Comparison of Fuel Cell DC/DC Power Supply Topologies

Guofu Chen¹, Fengjiao Dai²,* and Wei Kang³
¹,²,³ State Key Laboratory of Advanced Power Transmission Technology (Global Energy Interconnection Research Institute Co., Ltd.), Changping District, Beijing 102209, China

*Corresponding author email: daifengjiao@geiri.sgcc.com.cn

Abstract. With the development of fuel cell products and technology, power electronics researchers have proposed a variety of fuel cell DC/DC power supply topologies for the output characteristics of fuel cells. This article compares and analyzes several existing non-isolated and isolated topological structures, summarizes the respective advantages and disadvantages of different topological structures and applicable scenarios, and provides references for further in-depth discussion of related issues.

Keywords: DC/DC; Non-isolated topology; Isolated topology.

1. Introduction

It has become a global trend for green renewable energy to replace traditional energy. Because of the random and intermittent characteristics of new energy sources such as solar and wind energy, they cannot provide continuous and stable power supply. Fuel cell is an energy conversion device that directly converts the chemical energy of the supplied fuel into electrical energy. It is a power generation device that can continuously obtain electricity by continuously supplying fuel, and its introduction can effectively solve the above-mentioned problems.

As an efficient and clean power generation device, the comprehensive energy conversion rate of fuel cells can reach 70% to 90%. Due to the decentralized nature of fuel cell power generation equipment, it allows users to get rid of the limitation of centralized power generation and reduce the loss of power in the transmission process, so it has great development potential[1]. High current ripple will shorten the service life of the fuel cell faster, and the addition of electromagnetic interference (EMI) filters will reduce the efficiency and power density of the subsequent power supply[2]. Moreover, the efficiency of the fuel cell DC/DC power supply will directly affect the overall efficiency of the fuel cell energy conversion system. In order to realize the connection between the power generation side of the fuel cell and the DC bus side, while ensuring the quality and reliability of power supply, the fuel cell DC/DC power supply must be characterized by high voltage gain, low input current ripple, high efficiency and high reliability.

According to the Made in China 2025 proposal issued by the Ministry of Industry and Information Technology, the Energy Technology Revolution and Innovation Action Plan (2016-2030) and Energy-saving and New Energy Vehicle Route Technology Map 2.0 jointly issued by the National Development and Reform Commission and the National Energy Administration, fuel cell technology is listed as one of the important directions of the energy technology revolution. These documents clearly define the development goals of the fuel energy industry. Since 2020, under market demand and market incentives, hydrogen fuel cells are expected to develop simultaneously in multiple fields[3-5].
This paper separately summarizes the existing non-isolated and isolated topological structures and their characteristics for fuel cell DC/DC power supplies, and prospects the key issues of the fuel cell DC/DC power supply topology with broad application prospects and key issues to be solved, so as to provide technical reference for driving the engineering application of fuel cell DC/DC power supply technology.

2. Non-isolated Fuel Cell DC/DC Power

The topological types of traditional non-isolated DC/DC power supplies include Buck, Boost, Buck-Boost, Cuk, Speic and Zeta. Because of its simple structure and control, and low cost, Buck, Boost and Buck-Boost topologies are widely used in converters of fuel cell vehicle and other related fields. The structure of the traditional cascaded Boost topology has the advantage of high gain. However, when the operating frequencies of the current stage and the subsequent stage are different, power devices and more complex control circuits need to be added, which will increase energy consumption and also affect the system stability. A new type of high-gain boost fuel cell DC/DC power supply form that adds a capacitor \(C_2\) and a diode \(VD_3\) to the traditional cascaded Boost is proposed in literature [6], as shown in Figure 1.

![Figure 1. DC/DC power supply for a new type of high-gain boost fuel cell.](image)

In this paper, the working states of the circuit is analyzed in continuous conduction mode. According to the experimental waveform, it can be seen that when \(VS_1\) is turned off, and after the current flows through \(VD_3\) from the inductor \(L_1\), \(VD_1\) is turned on. At this time, the switching loss of \(VD_1\) is zero, and \(VD_3\) achieves zero current shutdown (ZCS). This solves the problem of reverse recovery loss of the output diode in the traditional cascaded Boost circuit. When the duty cycle \(D\) of the power supply topology is in the range of \(0.5 \leq D < 1\), the voltage stress of the switch tube is lower, and the boost ratio is high. The voltage of the front stage and the voltage of the rear stage are connected in series to supply power to the load.

