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A High-Voltage Gain Quasi-Z-Source Boost Dc-Dc Converter for Fuel Cell Supported Electrical Vehicles

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ABSTRACT-For fuel cell cars, a shifted capacitor-based quasi-Z-source boost dc-dc converter is suggested. Only a low-voltage stress is needed to be applied across each component of the design in order to achieve a high-voltage gain over a broad input voltage range. Comparisons are made between the suggested converter's efficiency and that of other converters that employ Z-source networks. To verify the suggested technology, a 400-V/400-W scaled-down version is created. Due to the PI controller in the voltage loop, when the input voltage varies widely, the corresponding fluctuation in the output voltage is prevented, and a maximum efficiency of 95.13% is observed.

Key Terms: Wide variety of voltage gain, quasi-Z source, shifted capacitance, voltage PI driver, and boost dc-dc converter.

I. INTRODUCTION

Due to the growing adoption of green energy sources and the requirement to decrease the use of fossil fuels, there is a pressing need to create pure energy solutions for enhancing the ecosystem and resolving the problems associated with energy utilization. As the world's population of cars continues to grow, which also helps to raise air pollution, this is becoming a bigger issue. Clean energy car development has picked up recently, and they are becoming more prevalent as a share of overall transit. Due to their high-density current production, pure power generation, and high-efficiency working features, fuel cell cars are a significant component of these renewable energy vehicles and have been used extensively in practice [1], [2]. The fuel cell output voltage, in contrast to batteries, which have a relatively steady output voltage, rapidly decreases as output current increases [3]–[6]. As a result, a step-up dc-dc converter with a broad voltage gain range must be used to connect it to the inverter's high-voltage dc-link network [2]. A large voltage increase can be readily attained by the standalone step-up dc-dc converter. However, the energy from the transformer's leaky inductance has the potential to boost switching losses, create high-voltage stress, and result in dangerous electromagnetic interference [7]. Therefore, a no isolated step-up dc-dc converter is frequently preferred to cut costs, decrease converter size, and boost conversion efficiency. The standard boost dc-dc converter is one of the most popular no isolated step-up converters. The converter has a straightforward design with just one power button. The voltage increase can be infinite because the potential duty cycle of the power switch is adjustable from 0 to 1 [8], [9]. However, the voltage increase is constrained by the existence of parasitic components in the circuit [10], [11]. Additionally, when the output voltage is high, the power switch must be high-voltage rated because the voltage stress it experiences is equal to that of the output voltage.

Numerous remedies have been offered to this task in light of the issues mentioned. To lessen the voltage stress and match the voltage levels, a hybrid boost three-level dc-dc converter with a high voltage gain was suggested as a power link between the low-voltage photovoltaic (PV) panels and the high-voltage dc bus for the PV production system [12]. Despite achieving the desired voltage stress and gain, noncommon grounds are visible between the input and output sides, which may restrict its uses. The fuel system was given a dc-dc converter with a high voltage gain and decreased switch stress in [13], but this requires a complicated three-winding linked inductor, and the switch spike voltage may be brought on by the leaky inductor. A dc-dc converter can achieve a large voltage gain and decreased voltage stress based on diode-capacitor voltage multiplication [14]. However, as the number of multipliers rises, an increase in the internal voltage loss will result in a decline in the output voltage. Boost dc-dc converters have also been used with Z-source and

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quasi-Z-source networks [15]–[18], and this has allowed for a rise in voltage gain of up to 1/(1 2d), where d is the duty cycle of the power switch.

In high-voltage-gain uses, a limit in the voltage gain of these converters with Z-source and quasi-Z-source networks has been discovered. A combination of the Z-source converter has been suggested in [19] and [20] as a way to further increase the voltage gain of the boost dc-dc converters with the Z-source network. As an alternative, it has been suggested in [21] to combine a quasi-Z-source network with a shifted inductor, and in [22] to combine a quasi-Z-source network with a linked inductor. They still have limitations, though, like increased bulk, greater expense, and decreased efficiency as well as circuit intricacy. The switched-capacitor circuit was researched in [23] and [24] and can be used in conjunction with other dc-dc converters [25] to [28] to accomplish variable voltage control. The voltage gain of the Z-source boost dc-dc converter can be increased by using the switched capacitor's voltage multiplier function in a Z-source dc-dc converter that has a cascaded switched capacitor, as shown in [29]. Due to the cost of the irregular input current and noncommon roots between the input voltage source side and the load side, this converter may, in comparison to the quasi-Z-source network, cause extra maintenance safety problems for fuel cell cars.

