High-Gain DC-DC Converter Applied in Fuel Cell Vehicles to Obtain High Gain, Low Stress, Compared with Conventional Methods

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Abstract— The DC-DC converter for fuel cell vehicles should be characterized by high-gain, low voltage stress, small size and high-efficiency. However, conventional two-level, three-level and cascaded boost converters cannot meet the requirements. A new non-isolated DC-DC converter with switched-capacitor and switched inductor is proposed in this paper, which can obtain high-gain, wide input voltage range, low voltage stresses across components and common ground structure. In this paper, the operating principle, component parameters design, and comparisons with other high-gain converters are analyzed. Moreover, the state-space averaging method and small-signal modeling method are adopted to obtain the dynamic model of converter. Finally, simulation and experimental results verify the effectiveness of the proposed topology. The input voltage of the experimental prototype ranges from 25V to 80V. The rated output voltage is 200V and rated power is 100W. The maximum efficiency is 93.1% under rated state. The proposed converter is suitable for fuel cell vehicles.

Index Terms—Fuel cell vehicles, DC-DC converter, switched-capacitor and switched inductor, high-gain, low voltage stress.

I.INTRODUCTION

HE development of the transportation industry plays a vital role in the national economy. However, an increase in the number of fuel vehicles not only consumes a large amount of oil resources, but also causes serious environmental pollution problems. Therefore, all countries turn their attentions to the clean energy [1], [2]. The development of new energy vehicle industry provides new ideas to solve these problems. Fuel cell vehicle has become a very promising development direction in the new energy vehicle industry due to its advantages of zero emissions, no pollution and high efficiency [3], [4].

The typical system structure of fuel cell vehicle is shown in Fig. 1. The low output voltage of fuel cell makes it difficult to meet the demand of DC bus voltage in front of inverter. Moreover, the fuel cell has a "soft" output voltage characteristic, i.e., the output voltage drops too fast with the increase of the output current [5], [6]. Therefore, the DC-DC converter with high-gain, wide input voltage range and small size should be applied to fuel cell vehicles to raise the fuel cell voltage to a higher voltage level and ensure the stability of the DC bus voltage.

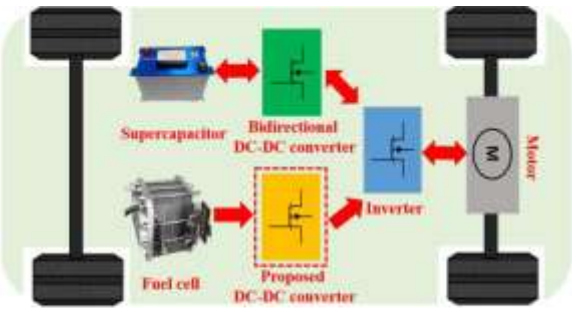

Fig. 1. The typical system structure of fuel cell vehicle.

Isolated DC-DC converter can easily achieve high-gain by changing the transformer turns ratio. However, due to the leakage inductance of the transformer, the circuit will produce a peak voltage, which is easy to breakdown the devices in the circuit. The leakage inductance can also reduce the efficiency of the converter and cause electromagnetic interference problems. In addition, transformer in the isolated converter also increases the size of the converter [7], [8]. Considering the size, cost and efficiency, the non-isolated DC-DC converter is more suitable for fuel cell vehicles.

The traditional boost DC-DC converter is still used in many applications because of the small number of components and simple structure. The theoretical voltage gain of the boost converter is 1/(1−d), where d is the duty cycle of the drive voltage for power switch. However, the voltage gain is limited due to the parasitic parameters of the actual circuit and components. The voltage stresses across components in the circuit are also high, which needs more expensive high-voltage components, resulting in increased size and cost [9]. In addition, there is an extreme duty cycle in traditional boost converter when achieving high-gain, which causes serious diode reverse recovery problems, resulting in increased losses [10], [11]. In terms of these disadvantages, conventional boost converter is not suitable for fuel cell vehicles. The cascaded boost converter can achieve high-gain and wide input voltage range by sacrificing the overall power density and efficiency of converter, but the voltage stresses across components are high and the circuit structures are complex [12], [13]. The boost three-level DC-DC converter can reduce the voltage stresses across components, but the voltage gain is still as low as the conventional boost converter [14].

