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Review

Topology and Control of Fuel Cell Generation Converters

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Abstract: Fuel cell power generation is one of the important ways of utilizing hydrogen energy, which has good prospects for development. However, fuel cell volt-ampere characteristics are nonlinear, the output voltage is low and the fluctuation range is large, and a power electronic converter matching its characteristics is required to achieve efficient and stable work. Based on the analysis of the fuel cell's characteristic mechanism, maximum power point tracking algorithm, fuel cell converter characteristics, application and converter control strategy, the paper summarizes the general principles of the topology of fuel cell converters. In addition, based on the development status of new energy, hydrogen energy is organically combined with other new energy sources, and the concept of 100% absorption system of new energy with green hydrogen as the main body is proposed to provide a reference for the development of hydrogen energy.

Keywords: hydrogen energy; fuel cell; power electronic converter; new energy; current ripple

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1. Introduction

With the rapid development of the social economy, the shortage of fossil energy and environmental pollution are becoming more and more serious. Therefore, the development of new energy has become the key to solving the problem of energy and pollution [1,2]. However, the inherent interstitial and fluctuating nature of new energy sources has led to a large amount of wind and photovoltaic energy being wasted. In contrast, hydrogen energy, as a clean secondary energy source, not only does not cause pollution to the environment, but also has the advantages of long-distance transportation and large-scale storage, which can store new energy and effectively solve the problem of wasting new energy [3–5]. Therefore, hydrogen energy is regarded as an important part of the future energy system.

A fuel cell is a device that converts chemical energy into electrical energy through an electrochemical process using hydrogen as fuel, which has the advantages of cleanliness, efficiency and low noise, and is one of the main ways of utilizing hydrogen energy [6]. However, the fuel cell's volt-ampere characteristics are nonlinear and the output voltage is low and fluctuating, which leads to the fact that the fuel cell cannot be directly connected to the load and requires a power electronic converter with matching characteristics for regulation [7]. The power electronic converter is a bridge between the fuel cell and the load, and is an indispensable link in the fuel cell power generation system.

The paper will first analyze fuel cell characteristics to provide a basis for designing power electronic converter topologies. Subsequently, the converter topologies and control strategies applicable to fuel cells are categorized and described for different application conditions, as shown in Figure 1. The problems of fuel cell power generation devices are summarized and optimization measures are proposed. Finally, the prospects of hydrogen energy development are presented in the context of new energy sources.

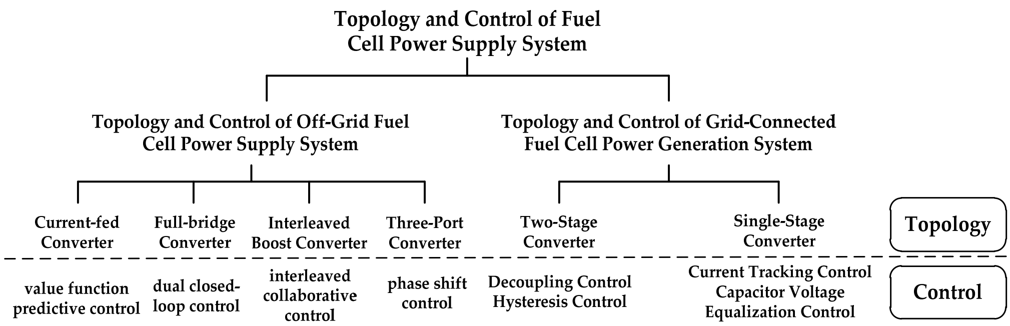

Figure 1. Classification of fuel cell power generation.

2. Characteristics of Fuel Cells

At present, fuel cells can be mainly divided into five categories according to different electrolyte types: alkaline fuel cells (AFCs), phosphoric acid fuel cells (PAFCs), proton exchange membrane fuel cells (PEMFCs), molten carbonate fuel cells (MCFCs) and solid oxide fuel cells (SOFCs) [8]. AFCs mainly operate at room temperature, which is costly and unstable in chemical reactions at high temperatures. PAFCs can use natural gas, oil or methanol as fuel, at relatively low cost, but high loss. MCFCs operate in a temperature range of 600–700 °C and are primarily used in submarines. The fuel of SOFCs is natural gas, methanol and coal gas. The working temperature is about 1000 °C, which is generally used in high-temperature scenarios [9]. Among them, PEMFCs have the characteristics of high energy density, wide application range, rapid start-up, etc., and have a good application prospect in fuel cells [10].

The structure of a PEMFC fuel cell is shown in Figure 2, which mainly includes: (1) electrode plate: plays the role of conducting current and supporting the electrode; (2) gas diffusion layer: provides support for the catalyst layer, provides a gas flow channel and manages the produced water; (3) catalyst layer: reduces the activation energy of the reaction and promotes the chemical reaction; (4) proton exchange membrane [11]. The PEMFC stack is made of repeating single PEMFCs. Increasing the number of single PEMFCs in the stack increases the voltage, while increasing the surface area increases the current.

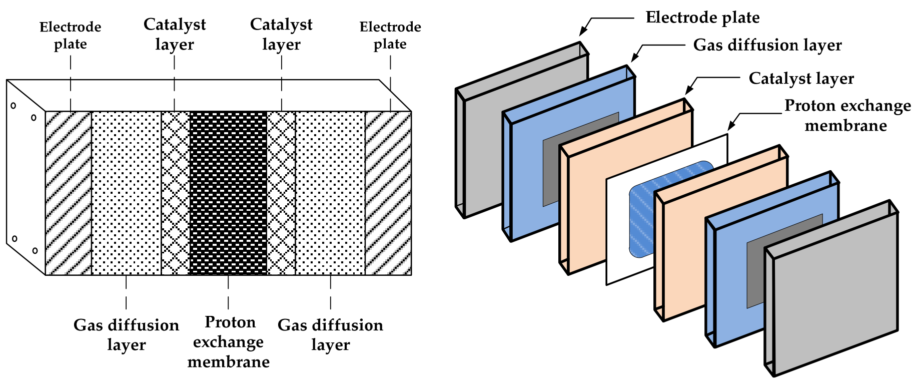

Figure 2. Structure diagram of PEMFC fuel cell.

The chemical reactions taking place in the fuel cell are displayed below:

$$\text{Cathode}: \frac{1}{2}O_2 + 2H^+ + 2e^+ \rightarrow H_2O \tag{1}$$

$$\text{Anode}: \ H_2 \rightarrow 2H^+ + 2e^- \tag{2}$$

$$\text{Overall}: \ H_2 + \frac{1}{2}O_2 \rightarrow H_2O + Q_1 + Q_2 \tag{3}$$

where Q_1 is electrical energy and Q_2 is heat energy.

