Research on Hydrogen Power Station Accessing to Traction Power Supply System

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Abstract. In order to realize the control, utilization and consumption of hydrogen power generation, improve the proportion of green energy in the energy consumption of traction power supply system, save energy and reduce emissions. Firstly, the two types of hydrogen power plants are technologically analyzed, and then the topology and control strategy of hydrogen power generation accessing to traction power supply system in order to reduce the three-phase unbalance of common connection point are put forward. Finally, a simulation example is given to verify the effectiveness of the proposed topology and control scheme. The results show that hydrogen power generation can be used as the auxiliary power generation form of traction power supply system, and can better solve the negative sequence problem of traction power supply system.

Keywords: Hydrogen power generation · Traction power supply system · Technical analysis · Access scheme · Negative sequence compensation · Control strategy

1 Introduction

With the rapid development of China's railway industry, the traction power supply system has become one of the major power users in the power sector. At present, the electric energy used by the traction power supply system basically comes from the three-phase power grid, and electricity costs account for a relatively high proportion of operating expenses. If the traction power supply system can spontaneously use local energy to generate electricity for the traction network, it can save a lot of bills every year and improve economical operation of the power supply system. Today, China has self-operated railways represented by the Shenhua Railway. Its coal chemical industry will produce hydrogen as an industrial by-product, which can be used as a clean energy power generation to better implement the basic national policy of energy conservation and emission reduction.

In the international energy situation, hydrogen energy, as a low-carbon, clean energy form, is full of vitality. It is estimated that by 2050, hydrogen energy will account for about 10% of China's energy system, and will eventually play an important role in the global energy structure. Hydrogen energy has a wide range of sources [1, 2]. It can not

L. Jia et al. (Eds.): EITRT 2021, LNEE 864, pp. 711–722, 2022.
https://doi.org/10.1007/978-981-16-9905-4_79

only be produced from fossil energy to make the use of fossil energy cleaner, but also can be produced by renewable energy such as solar energy and wind energy. Hydrogen is generally considered the most suitable for future applications in the world, and it is a key solution to the current global energy crisis and environmental degradation [3].

Therefore, in order to promote the application of hydrogen energy in the traction power supply system, the technical analysis of hydrogen power generation is provided and the topology and control strategy of the hydrogen power generation system accessing to the traction power supply system are proposed in this paper. Then the typical working conditions are simulated by MATLAB/Simulink and the results show that the control strategy is effective in reducing the three-phase imbalance at PCC point.

2 Scheme of Hydrogen Power Generation System

2.1 Principle of Hydrogen Power Generation

The power generation mode of hydrogen energy can be divided into strong reaction mode and weak reaction mode. The former is the direct combustion of hydrogen for power generation, hydrogen can use an internal combustion engine or gas turbine to generate electric energy. Chemical energy is mainly transformed into mechanical energy and thermal energy, and then mechanical energy is transformed into electric energy through the movement of the piston or turbine. The latter is the electrochemical mode. The fuel cell is used to convert chemical energy into electrical energy. The redox reaction process of hydrogen fuel cell is essentially the reverse process of electrolytic water, which does not involve dangerous processes such as combustion.

2.2 Technical Analysis

Development of Hydrogen Gas Turbine Power Generation Technology

Since the 1980s and 1990s, many countries and international organizations have formulated hydrogen gas turbines and hydrogen energy-related research plans [4], and many companies are focusing on the development of high-efficiency and low-carbon pure hydrogen gas turbines [5]. For gas turbines, due to the high calorific value of hydrogen, fast combustion speed and high temperature, when the fuel is replaced with hydrogen, the main technical problems that need to be solved are:

- Control the thermal NO_x emissions produced by hydrogen combustion [6];
- Combustion oscillation and flashback control;
- Development of combustion chamber structure and materials required for high-temperature combustion of hydrogen fuel.