In [15], the voltage stresses across components are significantly reduced and the theoretical voltage gain can reach (1+d)/(1−d), which is slightly larger than the conventional boost converter. However, the voltage gain in [15] is still not

enough for fuel cell vehicles. Z-source and quasi-Z-source networks are applied to the DC-DC converter to obtain the high-gain, but the voltage stresses of components in the converter are still high [16], [17]. In [18], a converter based on a series structure of three Z-source networks is proposed, which can obtain high-gain, wide input voltage range and low stress. However, there are too many inductors and power semiconductors in the circuit, which increases the cost and size of the converter. The converters proposed in [19]–[21] can achieve high-gain and low voltage stress, but there is a non-common ground structure between the input and output ports of each converter. When the converter is working, there is a high frequency pulsated voltage between the input and output ports, which can cause serious EMI problems. In addition, the main problem is about the voltage feedback for the non-common ground structure. An isolated voltage feedback should be adopted, such as: linear optocoupler, which can increase the complexity of the sampling circuit [22]. The multi-level converters proposed in [23], [24] can achieve high-gain and low voltage stresses across components. However, there are too many power semiconductors in the the circuit, resulting in increased cost and size. Multiple power switches also increase complexity to the drive circuit and control strategy. The non-isolated converters with coupled-inductor proposed in [25]–[27] can easily achieve high-gain, reduce the size of inductor and increase the power density of the converter. However, due to the existence of leakage inductance, additional clamp circuit or absorption circuit should be adopted to absorb the leakage inductance energy, which increases the complexity of the converter.

In this paper, a DC-DC converter based on switched-capacitor and switched-inductor is proposed. The converter can obtain high-gain, wide input voltage range, low voltage stress and common ground structure between input and output ports. In addition, there is no extreme duty cycle and the power switches need only one PWM drive signal in circuit topology. This paper is organized as follows: In Section II, the operating principle, voltage gain and voltage stresses across components are analyzed. And the converter is also compared with other high-gain DC-DC converters. In section III, the component parameters are designed. The dynamic model of the converter is presented by using state-space averaging method and small-signal modeling method. In Section IV and Section V, the simulation and experimental results are presented respectively to verify the effectiveness of proposed converter. Finally, the conclusion is given in Section VI.

II. PRINCIPLE OF THE PROPOSED CONVERTER

A. Configuration of the Proposed Converter

The circuit topology of the proposed converter is shown in Fig. 2. Uin and UO are the input voltage and output voltage respectively. RL is the load resistance. The converter consists of two power switches (Q1, Q2), five diodes (D1-D5), four capacitors (C1-C4) and an inductor L. Q1 and Q2 are turned on and off simultaneously by using the same gate drive signal S. When power switches Q1 and Q2 are turned on, S=1, and vice versa, calling S=0.

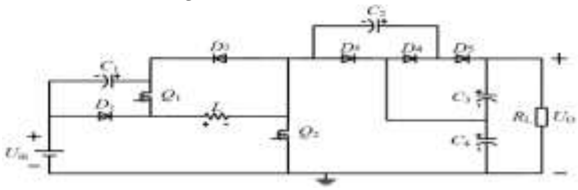

Fig. 2. The circuit topology of the proposed converter.

B. Operating Principle of the Proposed Converter

In order to analyze the proposed converter topology, some assumptions are made as follow:

a) The forward voltage drop of diode and the on-state resistance of power switch are ignored. The equivalent series resistances of inductor and capacitors are equal to 0.

b) The inductor is large enough in order to ensure that the circuit works normally. The capacitors are large enough in order to ensure that the voltage ripple of capacitors meets the requirements in this paper.

In this paper, the operating principle in Continuous Conduction Mode (CCM) is analyzed. The key operating wave forms of the proposed converter in CCM are shown in Fig. 3. According to the switching states of power switches, there are two operating states for the proposed converter, as shown in Fig. 4.