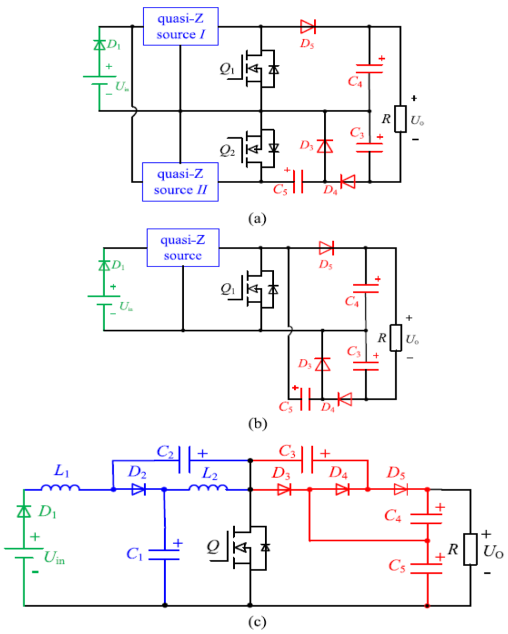

Fig. 1. Configuration of the proposed converter. (a) Combined interleaved topology with input-parallel and output-series. (b) Deduced and simplified topology. (c) Proposed converter.

II. PROPOSED CIRCUIT TOPOLOGY

1.1 Configuration of the Proposed Converter

Two quasi-Z-source converters are coupled with the input-parallel and output-series construction of the step-up dc-dc converter to increase the voltage, gain, and decrease the voltage stress across the power transistors. This merged design actually needs an additional quasi-Z-source network and an additional active power converter. The merged topology can share a shared quasi-Z-source network and active power switch Q1, leading to the inferred and reduced topology being achieved. In addition, the voltage differential across the roots between the input and output sides is virtually the steady voltage across capacitance C3. It is therefore preferable to infer that this shape is an absolute common ground one. A suggested quasi-Z-source step-up dc-dc converter with a high voltage gain, a low voltage stress, and a shared ground is made possible by the comparable mix of switched-capacitor networks. The fuel cell voltage source Uin and the inverted blocking diode D1 make up the converter's input voltage source. The switched-capacitor network is made up of C3 D4, C4 D5, and C5 D3, while the quasi-Z-source network is made up of "L1 D2 L2 C1 C2".

2.2 Analysis of Operating States

S = 1 and S = 0 are the two states for the suggested converter that correspond to the switching stages of the power switch Q (assuming that T is the switching period, d is the power switch Q's duty cycle, and d T is the interval of S = 1). The suggested converter's current flow in its two transitioning phases.

1) S = 1: The suggested converter's corresponding circuit in the switching state appears. According to the suggested converter's primary working patterns. While diodes D2, D3, and D5 are off, Q is switched on. Energy is transferred to the inductor L1 from the incoming voltage source Uin and the capacitance C2 via the diode D1 and the power switch Q. Through Q, C1 sends the energy to L2. Through D4 and Q, capacitor C5 supplies energy to C3 while capacitors C5 and C4 in series supply energy to the load.

2) S = 0: The suggested converter's corresponding circuit in the switching state S = 0. The suggested converter's main working waveforms show that while D2, D3, and D5 are switched ON, Q is turned OFF. Energy is transferred from Uin and L1 to C1 via D1 and D2. Energy is transferred from L2 to C2 by D2. Energy is transferred to C5 by Uin, L1, and L2 via D1, D2, and D3. In parallel, energy is transferred from Uin, L1, L2, and C3 in series to

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C4 and C5 in series and the burden through 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.

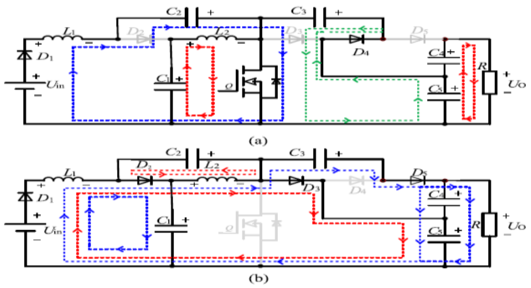

Fig. 2. Two operating states of the proposed converter. (a) S = 1.(b) S = 0.

