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An Electrical Vehicle Fuel Cell Supported High-Voltage Gain Quasi-Z-Source Boost Dc-Dc Converter

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Abstract- A shifting capacitor-based quasi-Z-source boost dc-dc converter is recommended for fuel cell vehicles. To get a high-voltage gain across a wide input voltage range, just a low-voltage stress has to be applied across each component of the design. The efficiency of the proposed converter is compared with comparable converters that use Z-source networks. In order to validate the proposed technology, a downsized 400-V/400-W version is developed. A maximum efficiency of 95.13% is seen when the input voltage fluctuates greatly because of the PI controller in the voltage loop, which prevents the matching fluctuation in the output voltage.

Key words: boost dc-dc converter, voltage PI driver, quasi-Z source, shifting capacitance, and wide range of voltage gain.

1. INTRODUCTION

Pure energy solutions must be developed immediately in order to improve the environment and address issues related to energy use, given the increasing popularity of green energy sources and the need to reduce the use of fossil fuels. This is become more problematic as the number of automobiles on the planet increases, contributing to the increase in air pollution. The production of clean energy vehicles has increased significantly, and their percentage of the total transportation fleet is growing. Fuel cell cars are an important part of these renewable energy vehicles and have been utilized widely in reality due to their high-density current production, pure power generation, and high-efficiency operating characteristics [1], [2]. Unlike batteries, which have a relatively constant output voltage, the fuel cell's output voltage quickly drops as the output current rises [3-6]. Consequently, it has to be connected to the high-voltage dc-link network of the inverter using a step-up dc-dc converter with a wide voltage gain range [2]. The standalone step-up dc-dc converter easily achieves a significant voltage boost. On the other hand, the energy generated from the leaky inductance of the transformer may increase switching losses, produce high-voltage stress, and lead to hazardous electromagnetic interference [7]. To save expenses, reduce converter size, and increase conversion efficiency, a no isolated step-up dc-dc converter is often used. One of the most often used no isolated step-up converters is the conventional boost dc-dc converter. The converter has a single power button and a simple design. Because the power switch's potential duty cycle may be adjusted from 0 to 1, the voltage rise might be limitless [8], [9]. Nevertheless, the presence of parasitic elements in the circuit limits the voltage rise [10], [11]. Furthermore, since the power switch endures voltage stress equivalent to that of the output voltage when the output voltage is high, it has to be high-voltage rated.

Several solutions have been proposed for this job in view of the aforementioned problems. A hybrid boost three-level dc-dc converter with a high voltage gain was proposed as a power connection between the low-voltage photovoltaic (PV) panels and the high-voltage dc bus for the PV production system in order to reduce the voltage stress and match the voltage levels [12]. Noncommon grounds between the input and output sides are apparent even after attaining the necessary voltage stress and gain, which may limit its applications. In [13], a dc-dc converter with a high voltage gain and reduced switch stress was added to the fuel system. However, this necessitates an intricate three-winding connected inductor, and the leaky inductor may be the cause of the switch spike voltage. Based on the diode-capacitor voltage multiplication, a dc-dc converter may obtain a substantial voltage gain and lower voltage stress [14]. The output voltage will, however, decrease as the number of multipliers increases due to an increase in internal voltage loss. Z-source and quasi-Z-source networks have also been used with boost dc-dc converters [15]–[18], resulting in a voltage gain increase of up to 1/(1 2d), where d is the power switch's duty cycle.

It has been shown that these converters with Z-source and quasi-Z-source networks have a voltage gain limit in high-voltage-gain applications. In order to further raise the voltage gain of the boost dc-dc converters with the Z-source network, a combination of the Z-source converter has been proposed in [19] and [20]. An alternate combination of a quasi-Z-source network and a shifted inductor has been proposed in [21] and [22], respectively, for the quasi-Z-source network and connected inductor. However, they still have drawbacks, such as increased size, higher cost, lower efficiency, and more complex circuitry. The

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switched-capacitor circuit was studied in [23] and [24]. Variable voltage control may be achieved by combining this circuit with other dc-dc converters [25] through [28]. In a Z-source dc-dc converter with a cascaded switched capacitor, as shown in [29], the voltage gain of the Z-source boost dc-dc converter may be improved by using the voltage multiplier function of the switched capacitor. Compared to the quasi-Z-source network, this converter may, because of the expense of the irregular input current and noncommon roots between the input voltage source side and the load side, result in additional maintenance safety issues for fuel cell automobiles.