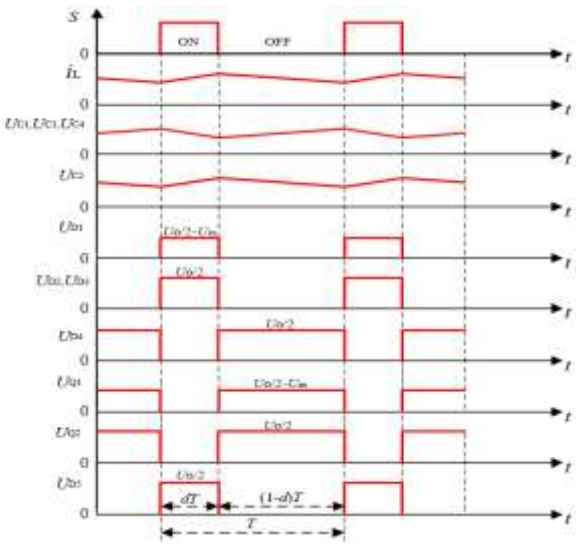

Fig. 3. The key operating waveforms of proposed converter in CCM.

When power switches Q1 and Q2 are turned on (S=1), the equivalent circuit is shown in Fig. 4(a), defined as ON state. The diode D1, D2, D3, D5 are reverse biased and three current loops appear in the circuit. Uin and C1 charge the inductor L through Q1 and Q2. Capacitor C4 charges the capacitor C2 through power switch Q2 and diode D4. The series part of the capacitors C3 and C4 transfers energy to the load RL. When power switches Q1 and Q2 are turned off (S=0), the equivalent circuit is shown in Fig. 4(b), defined as OFF state. The diode D4 is reverse biased and four current loops appear in the circuit. Inductor L charges capacitor C1 through D1 and D2.

Uin and L charge capacitor C4 through D1 and D3. Uin, L and C2 charge the series part of C3 and C4 through the diodes D1 and D5. The series part of the capacitors C3 and C4 still transfers energy to the load RL.

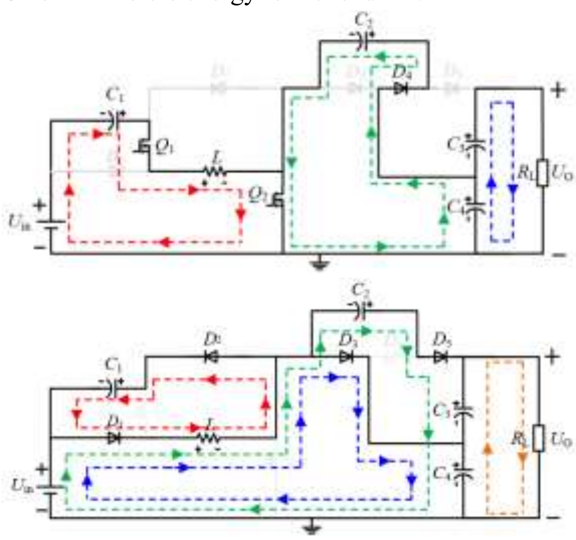

Fig. 4. Two operating states of the proposed converter. (a) ON state. (b) OFF state.

B. Dynamic Modeling Analysis

When the converter operates in the ON state, capacitors C2 and C4 are in parallel as shown in Fig. 4(a). The relationship between C2 and C4 is shown in (19), indicating that there is an invalid variable between C2 and C4. C2 C4 2 4 du du C C dt dt = − (19)

In order to eliminate the invalid variable between C2 and C4, the series equivalent resistance r1 is introduced into C2 and C4 loop and equation (19) can be written as (20). C2 C4 C2 2 1 du u u C dt r − = − (20)

where the r1 is the equivalent series resistance in C2 and C4 loop, defined as r1 = 0.01Ω.

When the converter operates in the OFF state, the series equivalent resistance r2 = 0.01Ω is adopted to eliminate the invalid variable of C1, C2, C3 and C4 loops as shown in Fig. 4(b). After adopting equivalent resistances r1 and r1, the equivalent circuit topology is as shown in Fig. 6.

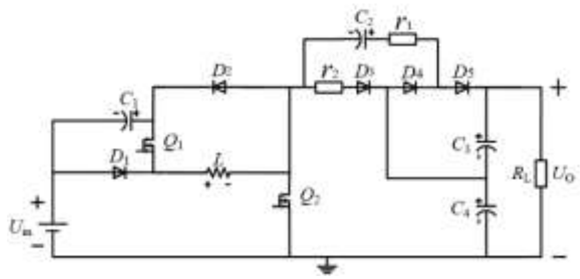

Fig. 6. Circuit topology after adopting equivalent resistances r1 and r2.