According to the thermodynamics, electrochemistry and the Nernst equation, the calculation formula for the internal electromotive force of the fuel cell is as follows:

$$E = E^{\circ} + \frac{RT}{2F} \ln(P_{H_2} P_{O_2}^{0.5}) \quad (4)$$

where: E° is the standard reference potential; R is the gas constant; T is the temperature; F is Faraday's constant (96,487 C/mol); P is the pressure of the gas. From Equation (1), it can be found that the electromotive force inside the fuel cell is related to a variety of factors, so the internal fuel cell is a complex reaction process.

The authors of [7,11] state that PEMFC is a nonlinear, multi-input and multi-output dynamic system with strong coupling and large delay. Its working process is accompanied by the mixed flow of liquid, steam and gas, heat conduction and electrochemical kinetic reaction, which leads to losses in the working process of fuel cells, making the actual output voltage lower than the derived internal theoretical electromotive force. As the output current density increases, the output voltage of the fuel cell decreases nonlinearly. The volt-ampere characteristic curve is shown in Figure 3 [12–14].

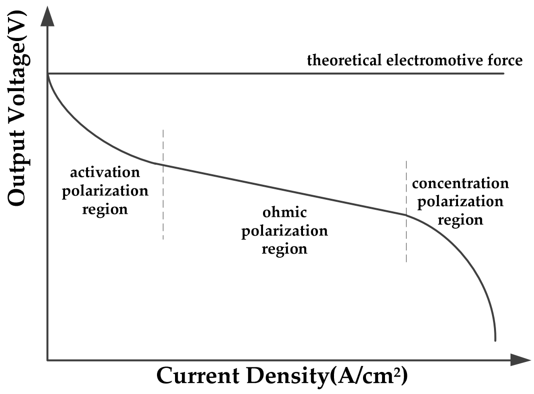

Figure 3. Volt-ampere characteristic curve fuel cell.

In Figure 3, the volt-ampere curve of a fuel cell is divided into three regions according to different losses: activation polarization region, ohmic polarization region and concentration polarization region. Activation polarization is due to the voltage loss caused by activation energy that needs to be overcome when protons pass through the reaction interface and concentrate in the region of low current density. Ohmic polarization is the voltage loss caused by the ohmic resistance inside the battery, which is mainly affected by the humidity of the gas diffusion layer inside the battery and the operating temperature of the battery. The ohmic polarization is concentrated in the middle current density region, where the voltage decreases linearly with the increase in current density. In most cases the fuel cells operate in the ohmic polarization region. Concentration polarization is a drop in the internal voltage of the battery due to diffusion transport resistance caused by the difference in reactant concentration. The concentration polarization region is located in the high current density region, where the current distribution on the electrode surface is very uneven and the working condition of the battery is very bad. In the use of the battery, the concentration polarization region should be avoided as far as possible [15,16].

In a fuel cell, the two electrode plates are divided into two parts by the electrolyte, which ensures the presence of two electrically opposite-charged layers at the boundary of the electrode and the electrolyte, similar to the structure of the capacitor, as shown in Figure 4. There are electric layers at both ends of the fuel cell, which is equivalent to two capacitors inside the fuel cell. This characteristic is called the electric double-layer capacitance effect of the fuel cell [12].

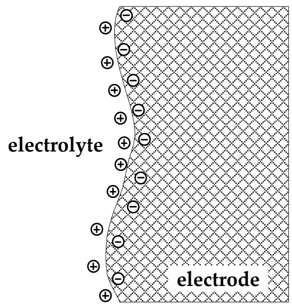

Figure 4. Capacitance effect at electrode interface.

The equivalent capacitance C of the boundary between the electrode plate and the electrolyte is expressed as follows:

$$C = \varepsilon \frac{A}{l} \tag{5}$$

where ε is the dielectric constant of the electrolyte, A is the effective area between the electrolyte and the electrode, l is the interval between the electrolyte layer and the electrode layer.

The voltage across the equivalent capacitor is

$$V_{\mathrm{C,cell}} = (i - C\frac{dV_{\mathrm{C,cell}}}{dt})(R_{\mathrm{act,cell}} + R_{\mathrm{conc,cell}}) \tag{6}$$

$R_{\mathrm{act,cell}}$, $R_{\mathrm{conc,cell}}$ are the activation polarization resistance and concentration polarization resistance of fuel cells. From Equation (6), the time constant $\tau = (R_{\mathrm{act,cell}} + R_{\mathrm{conc,cell}}) \cdot C$ is only related to the activation polarization resistance and concentration polarization resistance of the fuel cell, which means that the dynamic response of the fuel cell is caused by the internal electrochemical reaction. The dynamic response characteristics of the fuel cell are shown in Figure 5. During the operation of fuel cells, the output current will change with different working conditions. Due to the electric double-layer capacitance effect of fuel cells, the output voltage will be delayed to a certain extent, resulting in a slow dynamic voltage response.

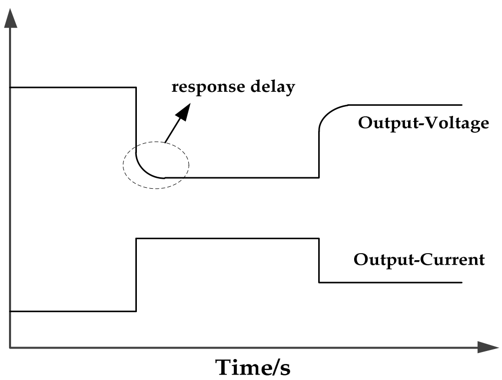

Figure 5. Dynamic response of fuel cell.

According to the V-I curve of the fuel cell shown in Figure 3, the P-I characteristic curve of the fuel cell is obtained [17], as shown in Figure 6.

From Figure 5, it can be seen that as the current density increases, the output voltage decreases and the output power increases and then decreases, so there is a maximum output power point. The maximum power point output not only improves the overall efficiency of the fuel cell, but also helps to improve the performance of the fuel cell. Therefore, the maximum power point output of fuel cells is one of the effective ways to improve efficiency [18].