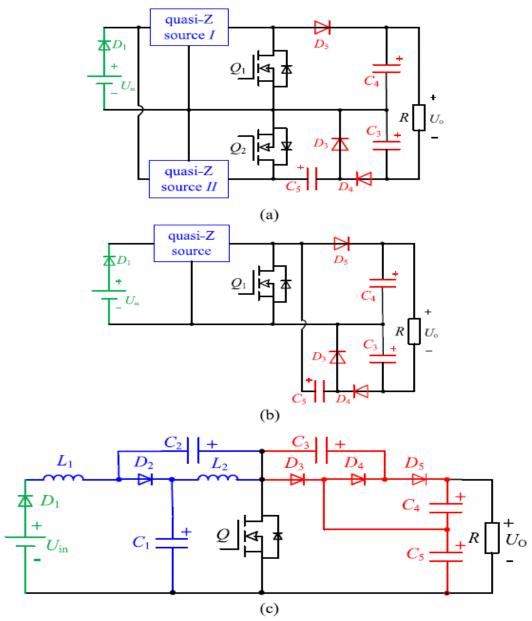

Fig. 1. Configuration of the proposed converter. (a) Combined interleaved topology with input-parallel and output-series. (b) Deduced and simplified topology. (c) Proposed converter.

1. PROPOSED CIRCUIT TOPOLOGY

1.1 Configuration of the Proposed Converter

To boost the voltage, gain, and lessen the voltage stress across the power transistors, two quasi-Z-source converters are connected with the input-parallel and output-series design of the step-up dc-dc converter. An extra quasi-Z-source network and an additional active power converter are really required for this combined system. The inferred and reduced topology may be attained by the merged topology by sharing an active power switch Q1 and a shared quasi-Z-source network. Furthermore, the constant voltage across capacitance C3 is almost exactly the same as the voltage difference across the roots between the input and output sides. Thus, it is better to assume that this form is a perfect example of common ground. The same combination of switched-capacitor networks allows for a proposed quasi-Z-source step-up dc-dc converter with a high voltage gain, a low voltage stress, and a common ground. The input voltage source of the converter is composed of the inverted blocking diode D1 and the fuel cell voltage source Uin. C3 D4, C4 D5, and C5 D3 comprise the switched-capacitor network, while "L1 D2 L2 C1 C2" makes up the quasi-Z-source network.

2.2 Analysis of Operating States

If T is the switching period, d is the duty cycle of the power switch Q, and d T is the interval of S = 1, then the two states for the proposed converter are S = 1 and S = 0 which correspond to the switching phases of the power switch Q. Current flow of the proposed converter during its two transitional stages.

1) S = 1: The corresponding circuit in the switching state of the proposed converter emerges. In line with the main operational patterns of the recommended converter. Q is turned on while diodes D2, D3, and D5 are off. Via the diode D1 and the power switch Q, energy is sent to the inductor L1 from the capacitance C2 and the incoming voltage source Uin. C1 transfers the energy to L2 via Q. Capacitor C5 provides energy to C3 via D4 and Q, and in series, capacitors C5 and C4 provide energy to the load.

2) S = 0: The matching circuit of the proposed converter in the switching condition S is equal to 0. The primary working waveforms of the proposed converter indicate that Q is turned OFF while D2, D3, and D5 are turned ON. Through D1 and D2, energy is moved from Uin and L1 to C1. D2 transfers energy from L2 to C2. Through D1, D2, and D3, Uin, L1, and L2 transmit energy to C5. Parallel to this, energy moves in sequence from Uin, L1, L2, and C3 to C4 and C5, while the load passes via D1, D2, and D5.