The dynamic model of proposed converter in (26) is written into the pole-zero form as shown in (27). In order to simplify analysis, the original model in (27) is reduced from 5 to 4 order to obtain the simplified model in (28). By appropriate pole-zero elimination method, the (s+3.135×105) in numerator and the (s+4.283 ×105) in denominator are eliminated in (27). The BODE diagram curves of (27) and (28) are shown in Figure 7. From Fig. 7, it can be seen that the original and simplified model curves are approximately the same. Therefore, the PI controller is designed based on (28).

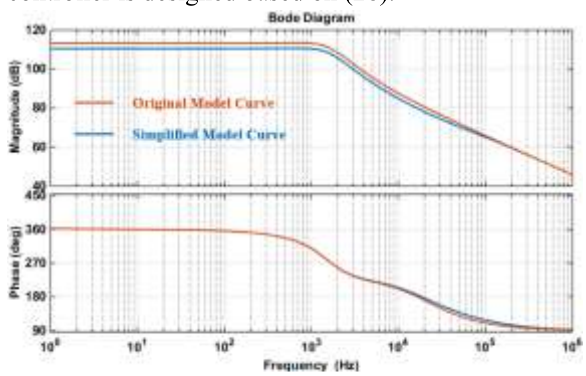

Fig. 7. Bode diagram of the proposed converter.

The PI controller is designed in order to achieve stable operation for the converter system. The block diagram of the closed-loop control system for the converter is shown in Fig. 8. GFB(s) is the feedback network transfer function. The actual prototype adopts the Hall sensor to collect the output voltage.

Gd → uo(s) is the transfer function of converter from control to output. GPI(s) is the transfer function of PI controller as shown in (29). The converter system can obtain good dynamic and static performance by using the PI controller.

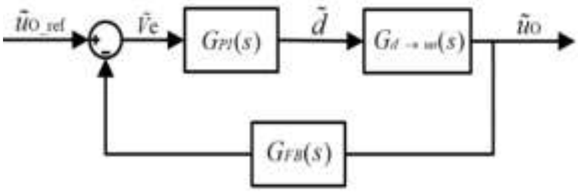

Fig. 8. The block diagram of the closed-loop control system of the converter

TABLE II
DESIGN PARAMETERS OF THE CONVERTER

Parameters	Values
Rated power P	100 W
Input voltage U_{in}	25 V-80 V
Rated output Voltage U_O	200 V
Rated load resistance R_L	400 Ω
Switching frequency f	20 kHz
Inductor L	800 μH
Capacitors C_1, C_2, C_3, C_4	470 μF
Power switches Q_1, Q_2	IXTK102N30P
Diodes D_1, D_2, D_3, D_4, D_5	DSEC60-03A

III.RESULTS OF SIMULATION

In order to verify the effectiveness of the proposed converter,a simulation model is built for the converter system and simulation parameters are shown in Table II. When the input voltage is Uin=25 V and the reference output voltage is set as

UO_ref =200 V, the simulation results are shown in Fig. 10. From Fig. 10, the inductor current IL is 7.5 A, which are consistent with the theoretical calculation result in (10). The output voltage UO has been stable at 200 V. The voltage stresses across

all capacitors and power semiconductors are as follows: UQ1=UC1 =UD1 ≈ 75 V UQ2 =UC2 =UC3 =UC4 =UD2 =UD3

=UD4=UD5 ≈ 100 V, which are consistent with the theoretical calculation results obtained in (8). The simulation results show that the proposed converter has advantages of high-gain and

low voltage stresses across components, which verifies the effectiveness of the circuit topology.