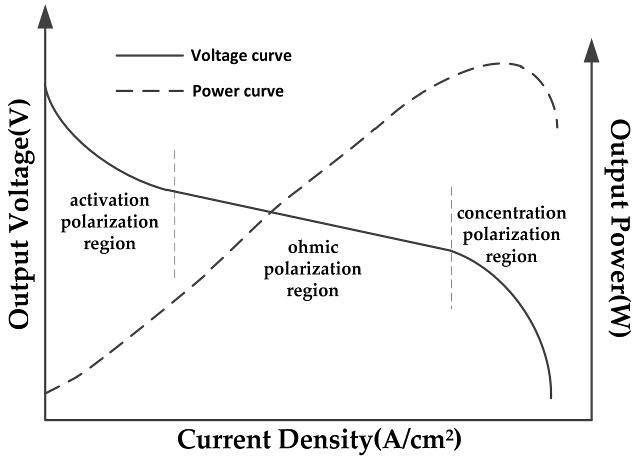

Figure 6. *V-I* and *P-I* characteristic curves of fuel cells.

3. Topology and Control of Fuel Cell Power Supply System

In addition to the above fuel cell characteristics, current ripple increases the loss of the fuel cell, reduces the efficiency [19,20], and shortens the service life of the fuel cell [21]. In actual working conditions, the output voltage of the fuel cell is low; the output voltage of a single PEMFC battery is about 1 V, while the voltage required by a DC microgrid or new energy vehicle is 250~750 V. The voltage difference between the two voltages is very large, so an external converter with a high boost ratio is required to meet the voltage matching problem at the load end [22].

Depending on the connected load, fuel cell power generation devices can be divided into two types, namely off-grid fuel cell power generation systems and grid-connected fuel cell power generation systems, which are directly connected to the load and grid-connected.

3.1. Topology and Control of Off-Grid Fuel Cell Power Supply System

The off-grid fuel cell power generation system converts the nonlinear, low-voltage fuel cell voltage into a stable, high-voltage DC voltage through a DC/DC converter to meet the voltage requirements required by the load.

In order to improve the fuel battery life and solve the problem of mismatch between fuel cell and bus voltage, the literature [23] proposes a current-fed DC/DC converter based on the fuel cell model and the special working conditions of load disturbance. The topology is shown in Figure 7. The converter has two inductors L_1 and L_2 on the primary side and two interleaved switches S_1 and S_2, which can be equivalent to an isolated interleaved parallel boost converter that not only boosts but also suppresses input current ripple. The secondary side is a full-bridge rectifier circuit, which realizes the ZVS/ZCS of the switch tube through modulation and suppresses the voltage spike of the switch tube on the primary side. This topology has the advantages of a high boost ratio, low current ripple and high reliability and is suitable for scenarios with a high level of interference.

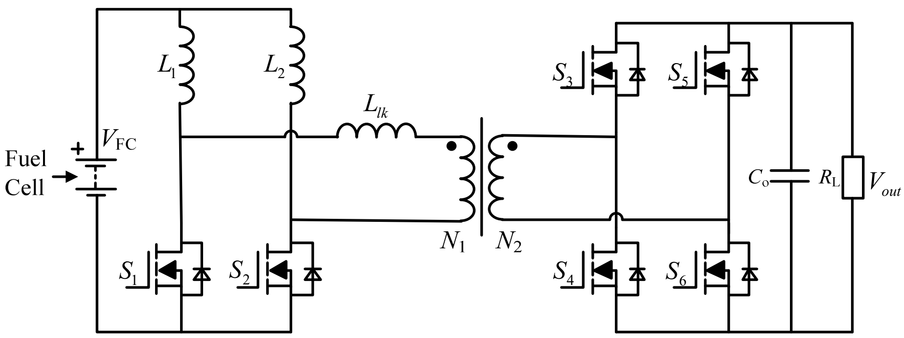

Figure 7. Current-fed DC/DC Converter.

Based on the constructed converter, the model predictive control inner loop controller and feed-forward control outer loop controller are designed to improve the response performance of the system. Current internal loop control introduces model predictive control, which uses the difference between the predicted state and the ideal dynamics of the system to construct the system value function, achieving fast tracking of system dynamics through the value function and improving the dynamic response within the system while suppressing current ripple. For the voltage outer loop, a method is proposed for giving dynamic current reference values based on load power observations. The real-time estimated load variation obtained from the expanded Kalman observer is combined with the fuel cell power and current characteristics and the principle of energy conservation to obtain a dynamic current reference value, which is corrected in real time for the given current. The overall control block diagram is shown in Figure 8. This control strategy is complex in design and is suitable for applications with frequent load changes and many disturbance factors.

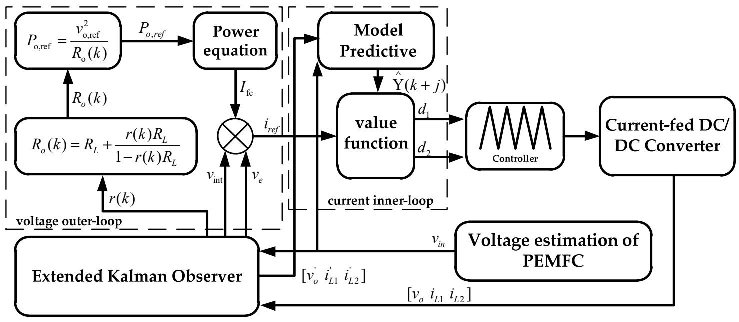

Figure 8. Control block diagram of Current-fed DC/DC Converter.

In the literature [24], based on the traditional phase-shifted full-bridge converter, a double-parallel structure is used to further enhance the boosting capability of the topology by reversing the parallel connection of the two secondary sides. Moreover, the dual-parallel sides can be adjusted complementarily to each other, increasing the stability and practicality of the device. This topology takes full account of the need for high boost ratios in fuel cells and is used in situations where the voltage levels differ significantly, as shown in Figure 9.

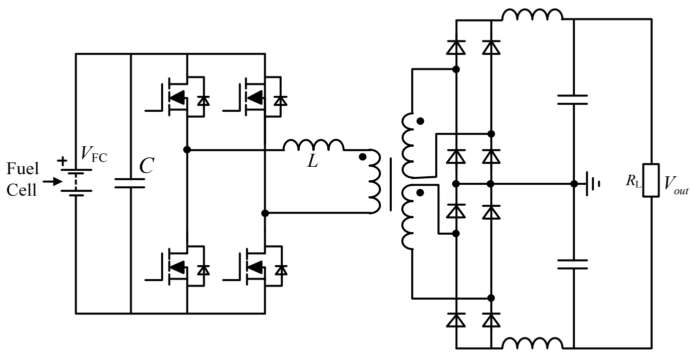

Figure 9. Phase-shifted full-bridge converter.