![Figure 2. Three-port boost power supply for fuel cell.](image)

When the fuel cell is used in a fuel cell vehicle as a separate power system, it has a poor dynamic response capability. During sudden acceleration and low-speed driving, its operating efficiency is low. In addition, fuel cells do not support two-way flow of energy. In order to solve these problems, literature [7] proposes a three-port boost power supply for fuel cells based on Boost power supply and two-phase coupled inductance interleaved power supply, as shown in Figure 2. Combining the coupled inductance interleaved control technology [8], the power supply can realize the synchronous work between auxiliary power units such as fuel cells, super capacitors, and loads. This
structure not only has a higher boost ratio, but also the two inductors on the input side can evenly distribute the input current, thereby effectively suppressing the low-frequency current ripple on the input side and controlling the ripple to about 0.05%. In addition, the structure has fewer energy conversion stages because it uses non-isolated PWM technology, which reduces the energy loss between each unit. Compared with the basic Boost, its energy conversion efficiency is greatly improved, reaching about 92%.

In order to realize energy transmission and flow between fuel cell and other power devices in fuel cell vehicles, literature [9] proposes a DC/DC power supply based on a 4-way Boost boost parallel circuit, as shown in Figure 3. The 4-way Boost boost circuit of the power supply is completely symmetrical, which provides a hardware basis for the current sharing characteristics of the main circuit of the power supply. It adopts quadruple phase-shifting PWM control, that is, the conduction time of the 4 switching tubes differs by 90° for every two. This can effectively reduce the output ripple. At the same time, the power supply has the advantages of high power and high efficiency, and its efficiency can reach 97%. In addition, literature [10] also uses a 4-way Boost structure, and its circuits are connected in a staggered parallel manner. The n-phase interleaving technology can make the phase difference of each phase circuit $2\pi/n$, and the inductor current of each phase is also reduced to $(I_{in}+I_{out})/n$, which increases the total inductor current frequency by n times. The high switching frequency can reduce the input current and output voltage ripple, which is beneficial to improve the life of the fuel cell and improve the stability of the system. SIC MOSFET is selected as the switching device to further reduce the switching loss and improve the conversion efficiency. This helps reduce the overall size and weight of the power supply and further increase the power density of the power supply.

In order to reduce the current ripple output by the fuel cell and prolong the service life of the fuel cell stack, a fuel cell DC/DC power supply is proposed in [11]. The power supply adds a filter inductor on the input side of the interleaved Boost topology, which greatly reduces the DC/DC input current ripple, making the ripple factor ≤1%, as shown in Figure 4. The multi-phase interleaved topology can better reduce the voltage and current ripple of the fuel cell, and reduce the voltage and current stress on the power device. At the same time, it can also effectively increase the output power level.
In order to effectively improve the voltage gain and reduce the stress of the device, the literature [12] proposes a new type of DC/DC boost power supply composed of only one switch tube, capacitors $C_1$–$C_4$, inductors $L_1$, $L_2$, and diodes $VD_1$–$VD_5$, as shown in Figure 5.

![Figure 5. New DC/DC boost power.](image)

Compared with the traditional quadratic Boost, Buck-Boost and Boost cascaded power supplies, it not only effectively improves the voltage gain, significantly reduces the capacitor voltage stress and the switching stress of the power device, but also effectively reduces the volume and cost of the power supply. Its efficiency can reach 88.75%.

| Topology              | Applicable occasions                                                                 |
|-----------------------|--------------------------------------------------------------------------------------|
| Figure 1 topology     | Occasions where the input and output voltages are very small.                         |
| Figure 2 topology     | Occasions with low input voltage and high output                                     |
| Figure 3 topology     | Voltage such as fuel cell unit driving electric load or grid-connected power generation |
| Figure 4 topology     | Fuel cell car                                                                        |
| Figure 5 topology     | Occasions with high power or medium power demand                                      |
| Figure 5 topology     | New energy grid connection, server power supply, communication power supply and other fields where high gain is required |

In table 1, these topologies of non-isolated fuel cell DC/DC power supply are shown. The topology listed has a smaller fuel cell current ripple, which can effectively reduce the voltage and current stress attached to the power device. The interleaved structure adopted can effectively control the excessive current, and only use part of the power devices to work at light load, and improve the efficiency of the converter[13]. Due to the non-isolated characteristics of the topology, the non-isolated DC/DC cannot be modularized in series expansion[14].

