicted to realize the blocking voltage across the switch per duty cycle.

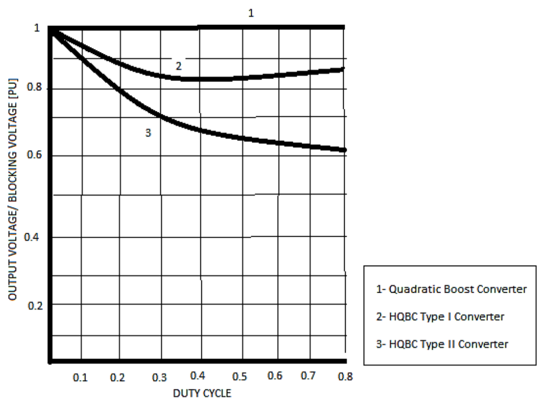

Figure 9. Blocking voltage required by the switch to complete the duty cycle function versus output voltage

6. BRUSHLESS DC MOTOR DRIVE CHARACTERISTICS

The DC motor has the most promising efficiency, speed control, and torque management characteristics of any electrical motor drive. This is because DC motors can instantly transform the energy from electricity into mechanical motion. Because of the commutator, the drive is now more complicated and bulkier than before. About half of the total anticipated price goes towards the commutator. Carbon brushes accelerate tarnish and machine wear in electrical motor drives, significantly increasing repair and maintenance costs [28].

The electronic commutator replaced the traditional commutator. The sensors are located on the stator, determine the location of the rotor magnets. The timing of the stator windings' power delivery and the timing of the required commutation for the motor's proper operation are set by the signals that come from the Hall sensors. The controller is in charge of decoding the signals transmitted by the hall sensors and delivering the proper current to the motor's stator windings. It is in charge of regulating the timing and order of commutation, ensuring the motor runs smoothly and effectively [29].

A brushless direct current (BLDC) motor's complicated control algorithm decides when and for how long to energize the stator windings depending on the rotor's location. This information is sent back into the motor control system. This control method improves the efficiency of BLDC motors while allowing for fast acceleration and deceleration. In addition, it enables fine-tuned control over velocity and torque. Electronic commutation and the absence of brushes in BLDC motors boost their efficiency relative to brushed motors, making them more effective. As a result, both the quantity of heat produced and the amount of energy used are decreased. Since BLDC motors lack brushes, they are substantially more resistant to wear and tear than brushed motors. They become more dependable as a result, and they live longer [30].

BLDC motors are a great option for situations that call for precise motion control due to their smooth and accurate control over both speed and torque. Comparing brushed motors to BLDC motors, the power-to-weight ratio of BLDC motors is higher. As a result, BLDC motors are the best choice for applications where size and weight are important considerations. BLDC motors are perfect for use in delicate electronic equipment since its electronic commutation produces less electromagnetic interference. This is due to the high level of dependability of BLDC motors [31]. In view of the significant beginning torque required at the lowest possible speed, torque plays a significant part in this job. According to the findings of the MATLAB simulation, the converter with a certain design, such as the converter that we have suggested, causes the motor to create a significant amount of beginning torque and also has running torque [32]. the speed vs time and torque vs time characteristics of the BLDC motor is studied and realized in Figure 10.

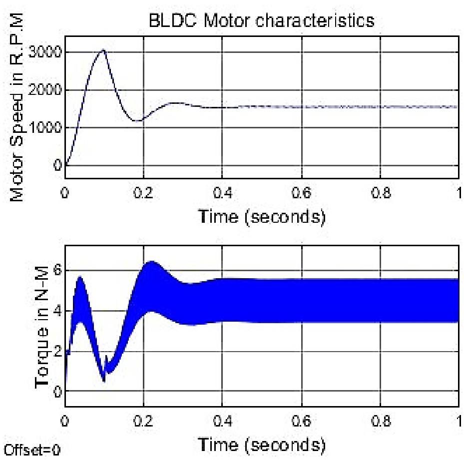

Figure 10. Speed vs time, torque vs time characteristics

7. RESULTS AND DISCUSSION

MATLAB simulations are used to compare the efficiency and voltage gain of the proposed hybrid quadratic boost converter Type I to those of a conventional quadratic boost converter. Findings indicate that hybrid quadratic boost converters of Type I perform better in terms of efficiency and voltage gain. Using the examples below, the efficacy of the proposed converter is compared to that of the conventional converter.

Here is a clip from a virtual test drive of a fuel cell electric vehicle using a standard quadratic boost converter shown in Figure 11. After performing simulations with the aid of the MATLAB application, the converter's efficiency is calculated. The simulation evidence shown here depicts the gradual increase in voltage from the starting point. The planned converter takes in 40 V of input and operates at a duty cycle of 0.7. Assuming a zero-volt starting point, the converter quickly increases the voltage to about 400 volts. By shortening the converters on time to 0.18 seconds and setting its output voltage to 180 volts, the controller exerts control over the converter. As can be seen in Figure 12, the controller settled on a constant set voltage of 220 V. The BLDC motor is connected to the converter's output, which was carefully planned.