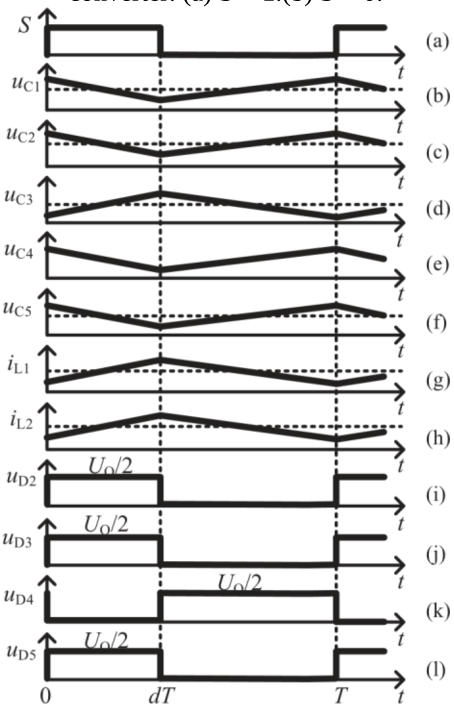

Fig. 3. Key waveforms of the proposed converter.

S = 1:

$$\begin{cases} UL1_{on} = Uin + UC2 \\ UL2on = UC1 \\ UC3 = UC5 \\ UO = UC4 + UC5. \end{cases} \quad (1)$$

S = 0:

$$\begin{cases} UL1off = Uin - UC1 \\ UL1_{off} = Uin - UO + UC2 + UC3 \\ UL2off = -UC2 \\ UC3 = UC4. \end{cases} \quad (2)$$

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

UL1on × dT + UL1off × (1 − d)T= 0

UL2on × dT + UL2off × (1 − d)T= 0.

2.4 Comparisons with Other High-Voltage-Gain Converters

The suggested design is compared to other high-voltage-gain boost dc-dc converters and voltage gain versus duty cycle ratios, as shown in Table I. Voltage multipliers were applied to the boost dc-dc converter [7] to reduce the voltage stress of the semiconductors as UO/2. On the one hand, the voltage gain of the proposed converter is twice as high as the conventional quasi-Z-source boost dc-dc converter. On the other hand, the voltage stress across the power switch is half as high as the output voltage, as opposed to the full output voltage UO. The converter in [7] may experience severe duty cycles (i.e., over d = 0.8 0.9), whereas the suggested converter can function well with duty cycles close to 0.5 (i.e., around d = 0.4 0.45), if the broader voltage-gain range (including M = 10 20) is needed. When compared to the converter in [7] and the traditional quasi-Z-source boost dc-dc converter, the converter with a Z source and cascaded switch capacitors in [29] has a much greater voltage gain. Although this converter has a broader voltage-gain range than the one that was suggested, particularly in the lower duty cycle range, it still has some drawbacks, such as more inductors, greater voltage stress across semiconductors, and non-common grounds between the input and output sides. In reality, the dual-coupled inductors used for the converter in [30], where the coupled inductors' turns ratio is N = 19/18, can reduce the number of inductors. However, the turns ratio N affects its voltage increase. Even worse, owing to the noncommon roots, the potential differential between the input and output sides manifests as the pulse width modulation voltage. While the stacked step-up dc-dc converter in [31] can achieve a common ground and has the same voltage gain as the converter in [30], it does not have a common ground. Due to the interlaced construction with a third power switch, the fluctuation of its incoming current can also be decreased further when the duty cycles of the two power switches are around 0.5. The suggested converter, however, has a broader voltage-gain range than this one in the lower duty cycle range (i.e., d = 0 1/3), according to the voltage gain versus duty cycle graphs in Fig. 4. Additionally, the voltage gain of the converter in [31] is smaller than that of the suggested one in the greater duty cycle region. Particularly, duty cycle levels below and above 0.5 will have an impact on the incoming current's ability to reduce ripple. In [32], a three-level boost dc-dc converter with a quasi-Z source was suggested for use in fuel cell cars. Due to the three-level converter construction, the voltage stress is half that of the output voltage, and the duty cycles for the two power switches can be in the range of 0.5 to 0.75, which is near to that value. Although it has a smaller voltage gain than the suggested converter, its fundamental voltage gain is still the same as that of the quasi-Z-source converter. With the help of the examples above, it can be seen that the converter under consideration has several combined benefits, including high voltage gain without high duty cycles, low voltage stress on transistors, and a shared ground between the input and output sides.