2.3 Voltage Gain

It is presumptive that the topology's capacitance and inductance are sufficient, and that all power transistors' forward voltage dips, on-state resistances, and parasitic parameters are disregarded. The inductor voltages across L1 and L2 are UL1on and UL2on when the power control Q is turned ON, and the inductor voltages across L1 and L2 are UL1off and UL2off when Q is turned OFF. The capacitor voltages across C1, C2, C3, C4, and C5 are UC1, UC2, UC3, UC4, and UC5, respectively. The following formulae can be obtained for S = 1 and S = 0, respectively, by employing Kirchhoff's voltage rules.

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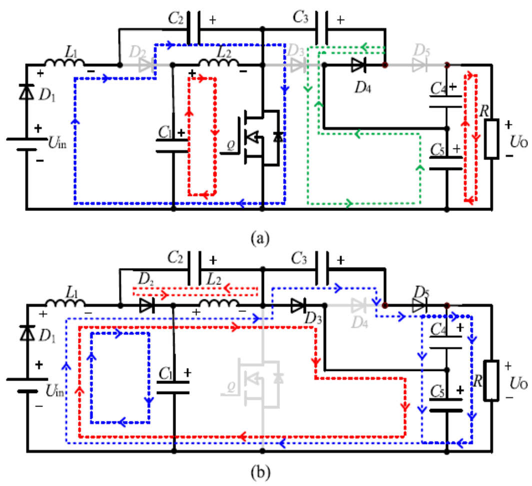

Fig. 2. Two operating states of the proposed converter. (a) S = 1.(b) S = 0.

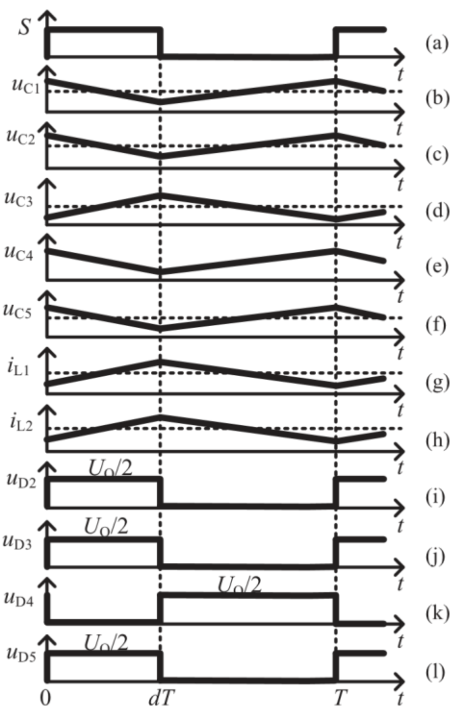

Fig. 3. Key waveforms of the proposed converter.

$S = 1$:

$$\begin{cases} U_{L1on} = U_{in} + U_{C2} \\ U_{L2on} = U_{C1} \\ U_{C3} = U_{C5} \\ U_O = U_{C4} + U_{C5}. \end{cases} \quad (1)$$

$S = 0$:

$$\begin{cases} U_{L1off} = U_{in} - U_{C1} \\ U_{L1off} = U_{in} - U_O + U_{C2} + U_{C3} \\ U_{L2off} = -U_{C2} \\ U_{C3} = U_{C4}. \end{cases} \quad (2)$$

By applying the voltage–second balance principle to the inductors L1 and L2 in the continuous-current mode, (3) can be obtained as