The dynamic simulation results of the converter are shown in Figure 11. When the simulation time is 1s, the input voltage of the converter Uin starts to drop from 60V and finally drops to 25V, with a total time of 14s. When the simulation time is 16s,

the output current IO changes suddenly from 250mA to 500mA and remains 200ms. Then the IO changes suddenly from 500mA to 250mA. From Fig. 11, it can be concluded that the converter

can maintain the output voltage stable around the reference voltage under the input voltage and load disturbance. The system can obtain a good anti-interference performance

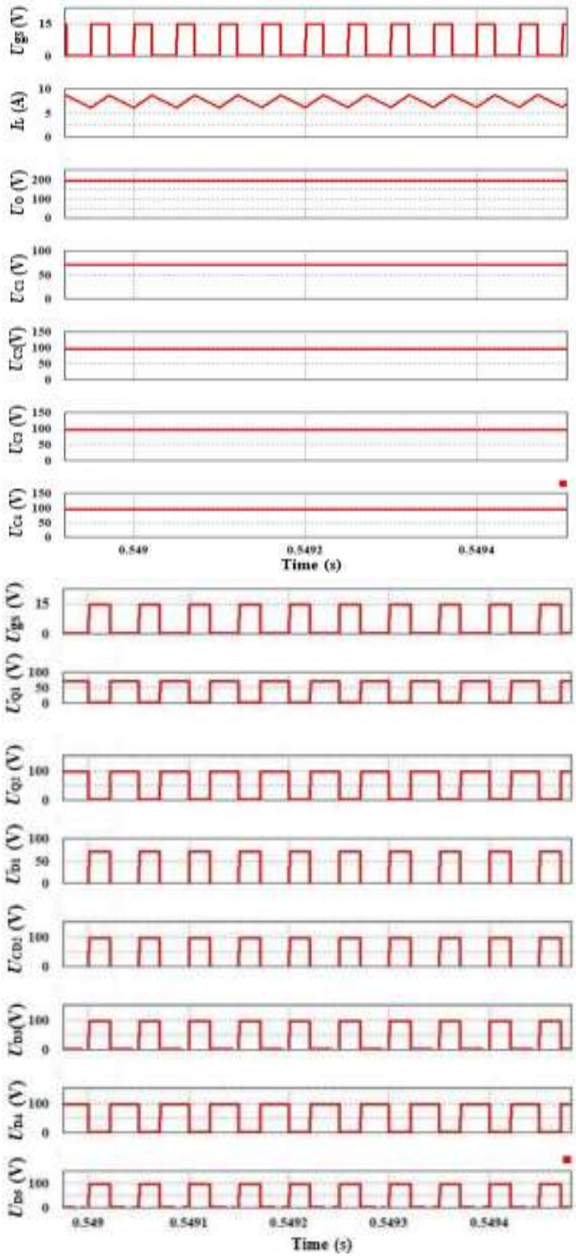

Fig. 10. Simulation results of converter. (a) Drive voltage Ugs, inductor current IL, output voltage UO and voltage stresses across C1, C2, C3, C4. (b) Drive voltage Ugs, voltage stresses across Q1、Q2, voltage stresses across D1, D2, D3, D4, D5.

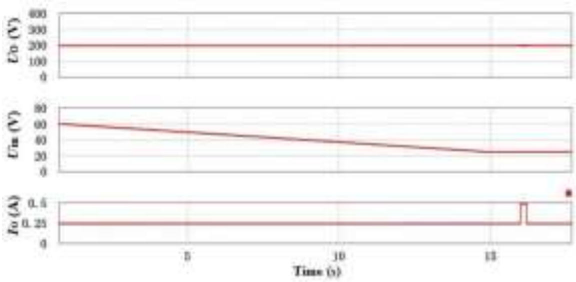

Fig. 11. Simulation results of the converter under the input voltage disturbance and load disturbance.

VI.CONCLUSION

These multilevel inverter topologies are to be stabilized during load disturbance conditions with low total harmonic distortion, a lesser number of switches and increased output voltage levels. The voltages and THD are to be analyzed using This research presents the implementation and analysis of a 17 level symmetric and asymmetric multilevel inverters. The proposed 17 level inverter systems have been effectively tested with unity and lagging power factor loads. In case A, testing has been carried out under steady-state condition, load disturbance conditions and analysis of THD with 17 level symmetric inverter output were presented. It is inferred from case A results that the system is readily adaptive and maintains a stable output voltage with 5.41 % THD for the aforesaid conditions while in case B, a THD with 4.54 % has been achieved, which is on par with IEEE standards. During load disturbances, the proposed topology is suitable for sudden load variant applications also. Due to low THD, these topological inherently utilize a lesser number of switches and a minimum number of dc input voltage sources; hence, the volume density of the proposed inverter is observed to have improved. that the proposed topology multilevel inverters are suitable for renewable energy-fed applications.

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