3. Isolated Fuel Cell DC/DC Power

Isolated DC/DC power supply refers to a power supply that uses isolation elements such as transformers to electrically isolate the primary and secondary sides. Isolated DC/DC can be divided into single-ended and double-ended circuits, in which, single-ended circuits include forward and flyback, while double-ended circuits include full bridge, half bridge and push-pull. Each circuit has many different topological forms and control methods. Compared with non-isolated DC/DC power supplies, isolated DC/DC power supplies can achieve a higher step-up/step-down ratio by changing the transformation ratio of the transformer. Its design is more flexible and its power level is higher.

At present, isolated fuel cell converters are mainly divided into two categories: Voltage-type and current-type transformers. Voltage source type DC/DC converter has the characteristics of high
frequency input current ripple and limited soft switching range. Its topological structure in the limited soft switching range is more complicated. At the same time, it will also have problems such as voltage ringing of the rectifier diode and loss of duty cycle, so it is not suitable for applications such as high gain and high current. The high circulating current flowing through the magnetic components and the relatively low efficiency in high voltage amplification and high input current applications require more electrolytic capacitors in parallel. However, if there are too many electrolytic capacitors, it will directly affect the life of the system. The current-type DC/DC converter uses an inductor on the input side to make the input current of the system smoother and more suitable for high gain occasions. The electrolytic capacitor required at the input end is reduced, thereby reducing the failure rate of the system and extending the service life\textsuperscript{[15-19]}.

3.1. Voltage-source Fuel Cell DC/DC Power

The traditional half-bridge LLC resonant converter is generally applied to occasions where the input high voltage is small current and the output low voltage is large current, thus being unsuitable for fuel cells. However, because it can achieve soft switching without auxiliary circuits and special control strategies, LLC resonant converters can improve conversion efficiency \textsuperscript{[20]}. Therefore, based on the traditional half-bridge LLC resonant converter, literature \textsuperscript{[21]} proposes a DC/DC power supply with a high boost ratio. The power supply consists of a three-element resonant network consisting of an excitation inductance $L_m$, a resonant inductance $L_r$ and a resonant capacitor ($C_{r1}+C_{r2}$), as shown in Figure 6.

![Figure 6. DC/DC power with high step-up ratio.](image)

Compared with the traditional half-bridge LLC resonant converter topology, if the primary side of the converter adopts the input current double structure, the current stress of the resonant capacitor can be reduced by 50%; if the secondary side adopts the output voltage doubling structure, the gain can be doubled, and the voltage stress of the output capacitor is also reduced by 50%.

Currently, fuel cells for electric vehicles are widely used. When accelerating suddenly, the power supply needs to provide a large current to the motor and a small output voltage ripple. Aiming at this characteristic, based on the phase-shifted full-bridge current-doubling topology, literature \textsuperscript{[22]} proposes to replace the diode on the secondary side with a switch tube, so as to form a phase-shifted full-bridge current-doubling rectifier bidirectional DC/DC power supply, as shown in Figure 7.

![Figure 7. Phase-shifted full-bridge current double rectifier bidirectional DC/DC power supply.](image)

The problem of softer fuel cell output characteristics can be improved by connecting supercapacitors in parallel with the fuel cell. This paper analyzes the working principle of the power supply during acceleration and deceleration of fuel cell electric vehicles. Its use eliminates the spike caused by the leakage inductance of the secondary side of the transformer during reverse operation.
3.2. Current-source Type Fuel Cell DC/DC Power

In high-current and low-voltage input applications, it has always been a challenge to achieve a wide range of voltage changes and variable output power/load zero voltage switching while maintaining high efficiency. In [23], a wide-range active clamp current-fed full-bridge DC/DC power supply is proposed, which makes full use of an active clamp circuit composed of a series connection of a capacitor and an active switching device to absorb the voltage spike when the switching device is turned off, as shown in Figure 8.