III. DYNAMIC MODELING

The inductors, capacitors, and power transistors are considered to be in their optimal states. The state-space averaging technique can then be used to derive the average model and small-signal model. When Q is turned on, C3 and C5 are linked in parallel, as shown in Fig. 2(a). It implies that C3 and C5 should have identical volts across them. As a result, the status value is incorrect. The connection between C3 and C5 can be eliminated to prevent the erroneous state variable by taking into account the comparable series resistance (for instance, r1 = 0.1) in the appropriate loop circuit. Similarly, in accordance with Fig. 2(b), by taking into account the comparable series resistance (for example, r = 0.1) in the associated loop circuit, the connection between C1, C2, C3, C4, and C5 can also be eliminated to prevent the erroneous state variables. The power transistor Q has two useful switching states when the suggested converter runs in the duty cycle region of 0 d 0.5: S = [0, 1]. The input, output, and control variables are denoted as uin(t), uo(t), and d(t), accordingly. The state variables are iL1(t), iL2(t), uC1(t), uC2(t), uC3(t), uC4(t), and uC5(t). The state-space average model can be calculated as (27), which is depicted at the foot of the page, where R is the load resistance, when S = 1 and the working duration is d(t) T. The working time is [1 d(t)] T when S = 0. The state-space average model can then be expressed in the form of (28), as seen at the foot of the page. The typical model of the converter can be created by combining (27) and (28), as shown at the foot of the following page as (29).

The equivalent small-signal disruption variables are iL1(t), iL2(t), uC1(t), uC2(t), uC3(t), uC4(t), uC5(t), uin(t), uo(t), and d(t), which can be used to characterise the state variables, input variables, output variables, and control variables. As a consequence, the converter's small-signal paradigm can be expressed 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)

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

The energy sources of fuel cell cars can be made up of a fuel cell source and supercapacitor or battery arrays based on the features of the fuel cell previously outlined. Figure 9 depicts the engine of fuel cell vehicles with the suggested converter. Dc-dc converters are necessary for the power interfaces of fuel cell vehicles as well as the common dc bus, with which the hybrid energy sources can be connected in parallel to provide the proper required powers for the motor, respectively, in order to decouple the power controls of the hybrid energy sources. As a result, the fuel cell source of the car only needs to supply the engine with an average amount of electricity without having to react quickly. The motor's needed high-frequency power can be produced by the supercapacitor or battery packs, or the battery packs can take in the motor's

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adjustable regeneration power. Additionally, a broad voltage-gain range of a power converter is also necessary for the fuel cell source because the terminal voltage of the fuel cell source changes significantly when its output current is within a wide range depending on the motor load.

The low-voltage fuel cell source is connected to the high-voltage dc path by the suggested dc-dc converter with a high voltage gain. By using the suggested converter to raise the fuel cell source's low voltage to the high dc bus voltage, the fuel cell source delivers the average power PFC for the dc bus. Due to the sluggish dynamic reaction qualities of the fuel cell source, when the fuel cell car accelerates, the supercapacitor stacks provide the immediate power needed from the dc bus by the bidirectional dc-dc converter (i.e., the fuel cell output current IFC). The output voltage UFC of the fuel cell source then declines with a broad range as IFC steadily rises. The suggested converter moves up the fluctuating fuel cell voltage to the steady high dc bus voltage during this operation. The supercapacitor stacks fully capture the regeneration energy when the fuel cell car slows down or stops, which causes the fuel cell source to reduce its output power, or IFC. The rising UFC also indicates that the suggested converter reduces its voltage gain in order to maintain the same dc bus voltage. When a fuel cell car is operating properly, the fuel cell source supplies the inverter with steady energy via the suggested converter with the appropriate voltage gain, and, if necessary, charges the supercapacitor stacks.

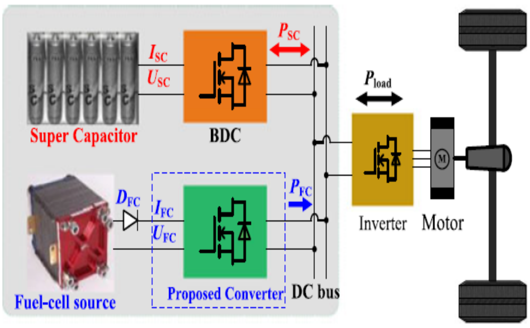

Fig. 4. Powertrain of fuel cell vehicles with the proposed converter.