In the first stage, a standard quadratic boost converter is simulated. The fuel cell's output is connected to the converter's input. The cell's parameters are 27 V, 40 A, and 1000 W. The converter has improved its voltage gain and is now supplying the vehicle's DC bus. The output of the converter is rated at 220 V, 4.2 A, and 940 W. At 0.7 duty cycle, the converter's voltage gain is 8.14 and its efficiency is 94%. The following diagrams depict the voltage, current, and power waveforms generated by the fuel cell and the converter.

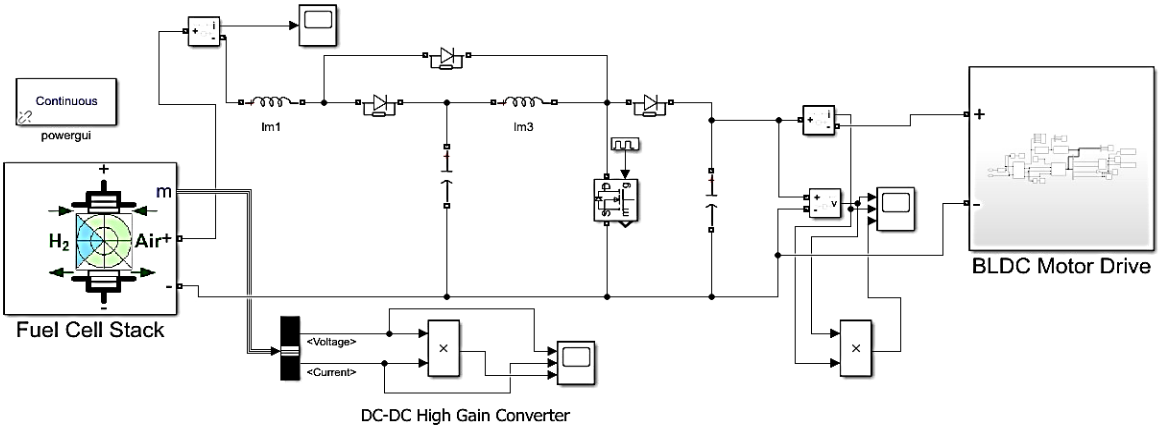

Figure 11. Simulation of conventional quadratic DC-DC boost converter

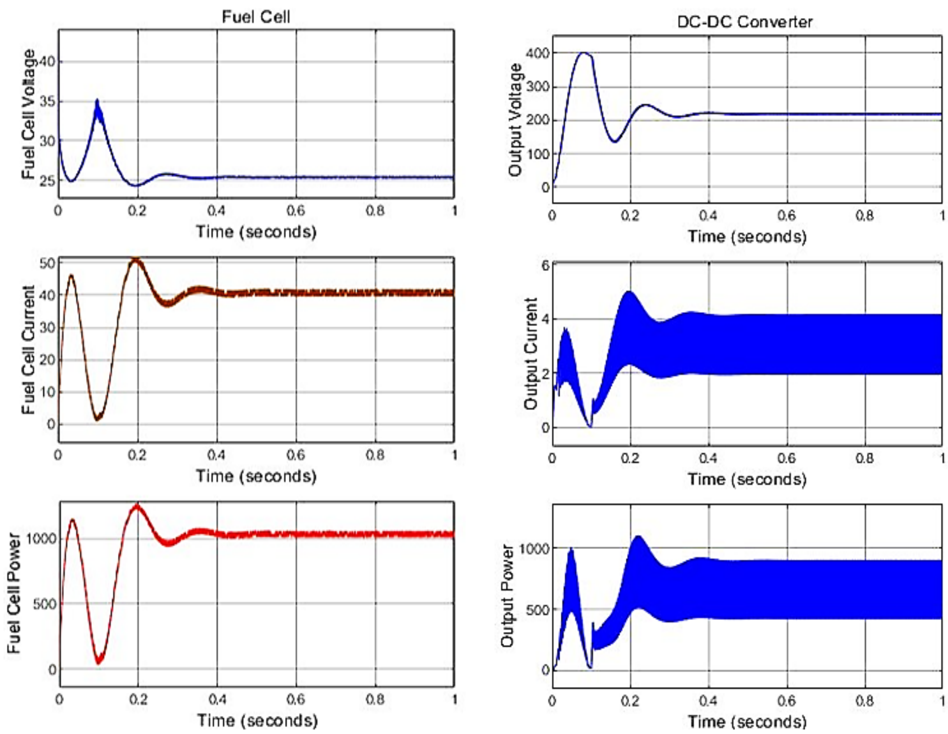

Figure 12. Characteristics wave forms of conventional quadratic DC-DC boost converter

The Figure 13 depicts the simulation diagram for a Type-1 hybrid quadratic boost converter fuel cell electric car. Furthermore, a MATLAB simulation is used to determine the converter's efficiency. MATLAB is also used to analyze the effectiveness and voltage gain of the Type-I hybrid quadratic boost converter. The proposed converter makes use of PEMFC's, which provide the same amount of energy as normal fuel cells (27 V, 40 A, and 1000 W). The suggested converter has 290 volts, 3.4 amps, and 986 watts of output power. The output voltage of this converter has been proved to be higher, and its efficiency has increased from the average to 98.6%. Figure 14 depicts the simulation results below.