In terms of control, a double closed-loop controller with self-adjusting parameters is proposed. Aiming at the shortcomings of traditional double closed-loop, such as the inability to eliminate dynamic differences and the difficulty of balancing rapidity and stability, gain compensation and dynamic self-adjustment PI parameter strategies are proposed to eliminate the interference caused by the wide-range voltage input and to improve the ability to adapt to the large-range change of the load. The compound voltage controller is composed of fuzzy inference and variable-parameter PI control, which improves the ability to suppress dynamic disturbance of the load. The proposed control strategy, shown in

Figure 10, is based on the traditional double closed-loop control with PI adaptive regulation, which speeds up the response to disturbances and is more adaptable to widely varying loads, but requires the design of more complex controllers and control algorithms.

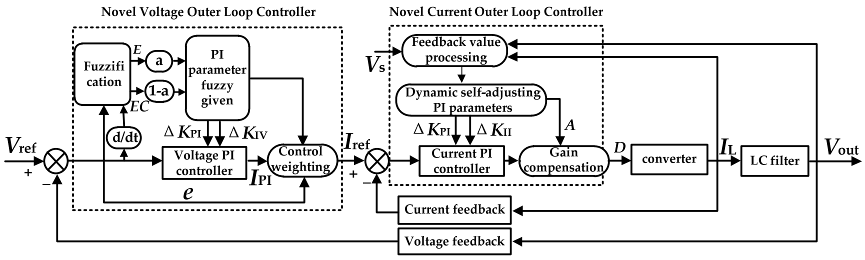

Figure 10. Novel double closed-loop controller's block diagram.

In order to greatly reduce the output current ripple of fuel cells, a multi-phase interleaved boost converter is proposed in the literature [25]. The topology is shown in Figure 11. The multi-phase interleaved fuel cell DC/DC converter can reduce the input current ripple and current stress, and improve the overall power of the converter. Each branch can operate independently with high flexibility and a large adjustable power range. This topology is suitable for applications with high current ripple requirements and a large power fluctuation range.

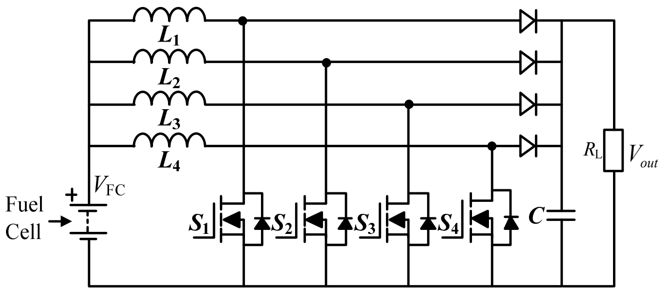

Figure 11. The four-phase interleaved DC/DC converter.

The uneven current of the multi-phase branch can cause the phenomenon of large differences in the current of each phase circuit, which can shorten the service life of a particular branch device and even lead to the damage of the whole converter. Aiming at the problem of uneven current in branches, a double closed-loop control strategy with multi-phase current inner loop is proposed in [25]. On the basis of the voltage outer loop, the multi-phase current inner loop control is used to control the current of each branch separately. The staggered conduction of each phase current is implemented, which greatly reduces the current ripple. The control block diagram is shown in Figure 12. The control strategy is more mature, simpler and has been widely used.

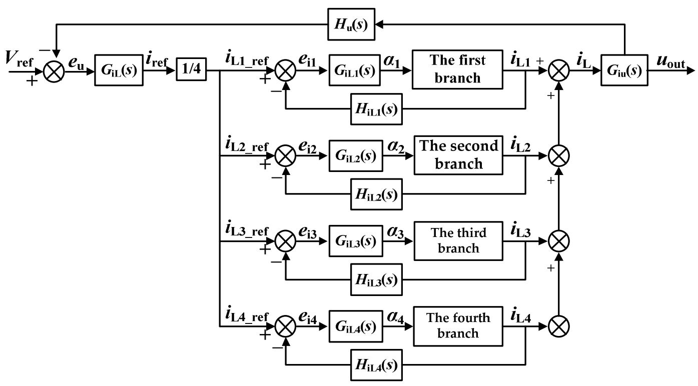

Figure 12. Control block diagram of four-phase interleaved converter.

To address the slow dynamic response of fuel cells, the literature [26] proposes a three-port triple-active-bridge converter topology, which compensates for the slow dynamic response of fuel cells through supercapacitors and reduces the current ripple of fuel cells. The topology couples the three full-bridge circuits through a high-frequency three-winding transformer to provide electrical isolation for all ports. All ports can transmit energy in both directions, enabling multiple power flow modes. The topology is shown in Figure 13. This topology is suitable for conditions such as frequent power changes and long working hours.

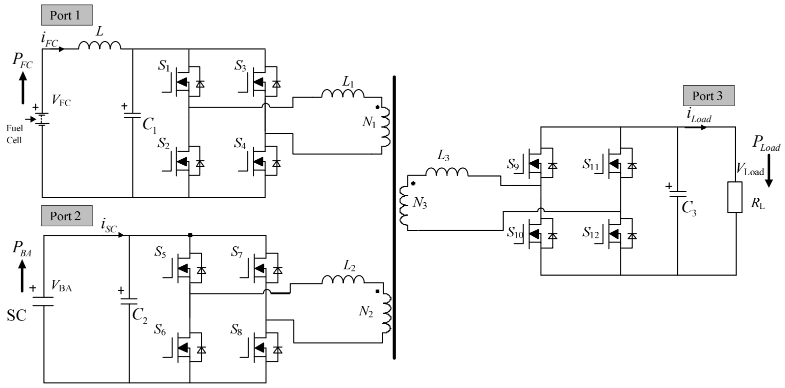

Figure 13. Three-port triple-active-bridge converter.

In the control, the power flow direction between each port is realized by adjusting the phase angle difference between the three ports. The control strategy aims to adjust the output voltage and fuel cell power simultaneously. The three variables of phase shift angle φ12, φ13 and duty cycle D are obtained through the fuel cell real-time power and battery energy manager to control the power flow and soft switching between the ports. The control block diagram is shown in Figure 14. The control algorithm is highly executable and can handle variable operating conditions through fuel cell management, which also causes the need for more data storage and calculations.