$$U_{L1on} \times dT + U_{L1off} \times (1 - d)T = 0$$

$$U_{L2on} \times dT + U_{L2off} \times (1 - d)T = 0.$$

2.4 Comparisons with Other High-Voltage-Gain Converters

Table I presents a comparison between the proposed design and existing high-voltage-gain boost dc-dc converters, as well as voltage gain vs duty cycle ratios. The boost dc-dc converter [7] was equipped with voltage multipliers in order to lower the semiconductors' UO/2 voltage stress. The voltage gain of the suggested converter is double that of the traditional quasi-Z-source boost dc-dc converter, on the one hand. However, rather than the whole output voltage UO, the voltage stress over the power switch is half that of the output voltage. If the wider voltage-gain range (including M = 10 20) is required, the recommended converter may perform well with duty cycles near to 0.5 (i.e., around d = 0.4 0.45), unlike the converter in [7], which may encounter severe duty cycles (i.e., above d = 0.8 0.9). The converter in [29] with a Z source and cascading switch capacitors has a substantially higher voltage gain than the converter in [7] and the conventional quasi-Z-source boost dc-dc converter. Despite having a wider voltage-gain range than the one that was recommended, this converter still has certain disadvantages, including additional inductors, more voltage stress across semiconductors, and non-common grounds between the input and output sides. This is especially true in the lower duty cycle range. In actuality, the number of inductors may be decreased by using the dual-coupled inductors for the converter in [30], where the linked inductors' turns ratio is N = 19/18. However, its voltage growth is dependent on the turns ratio N. Even worse, the potential difference between the input and output sides appears as the pulse width modulation voltage because of the noncommon roots. The stacked step-up dc-dc converter in [31] lacks a common ground even though it can obtain one and has the same voltage gain as the converter in [30]. The incoming current fluctuation may be further reduced when the duty cycles of the two power switches are about 0.5, thanks to the interlaced structure with a third power switch. The voltage gain vs duty cycle plots in Fig. 4 indicate that the recommended converter, however, has a wider voltage-gain range than this one in the lower duty cycle range (i.e., d = 0 1/3). Furthermore, in the larger duty cycle zone, the voltage gain of the converter in [31] is lower than the required one. The effectiveness of the incoming current to lessen ripple will be affected, in particular, by duty cycle values below and above 0.5. A quasi-Z source, three-level boost dc-dc converter was proposed in [32] for fuel cell vehicles. The voltage stress is half that of the output voltage because of the three-level converter structure, and the duty cycles of the two power switches may be close to that value, ranging from 0.5 to 0.75. Its basic voltage gain is the same as the quasi-Z-source converter's, but having a lower voltage gain than the recommended converter. Using the aforementioned instances, it is clear that the converter under discussion offers a number of advantages when coupled, such as reduced voltage stress on transistors, common ground between the input and output sides, and high voltage gain without high duty cycles.

3 DYNAMIC MODELING

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It is believed that the power transistors, capacitors, and inductors are operating at maximum efficiency. The average model and small-signal model may then be obtained using the state-space averaging approach. C3 and C5 are connected in parallel when Q is switched on, as shown in Fig. 2(a). It suggests that the voltage between C3 and C5 should be the same. The status value is inaccurate as a consequence. By considering the same series resistance (e.g., r1 = 0.1) in the suitable loop circuit, the link between C3 and C5 may be removed in order to avoid the false state variable. Similarly, as shown in Fig. 2(b), the connection between C1, C2, C3, C4, and C5 may also be removed to stop the incorrect state variables by accounting for the same series resistance (r = 0.1, for instance) in the related loop circuit. When the recommended converter operates in the duty cycle area of 0 d 0.5, the power transistor Q has two usable switching states: S = [0, 1]. The variables uin(t), uo(t), and d(t) represent the input, output, and control, respectively. iL1(t), iL2(t), uC1(t), uC2(t), uC3(t), uC4(t), and uC5(t) are the state variables. When S = 1 and the working time is d(t) T, the state-space average model may be computed as (27), which is shown at the bottom of the page. R is the load resistance. When S = 0, the working time is [1 d(t)] T. From there, the state-space average model may be represented as (28), as shown at the bottom of the page. Combining (27) and (28) yields the standard model of the converter, which is shown as (29) at the bottom of the page that follows.