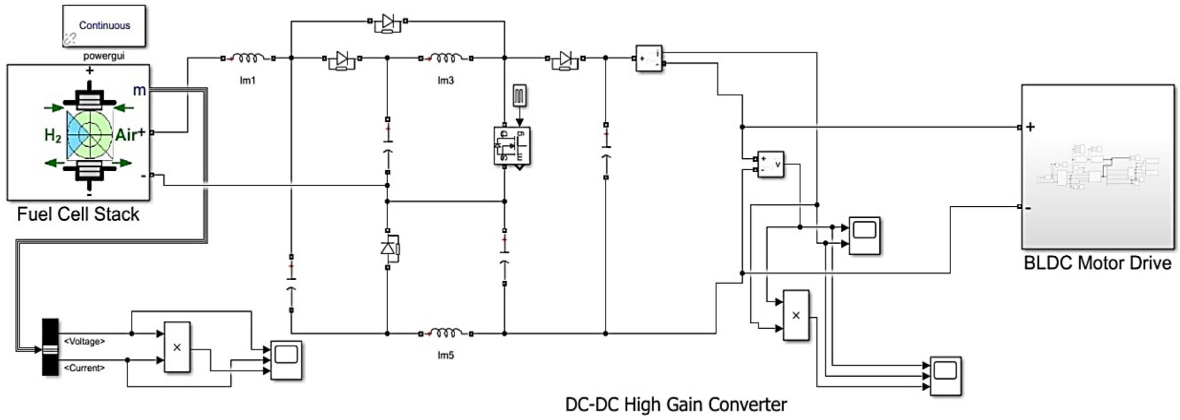

Figure 13. Simulation diagram for proposed hybrid quadratic DC-DC boost converter

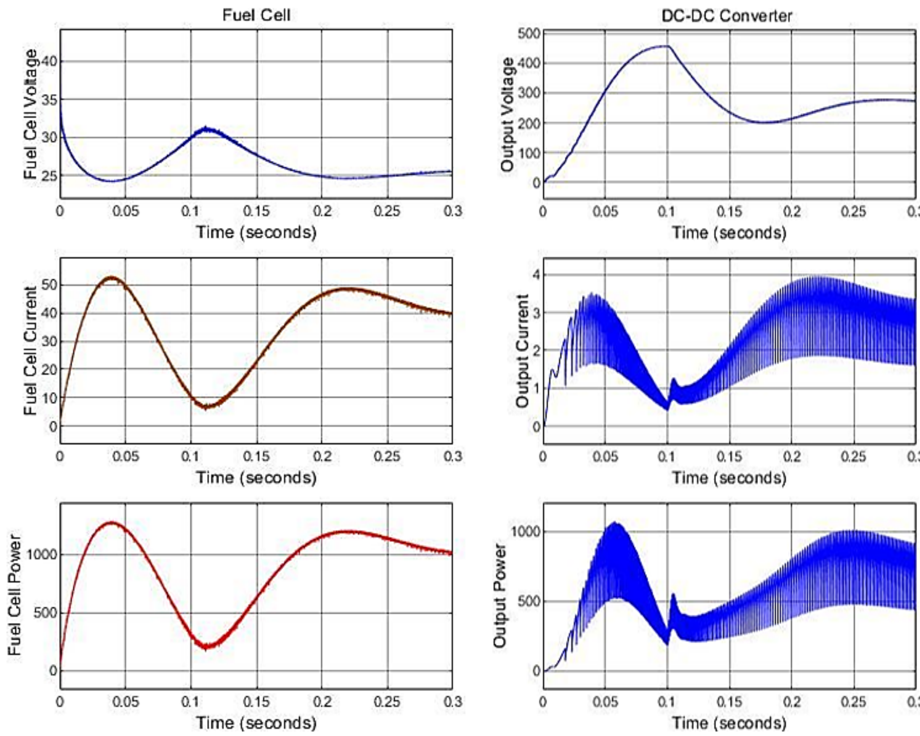

Figure 14. Characteristics wave forms for proposed hybrid quadratic DC-DC boost converter

8. CONCLUSION

In MATLAB, a Type-I hybrid quadratic boost converter is described and modeled. A fuel cell with the following characteristics serves as the input power source: 27 V, 40 A, and 1000 W. In a converter, the voltage from this input is multiplied by 10.7, producing an output of 290 V, 3.4 A, and 986 W. The output is found to be rather efficient when compared to a conventional quadratic boost converter output of the 220 V at 4.2 A and 940 W. We demonstrate the astounding efficiency of 98.6% that a Type I hybrid quadratic boost converter is capable of. After the output voltage has been measured, the BLDC motor may be driven by it. More gears may be added to enhance the speed if required. The motor may revolve at a maximum speed of 2500 rpm.

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