IV. SIMULATION RESULTS

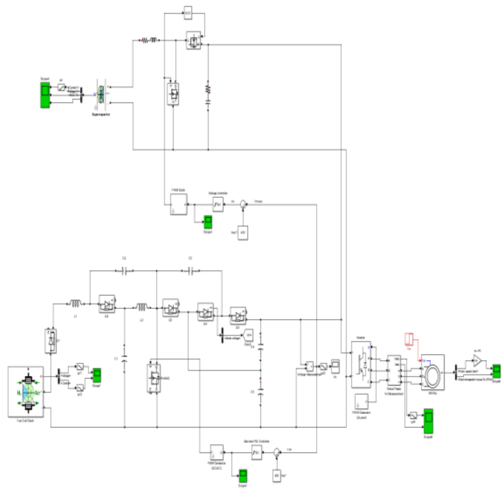

Fig5 simulation circuit

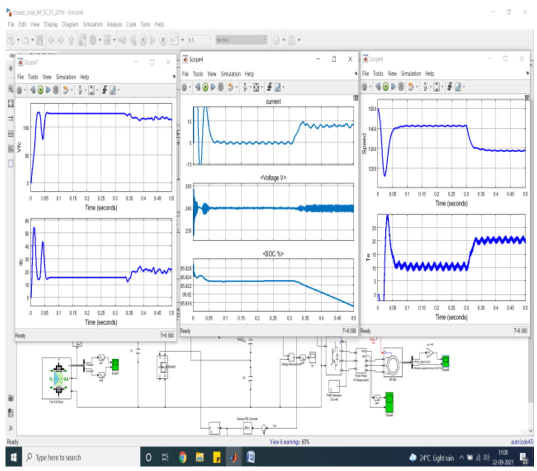

Fig 6 Switches voltage and currents

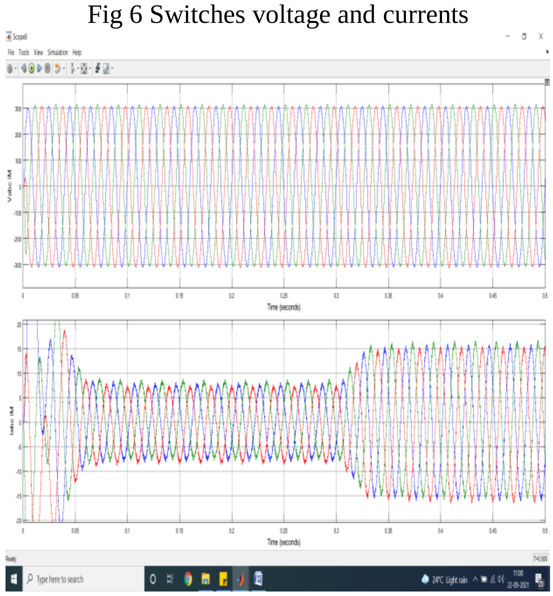

Fig 7 Three phase output voltage and currents in motor case

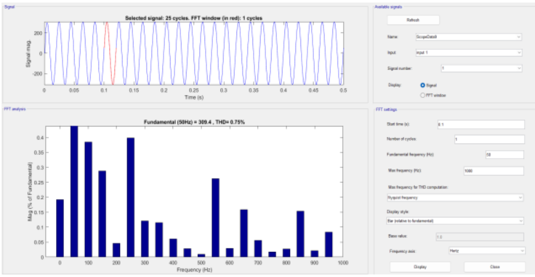

Fig 8 Voltage thd 0.75%

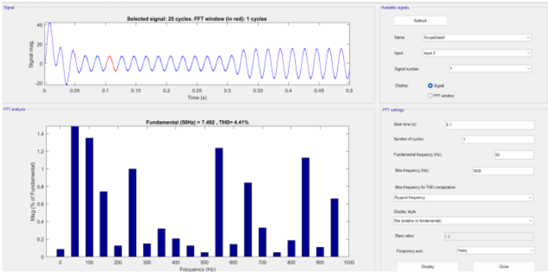

Fig 9. Current THD 4.41%

V. CONCLUSION

This article suggested the design of a shifted capacitor quasi-Z-source boost dc-dc converter. The proposed converter achieves a high-voltage gain 2/(1 2d) with the duty cycles between 0 and 0.5 for the power switch while maintaining all the benefits of the conventional quasi-Z-source topology, such as continuous input current and common ground between the input voltage source side and the load side. Additionally, the output voltage is half of the converter's suggested maximum voltage loads for every component. Furthermore, the capacitor voltages of the quasi-Z-source network can limit the voltages of the output capacitors at half the output voltage. As a result, the suggested adapter works well with fuel cell cars' electrical link.

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