The variables iL1(t), iL2(t), uC1(t), uC2(t), uC3(t), uC4(t), uC5(t), uin(t), uo(t), and d(t) are comparable small-signal disruption variables that may be used to characterize the state, input, output, and control variables. Consequently, the small-signal paradigm of the converter may be written as

uC1(t) = UC1 + ∧uC1(t) uC2(t) = UC2 + ∧uC2(t)

uC3(t) = UC3 + ∧uC3(t) uC4(t) = UC4 + ∧uC4(t)

uC5(t) = UC5 + ∧uC5(t) uin(t) = Uin + ∧uin(t)

Table 1. Main Experimental Parameters Of The Proposed Converter

Parameters	Values (units)

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by the

Input dc voltage U_{in}	40–150 V
Output dc voltage U_O	400 V
Inductor L_1	323 µH
Inductor L_2	318 µH
Capacitor C_1	520 µF
Capacitor C_2	780 µF
Capacitors C_3, C_4, and C_5	520 µF
Rated power P_n	400 W
Load resistor R_L	400
Switching frequency f_s	20 kHz
MOSFET Q	IXTK102N30P
Diodes $D_1 - D_5$	DSEC60-03A

3.1 Application of the Proposed Converter for Fuel Cell Vehicles

Depending on the previously described characteristics of the fuel cell, the energy sources of fuel cell automobiles may consist of a fuel cell source combined with a supercapacitor or battery arrays. The engine of a fuel cell car with the recommended converter is shown in Figure 9. In order to decouple the power controls of the hybrid energy sources, dc-dc converters are required for both the fuel cell vehicle power interfaces and the common dc bus, to which the hybrid energy sources can be connected in parallel to supply the necessary powers for the motor. This means that the car's fuel cell source doesn't have to respond quickly—it only has to provide the engine with an average quantity of energy. The supercapacitor or battery packs may provide the high-frequency power required motor, or the battery packs can absorb the motor's adjustable regeneration power. Furthermore, a power converter with a large voltage-gain range is also required for the fuel cell source since, depending on the motor load, the fuel cell source's terminal voltage varies greatly when its output current is within a wide range.

The recommended high voltage gain dc-dc converter connects the low voltage fuel cell source to the high voltage dc channel. The fuel cell source provides the average power PFC for the dc bus by utilizing the recommended converter to elevate its low voltage to the high dc bus voltage. When the fuel cell automobile accelerates, the supercapacitor stacks provide the instantaneous power required from the dc bus via the bidirectional dc-dc converter (i.e., the fuel cell output current IFC) because of the slow dynamic response characteristics of the fuel cell source.

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Subsequently, when IFC increases gradually, the fuel cell source's output voltage UFC decreases throughout a wide range. During this operation, the recommended converter raises the varying fuel cell voltage to the constant high dc bus voltage. When the fuel cell automobile slows down or stops, the fuel cell source lowers its output power, or IFC, since the supercapacitor stacks entirely collect the regeneration energy. The recommended converter lowers its voltage gain to maintain the same dc bus voltage, as shown by the increasing UFC. as a fuel cell automobile is working correctly, the fuel cell source charges the supercapacitor stacks as needed and provides the inverter with constant energy via the recommended converter with the right voltage gain.

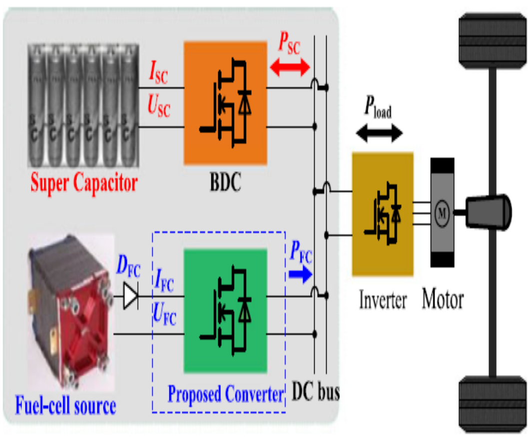

Fig. 4. Powertrain of fuel cell vehicles with the proposed converter.