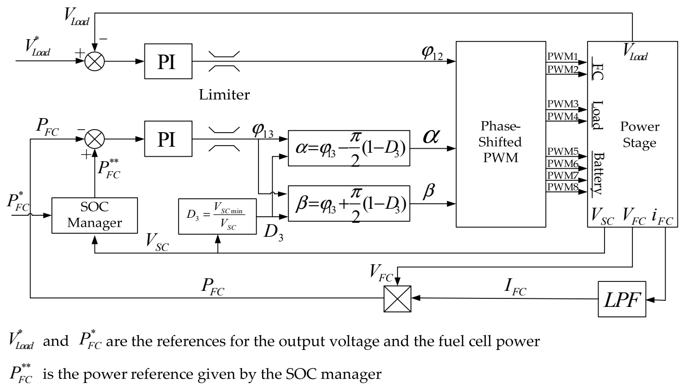

Figure 14. Control scheme three-port triple-active-bridge converter.

The maximum power point tracking algorithm of fuel cells is often used in DC/DC converters. Due to the characteristics of fuel cells, different from the maximum power point tracking of photovoltaic cells, the maximum power point tracking of fuel cells will have problems of limited working interval and maximum power point offset, etc. Therefore, a maximum power point tracking algorithm with strong stability is needed to track the optimal working point under different working conditions.

Naseri et al. applied the perturb and observe (P&O) method to the maximum power point tracking of fuel cells, but it is easy to produce misjudgment and oscillation, which reduces the service life of fuel cells [27–29]; the literature [30,31] uses a proportional-integral-derivative (PID) controller to improve the maximum power point tracking based on fuzzy logic, which has higher accuracy and faster response speed to track the maximum power point of the fuel cell; the literature [32] proposes that particle swarm control is better than fuzzy logic control in convergence time and overshoot, which is more suitable for fuel cell maximum power point tracking. Meanwhile, the literature [33] proposes a maximum power point tracking algorithm suitable for photovoltaic-fuel cell hybrid system based on particle swarm control, which realizes the maximum power point output of hybrid system. The literature [34,35] constructs the current reference estimation curve by fitting the function to obtain the current corresponding to the maximum power point as the reference current to achieve the tracking of the maximum power point.

Since the fuel cell is greatly affected by the external environment, the maximum power point of the fuel cell will be shifted. When the maximum power point is in the concentration polarization region, if the output is still at the maximum power point, the fuel cell service life will decay rapidly. The literature [36] fully considers the situation of the maximum power point of a fuel cell in different intervals, and proposes a hybrid maximum power point algorithm of resistance matching with adaptive step size to realize the maximum power point tracking of adaptive environmental transformation. The literature [37] uses the improved current-type disturbance observation method to identify the interval where the maximum power point of the fuel cell is located, which makes the fuel cell work in the ohmic polarization region to complete the maximum power point tracking of the fuel cell.

Off-grid fuel cell power generation devices are relatively mature in structure and control, and have a widespread application. The converter structure is designed according to the actual needs and has high flexibility. The controller usually adopts double closed-loop control, which has high stability. However, the shortcomings of off-grid fuel cell power generation devices are that the overall system efficiency is not high and it is difficult to apply them to high-power applications.

3.2. Topology and Control of Grid-Connected Fuel Cell Power Generation System

Grid-connected fuel cell systems can be placed in the power system to strengthen the grid and improve system integrity, reliability and efficiency. At the same time, the specific fuel cell power generation system can meet some specific grid operation requirements [38,39].

The literature [40] uses the boost converter as the front-end converter and the three-phase bridge inverter as the back-end inverter converter with the topology is shown in Figure 15. The front-end boost converter boosts and suppresses the output current ripple of the fuel cell. The back-end phase three-phase inverter converter converts DC power into AC power and connects to the distribution network.

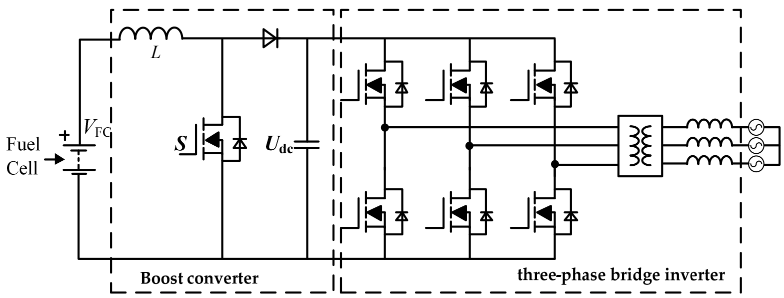

Figure 15. Boost+ three-phase bridge inverter topology.

In view of the slow dynamic response of the traditional fuel cell grid-connected system, the front-end boost adopts smooth control to stabilize the voltage at 110 V, which has fast dynamic response and strong robustness. The control strategy of the back-end inverter is composed of active and reactive power decoupling modules and a hysteresis comparison module. Based on feedforward control, the active power and reactive power are decoupled, and the real-time current error is compared with the hysteresis width to realize the overall control of the converter. The two parts of control have been decoupled, which makes the control much less difficult. The control block diagram is shown in Figure 16.

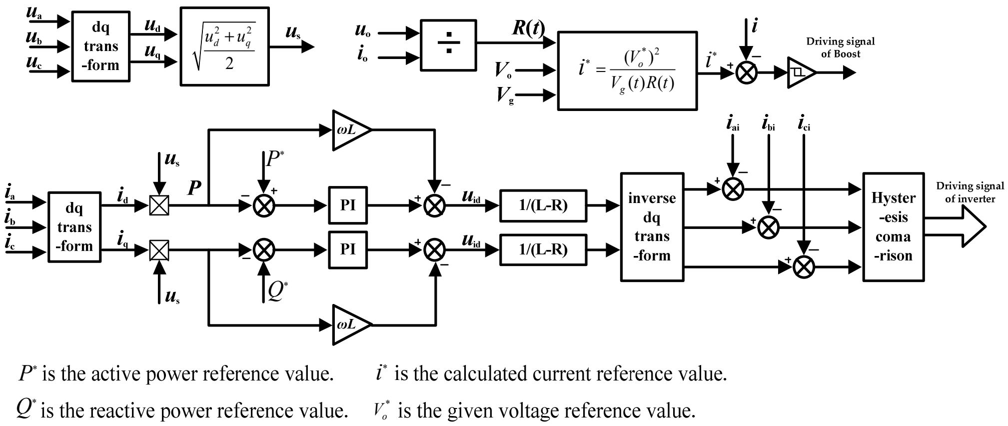

Figure 16. The control block diagram of Boost+ three-phase bridge.