![Figure 8. Active clamp current-fed full-bridge DC/DC power.](image)

Through adding additional commutation paths, the power supply enables all switching devices to achieve zero voltage switching (ZVS). In addition, it has large soft switching range. In particular, it can achieve zero voltage switching (ZVS) from full load to light load within a wide input voltage range. Since the duty cycle of the main switch of the power supply belonging to the current-type converter needs to be greater than 50%, its conversion efficiency can reach 94%. Although active clamping can suppress the voltage turn-off spikes of high-frequency switches, and it is beneficial to zero-voltage switching (ZVS), it has power limitations and is not a modular structure. A new type of current-fed bidirectional full-bridge isolated DC/DC power supply with naturally clamped zero current commutation is proposed in literature [24], as shown in Figure 9.

![Figure 9. Current-fed bidirectional full-bridge isolated DC/DC power.](image)

The power supply adopts secondary modulation technology to realize zero current natural commutation on the primary side, and clamps the voltage at both ends of it to a low voltage (reflected output voltage). In addition, the voltage on the primary side is independent of the duty cycle, which eliminates the need for active clamps or passive buffers. The power supply can use standard phase-shift modulation to achieve zero-current shutdown on the primary side with a relatively low circulating current, and zero-voltage turn-on on the secondary side. The switching loss is significantly reduced and the soft switching characteristics are not affected by the load. In addition, the power supply has an easily interleaved modular structure and can be expanded through modules for high-power applications.

![Figure 10. Soft-switch current DC/DC power.](image)
In [25], a soft-switching current-type DC/DC power supply with a wide input voltage range is proposed. Due to the existence of magnetizing inductance, the primary side switch always maintains zero voltage switching state (ZVS) within the working range, and the secondary side switch always maintains zero current switching state (ZCS) during operation. Thus the loss of the switching device can be effectively reduced. Its topological structure is shown as in Figure 10.

Compared with the traditional power supply, the power supply is characterized by being able to achieve soft switching on and off in a larger voltage range, and it can control the output voltage when the input voltage and load change significantly. The dual inductance structure in the power supply has current sharing characteristics, which can reduce the current stress of the power supply device. In order to realize the control of the load voltage, this paper also proposes fixed frequency hybrid modulation. It adopts current feeding technology, which is suitable for low voltage and high current applications.

The fuel cell stack is usually very sensitive to the current ripple on the output side. Literature [26] proposes a new type of current source hybrid dual active bridge DC/DC power supply. Its primary side is a double boost half-bridge structure, which is composed of switch tubes $Q_1, Q_1a, Q_2, Q_2a$ and DC inductor $L_1$ and $L_2$. Its secondary side is composed of full bridge and auxiliary half bridge, in which, the full bridge is composed of switching tubes $S_1, S_2, S_3,$ and $S_4$, and the auxiliary half bridge is composed of switching tubes $S_5, S_6$ and capacitors $C_u$ and $C_d$. The high frequency transformer connects the two sides together, as shown in Figure 11.

![Figure 11. New current source hybrid dual active bridge DC/DC power.](image)

During steady-state operation, the duty cycle of the switch on the primary side of the power supply is fixed at 50%, and the strobe signal of the interleaved boost circuit has a 180° gap. Compared with the traditional interleaving technology with variable duty cycle control, the power supply can reduce the input current ripple. The voltage feedback uses a notch filter. When the single-phase inverter is loaded, notch filter helps to reduce the low frequency input current ripple. In addition, the proposed duty cycle compensation strategy is adopted to further expand the soft switching range of switches, enable all switches to realize zero voltage switching (ZVS) in a wide input voltage and load range, reduce switching loss and improve power supply efficiency.