4 SIMULATION RESULTS

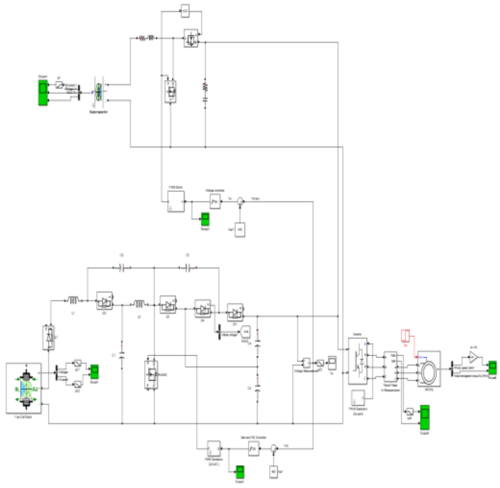

Fig5 simulation circuit

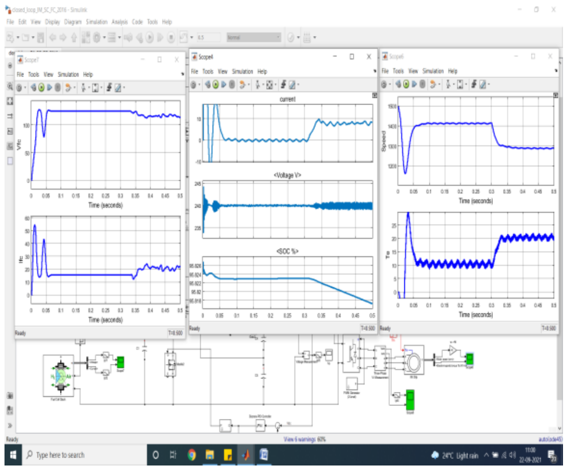

Fig 6 Switches voltage and currents

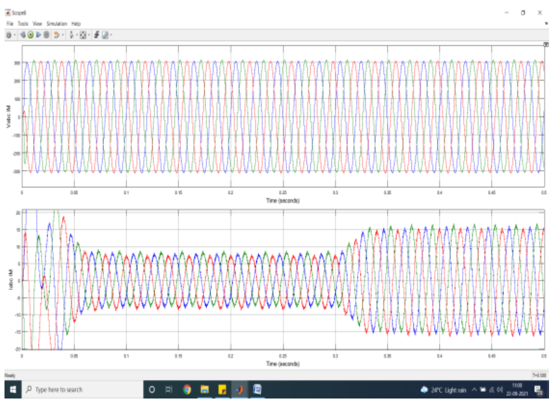

Fig 7 Three phase output voltage and currents in motor case

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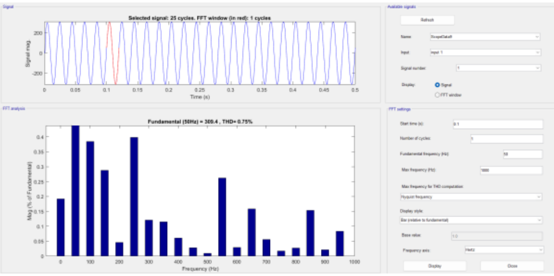

Fig 8 Voltage thd 0.75%

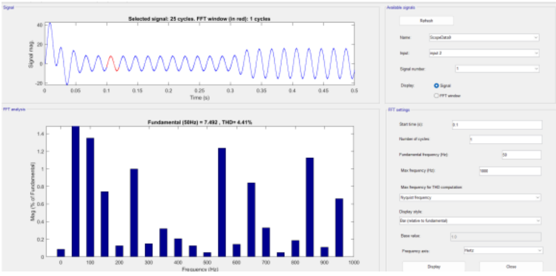

Fig 9. Current THD 4.41%

5 CONCLUSION

A quasi-Z-source boost dc-dc converter with shifted capacitors was proposed in this paper. With the duty cycles ranging from 0 to 0.5 for the power switch, the suggested converter attains a high-voltage gain of 2/(1 2d) while preserving all the advantages of the traditional quasi-Z-source topology, including continuous input current and common ground between the input voltage source side and the load side. Furthermore, the output voltage is half of the maximum voltage loads that the converter recommends for each component. Moreover, the quasi-Z-source network's capacitor voltages have the ability to restrict the output capacitor voltages to half of the output voltage. Thus, the recommended adapter functions well with the electrical connection of fuel cell vehicles.

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