In view of the influence of power frequency on fuel cells, a two-stage grid-connected fuel cell system based on an H6 inverter is proposed in the literature [41]. Figure 17 shows the grid-connected fuel cell system topology. The boost converter is used for the front-end DC/DC converter and the H6 bridge inverter is used for the back-end DC/AC converter. Compared with the H4 bridge inverter, the H6 bridge inverter realizes the isolation between the power grid and the DC side through two additional sets of switching tubes and diodes, and improves the efficiency of the inverter and prevents electromagnetic interference.

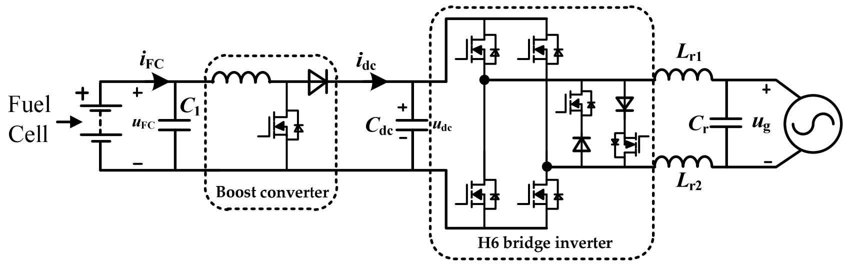

Figure 17. Circuits of single-phase grid-tied PEMFC system.

In order to improve the DC power quality of the fuel cell system, an improved model predictive control based on virtual vector is adopted. The front-end boost adopts feedforward-feedback compound control and the control block diagram is shown in Figure 18a. On the basis of the closed-loop of the fuel cell current, feedforward compensation calculated by the fuel cell voltage and the output voltage is introduced to further improve the performance of the current loop. In view of the frequency doubling disturbance caused by grid connection, the back-end converter adopts power decoupling control with notch filtering to eliminate the frequency doubling interference of the back-end DC/AC converter on the front-end DC/DC converter. The control block diagram is shown in Figure 18b. The control strategy isolates the interference of the grid with the fuel cell in two aspects, which greatly guarantees the high power quality and efficiency of the fuel cell, but there is no obvious decoupling relationship between the two stages of control, which increases the difficulty of control.

Fuel cell grid-connected converters often adopt a two-stage structure, with more devices and higher costs, while the literature [42] proposes a boost-type differential inverter to realize grid-connected power generation of fuel cells without increasing the hardware cost of the converter. The topology is shown in Figure 19. The topology consists of two boost converters with two output differential capacitors. The output voltage is obtained from the voltage differential of the two capacitors. By controlling the voltage of the capacitors, the current ripple of the fuel cell is effectively suppressed. This topology is suitable for small to medium power, small operating environments and frequent load changes.

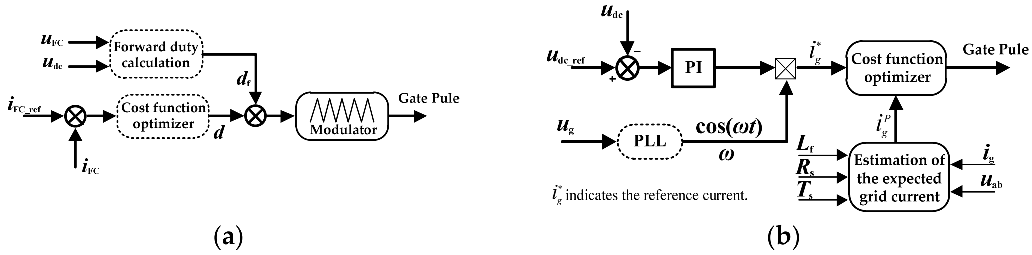

Figure 18. The control block diagram of Boost+ H6 converter.

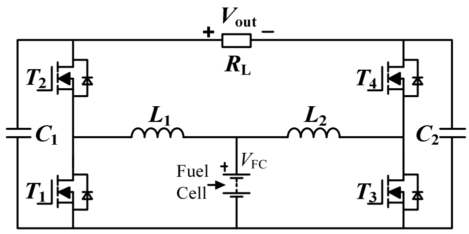

Figure 19. The boost-type differential inverter.

In order to suppress the current ripple of fuel cells, an active control method is proposed, as shown in Figure 20. Through the output current voltage and capacitance parameters, the given voltage of the capacitor is calculated, which is compared with the actual capacitance voltage to obtain the error, and finally the control signal of the switch tube is obtained through the double loop control. In view of the effect of DC deviation on the fuel cell, an output current DC tracking zero is introduced to suppress DC bias. Since the converter does not adopt a two-stage structure, this control strategy has to achieve multiple control objectives and needs to prevent signal interference, which is difficult overall and requires high control accuracy.

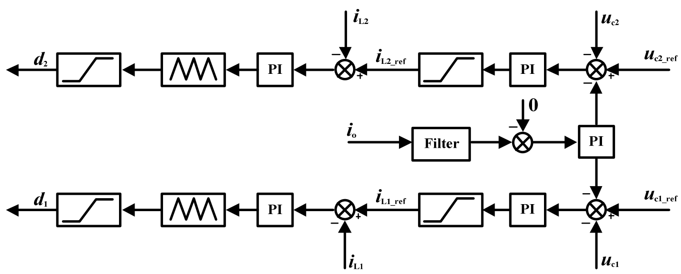

Figure 20. The control block diagram of the boost-type differential inverter.

For grid-connected fuel cell power generation systems, the fuel cell maximum power point tracking algorithm is still applied to the front-end DC/DC converter, which will not be repeated here.

The grid-connected fuel cell power generation system connects the fuel cell to the power grid through DC/DC converter and DC/AC converter, where the front-end DC/DC converter is used to adjust the output voltage of the fuel cell, make it adapt to the expected voltage of the DC/AC converter, and optimize the output current of the fuel cell [43,44]. The DC/AC converter converts the DC bus into AC power and connects it to the power grid.

In summary, the general principles of the fuel cell topology are summarized as follows: (1) The fuel cell converter adopts current-type converter to ensure the stability of the fuel cell output current, reduce the current ripple and improve the service life of the fuel cell; (2) In order to adapt to the output voltage range of the fuel cell, the converter should meet a wide input voltage; (3) In order to realize the adaptive connection between the fuel cell and the load end, the converter with a large boost ratio should be selected. The topology and control classification applicable to fuel cells are summarized in Table 1.