| Topology          | Applicable occasions                                                                 |
|-------------------|--------------------------------------------------------------------------------------|
| Figure 6 topology| Occasions that require input of low voltage and large current, output of high voltage and small current, and high boost ratio, such as fuel cell vehicles |
| Figure 7 topology| Occasions such as fuel cell vehicles and energy storage                               |
| Figure 8 topology| Occasions of inputting low voltage and high current                                   |
| Figure 9 topology| Fuel cell vehicle                                                                     |
| Figure 10 topology| Solar panels (20 V ～ 42 V), fuel cells (22 V ～ 41 V) and conventional batteries (24 V/36 V/48 V/60 V) and other fields |
| Figure 11 topology| Fuel cell power adjustment system                                                     |

Table 2 shows the applicable occasions of the above-mentioned isolated fuel cell DC/DC power supply topology. It is used in isolated DC/DC converters for fuel cells. While increasing the DC-DC
power supply voltage, the transformer can ensure that the voltage at the input end of the transformer is low and the current at the output end is low. The electrical isolation brought by the high-frequency transformer can also protect the fuel cell stack during overload.

4. Prospects for Key Technologies of Fuel Cell Power Supply
The output voltage of the fuel cell is greatly affected by the load and environmental conditions, and the control of its voltage and current is difficult. Different fuel cell stacks need to choose different fuel cell DC/DC power supply topologies. High precision and fast response are the core requirements of fuel cell DC/DC power supply control, but the control method still needs to be optimized according to different applications to achieve the performance indicators of the converter design. The research on the topology and control strategy to improve the stability, reliability and power efficiency of fuel cell DC/DC power supply has extremely high engineering application value[26].

The current fuel cell DC/DC power supply has the following development directions[27-29]:
(1) High performance
At present, vehicles using fuel cells are constantly developing. Like traditional power vehicles, fuel cell vehicles need to be highly maneuverable and must respond accordingly in various situations. Because the fuel cell has soft output characteristics and low output voltage, it cannot be directly driven as a power source. This requires to add a high-performance DC/DC to change the output characteristics of the fuel cell. This will jointly form a power source to power the car and convert it into a stable and reliable DC power source.

(2) High frequency
Using SiC Mosfet can make it acquire lower on-state resistance and faster switching speed. In addition, it can also reduce the switching loss and conduction loss, and improve the efficiency of the fuel cell DC/DC power supply. With the continuous development of the device, it can work at higher voltages and temperatures, and become stronger and achieve a longer life. Furthermore, its switching speed is much faster than traditional semiconductor devices. At present, the switching frequency has been gradually increased to megahertz. This helps to reduce the volume of magnetic elements and improve the total power density of fuel cell DC/DC power supply. Table 1 shows the comparison of fuel cell DC/DC power devices.

Table 3. Comparison of fuel cell DC/DC power device

|                  | IGBT | MOSFET | SiC |
|------------------|------|--------|-----|
| Switch           | Low  | High   | High|
| Efficiency       | Low  | Rather | High|
| Work voltage     | High | Rather | High|
| Power density    | Low  | Rather | High|
| Noise            | Yes  | No     | No  |
| Cost             | Low  | Rather | High|

(3) Digitization
The digital power supply has a relatively high degree of integration, and it has a fast response capability. In addition, it can reduce the power requirements for output filter capacitors. Its automatic diagnosis and adjustment capabilities make debugging and maintenance easier.

5. Conclusion
Fuel cell is an efficient and environmentally friendly technology. At present, various researches on fuel cell DC/DC power supply topology and control technology are still deepening and developing. Due to the difference in cost tolerance, fuel cells have been relatively mature in special fields such as aerospace and submarine. However, its application in civilian fields such as uninterruptible power supplies, charging stations, portable power supplies, and fuel cell vehicles is still in the demonstration stage. However, as the application technology of fuel cells improves day by day, how to choose the
fuel cell DC/DC power supply topology, how to control the fuel cell DC/DC power supply strategy, how to design the structure of the fuel cell DC/DC power supply to reduce the application cost, increase the service life of the fuel cell, increase the conversion efficiency, and increase the power density is very important. It is foreseeable that the research on the engineering application of fuel cell DC/DC power supply technology will also become the focus of research in the near future.

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