Table 1. Topology comparison and control mode summary of fuel cell power generation devices.

Classification	Off-Grid Type	Grid-Connected Type
Characteristics of topology	Connect fuel cell to load using DC/DC converter	Two-stage converter is adopted: the front-end DC/DC converter stabilizes the fuel cell and increases the voltage; the back-end DC/AC converter converts direct current into alternating current and connects the grid.
Advantages	High flexibility, wide application and high reliability	High utilization rate, high power density and large capacity
Shortcomings	Low efficiency, low power	High cost, grid interference, complex control
Control Strategies	DC/DC converter: dual closed-loop control, interleaved collaborative control, phase shift control, soft switching control, value function predictive control, maximum power point tracking DC/AC converter: DQ decoupling control, feed-forward decoupling control, hysteresis control, dual closed-loop control, current tracking control, capacitor voltage equalization control	

At present, various fuel cell power generation devices have made some progress, but they still need to be continuously optimized and improved, and further research is needed:

(1) Off-grid fuel cell power generation device is not suitable for high-power situations, which greatly limits the development of fuel cells. The overall power of the system can be improved by staggered cascading of multiple units,, while the interleaved cascade further reduces the output current ripple of the fuel cell from the system level;

(2) Grid-connected fuel cell devices usually require two-stage converters, resulting in complex control strategies. There is a problem that the power grid increases the ripple disturbance of fuel cells. The influence of the power grid on fuel cells can be eliminated by enhancing the integrity of the control algorithm and clarifying the interference between the front and rear stage converters;

(3) From the characteristics of fuel cells, their volt-ampere curves are nonlinear and their dynamic response is slow, which makes fuel cells unusable in many applications. These problems can be studied in terms of fuel cell internal materials and structure. Alternatively, other energy sources can be combined to form a multi-energy power generation device to compensate for the fuel cell characteristics;

(4) With the development of new generation semiconductor materials, power electronic devices can be applied to more applications. Fuel cell power generation devices can also use the new generation of power electronics devices to expand the range of use and improve performance.

4. New Energy 100% Absorption Green Hydrogen Energy System

In 2020, hydrogen accounted for less than 0.1% of the terminal energy system. According to the International Energy Agency, hydrogen will account for 2% of the final energy system by 2030, 10% by 2050, and contribute 6% to carbon reduction [45]. From the perspective of the development trend of hydrogen energy, the demand for hydrogen and the proportion of terminal energy will become larger and larger in the future. At present, the main source of hydrogen is gray hydrogen produced from fossil fuels, which accounts for about 96% of the hydrogen source market, but the production process generates a large amount of carbon emissions. In contrast, the green hydrogen produced by hydrogen production from new energy has almost no carbon emissions in the process, which can solve the absorption problem of new energy. New energy hydrogen production is mainly through electrolysis of water to produce hydrogen. Due to limitations such as scarce electrolytic hydrogen production equipment and catalyst materials, the cost of hydrogen production from electrolytic water is as high as 2.24~4.84 USD/kg, which is higher than the cost of hydrogen production from fossil fuels (0.98~1.73 USD/kg). However, with the advancement of technology, the cost of hydrogen production will be greatly reduced, and hydrogen production from new energy has great potential. It is the mainstream direction of hydrogen production in the future.

The hydrogen storage and transportation methods are mainly high-pressure gas tube trailer transportation, liquid hydrogen truck transportation and hydrogen pipeline transportation. The summary of various hydrogen transportation methods is shown in Table 2. High-pressure trailer transportation has the advantage of short-distance transportation cost, which increases sharply as the distance increases. The hydrogen carrying capacity is small, so it is suitable for short-distance and small hydrogen transportation occasions; due to the high density of liquid hydrogen, the hydrogen carrying capacity of liquid hydrogen trucks is large, but the loss in transportation projects is also large, which is suitable for long-distance and large hydrogen transmission situations; the initial construction cost of hydrogen pipelines is high, but the transportation cost is low. Hydrogen pipelines are suitable for large-scale hydrogen transmission and fixed hydrogen supply line [46]. The current standards of hydrogen storage and transportation are not perfect, and the appropriate storage and transportation plan is not formulated for customer needs, resulting in extremely high costs of hydrogen storage and transportation, which has become one of the important factors limiting the development of hydrogen.

Table 2. Comparison of different hydrogen transportation.

Hydrogen Transport Method	Transport Capacity	Transport Distance	Advantages	Shortcomings
High-pressure gas tube trailer transportation	200~300 kg	Below 100 km	Fast transportation, low cost and high flexibility	Short transportation distance, small transportation capacity and poor safety
Liquid hydrogen truck transportation	5000 kg	More than 300 km	Large transportation capacity, small container volume and long transportation distance	Large loss and high maintenance cost
Hydrogen pipeline transportation	-	More than 300 km	Low transportation cost, large transportation capacity and long transportation distance	High construction cost and poor flexibility

"-" Indicates that no relevant data were found.

With the implementation of carbon reduction policies, hydrogen energy, as a high energy density energy source, has been applied in many fields. In terms of transportation, hydrogen energy has been used in urban vehicles, short-distance buses, ships, aerospace and other applications. In industry, hydrogen is mainly used as industrial raw material, shielding gas and reducing gas for industrial production and manufacturing. In terms of energy supply, hydrogen is doped with natural gas to reduce its carbon emissions. Although hydrogen energy has been applied in transportation, industry and other fields, there are still problems such as imperfect terminal hydrogen refueling equipment and weak infrastructure equipment, which makes it difficult to realize efficient, deep and multiple utilization of hydrogen energy.

On the whole, there are certain deficiencies in the preparation, storage, transportation and application of hydrogen energy. The lack of overall layout of infrastructure makes it difficult for the upstream and downstream of the whole hydrogen energy industry chain system to form an effective linkage. In view of the problems existing in each link, a clean, low-carbon and efficient green hydrogen energy system should be built, as shown in Figure 21, to provide reference for the development of hydrogen energy.

It can be seen from Figure 21 that: (1) hydrogen is prepared through new energy sources to achieve 100% absorption of new energy. The use of new energy sources to produce hydrogen not only increases the proportion of new energy consumption, broadening hydrogen production channels, but also reduces the overall carbon emission level and provides a large-scale, stable and green hydrogen source; (2) According to hydrogen storage duration, hydrogen transport distance, hydrogen demand and customer distribution, one should select suitable storage and transportation methods taking into account real-time, economic and practicability requirements, and construct an efficient and large-scale hydrogen storage and transportation network; (3) In order to expand the hydrogen market, strengthen the infrastructure of hydrogen refueling stations, hydrogen heating stations, etc. Through the hydrogen storage and transportation network, the prepared green hydrogen will be put into transportation, electric power, industry, construction and other fields to achieve diversified hydrogen energy applications, deep carbon emission reduction in multiple fields and promote the development of hydrogen energy marketization; (4) In order to ensure the consumption of new energy and the quality of hydrogen use, predict the amount of hydrogen used by users and other new energy, combine artificial intelligence optimization algorithms and 5G high-speed communication technology to control the entire green hydrogen energy system in real time, improving the rational allocation and utilization of resources. Finally, the cloud computing terminal of the hydrogen energy system is built.

The construction of a 100% absorption system for new energy with green hydrogen as the main body is mainly carried out in two stages. (1) At this stage, a large-scale hydrogen energy network is constructed. Build hydrogen production plants in areas rich in new energy to ensure the consumption of new energy. Build hydrogen storage and transportation facilities such as hydrogen storage tanks and hydrogen pipelines to form multi-form and multi-channel hydrogen storage and transportation channels. Vigorously build hydrogen refueling stations and other hydrogen-using terminals to promote the transformation of the energy system; (2) In the next stage, after the completion of the infrastructure of hydrogen production, storage and transportation of hydrogen and hydrogen use, through the prediction of new energy and the scheduling of user loads, the use of 5G high-speed communication and artificial intelligence algorithms will form hydrogen-electric coupling intelligent control technology to coordinate the supply and demand of large-scale hydrogen energy. With 100% consumption of new energy and cost economy as the optimization goal, the optimal operation of the 100% absorption system of new energy with green hydrogen as the main body is achieved.

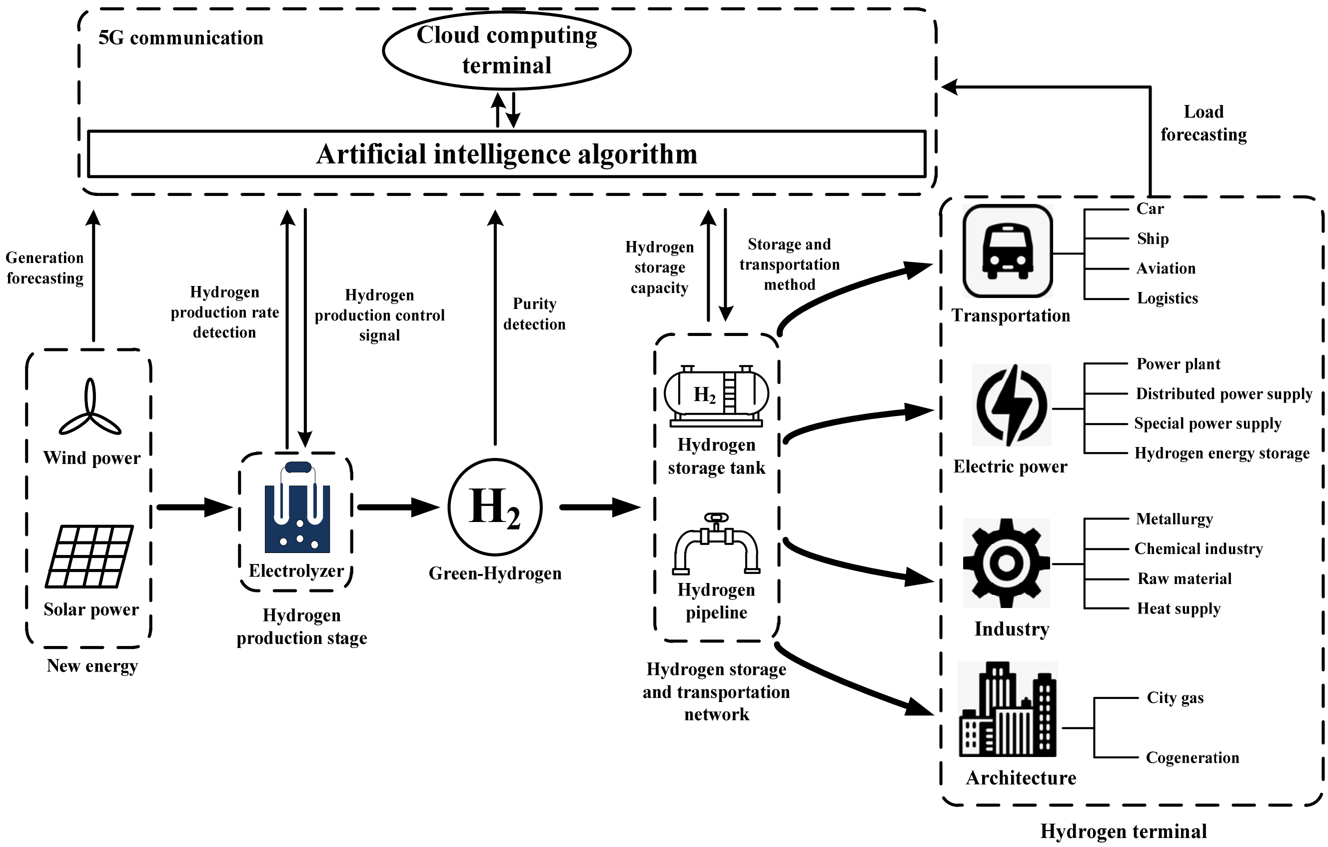

Figure 21. Schematic diagram of green hydrogen energy system.

5. Conclusions

The paper analyses the structure and characteristics of fuel cells; divides the fuel cell converters applicable at the present stage into two categories, describes each type of power electronic converter and its control strategy; and summarizes the characteristics and application scope of each type of device and points out the shortcomings and the focus of subsequent research. Combining energy development trends, artificial intelligence algorithms and 5G high-speed communication technology, a 100% new energy consumption system with green hydrogen as the mainstay is conceived. The construction targets for each stage are set, taking into account various aspects such as hydrogen production, storage, transportation and use.

At present, there is still much room for improvement in fuel cell power generation devices. Improve the power quality of fuel cells in terms of materials and structures. The use of fuel cell power generation system is relatively limited, so more targeted topologies and controls are needed to expand the use of fuel cell power generation devices. Overall, hydrogen energy is still in the preliminary development stage. Fuel cell power generation devices can be widely used only when the hydrogen energy system is established.

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