Mitsubishi Hitachi Power Systems successfully tested a new premix burner in 2018, which enabled the J series heavy-duty gas turbines to achieve 30% H_2 and CH_4 mixed gas stable combustion, reduce CO_2 gas emissions by 10% and make NOx emissions within an acceptable range [7]. Siemens developed a hydrogen gas turbine based on SGT-6000G (W501G). At present, the fourth-generation dry low-emission (DLE) combustion system hydrogen-rich combustion has been tested many times to prove that the NO_x emission of the system with a hydrogen concentration of 35% can be controlled within 20PPM. As of June 2020, the DLE combustor of Siemens SGT-600 in Germany has been running at full capacity with pure hydrogen combustion, and it can stably burn 60% hydrogen fuel on the whole machine, and the single tube combustion chamber test of 100% hydrogen combustion was completed. In 2021, the U.S. Department of Energy (DOE) announced that eight university-led projects will receive federal funds for turbine power generation projects that use hydrogen.

However, the energy conversion efficiency of gas turbines is low. When generating the same electric energy, gas turbines consume more hydrogen. When the amount of hydrogen is limited and the manufacturing cost is high, the practical value of using hydrogen fuel gas turbines for power generation is low.

Development of Hydrogen Fuel Cell Power Generation Technology

Fuel cell is hailed as a fourth-generation power generation technology after hydropower, thermal power, and nuclear power. Technical characteristics are as follows [8]:

- High battery efficiency. Energy conversion is not limited by Carnot cycle effect.
- The response is fast and stable. During the electrochemical reaction process, there is no mechanical noise, no pollutant emission, and low heat radiation.
- It has a high safety factor. Due to the high buoyancy and high diffusion rate of hydrogen, the concentration is difficult to reach explosive conditions.
- The power is adjustable. According to the required power requirements, a single fuel cell can be tiled or connected in series to make a fuel cell stack.

Fuel cell research in the United States, Europe, Japan, and South Korea started earlier and has a high degree of industrialization. Hydrogen fuel cell research and development and industrialization are also accelerating in China [9].

There are a variety of fuel cell types to choose for power generation [10]. The comparison of alkaline fuel cell, phosphoric acid fuel cell, molten carbonate fuel cell, solid fuel cell and proton exchange membrane fuel cell is shown in Table 1.

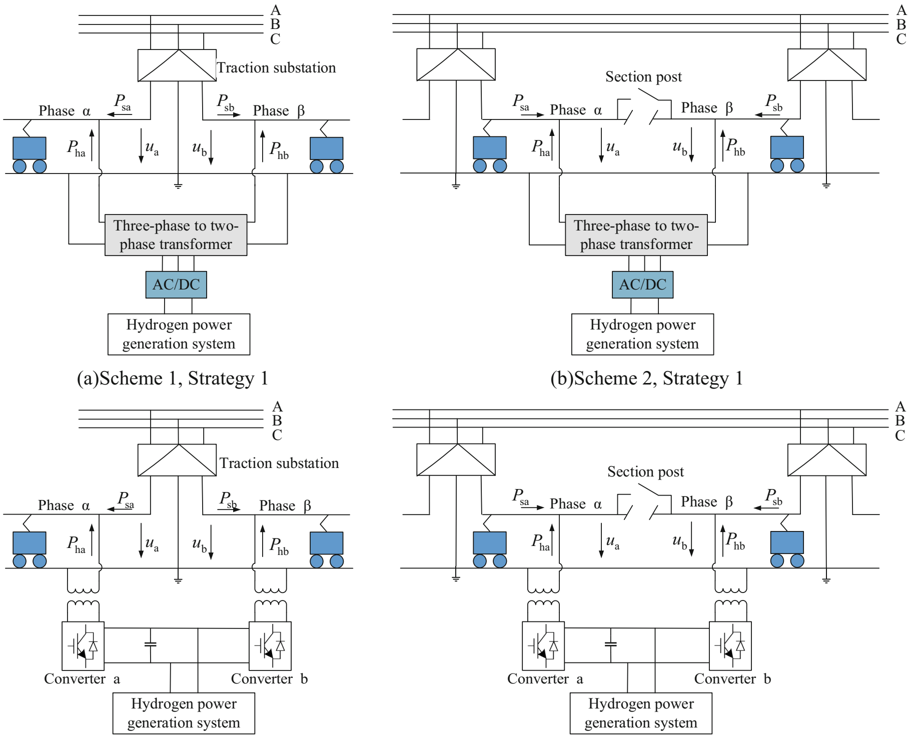
Table 1. Comparison of hydrogen fuel cells

Types	AFC	PAFC	SOFC	PEMFC
Electrolyte	35%–50%KOH	Concentrated Phosphoric Acid	Zirconium and Yttrium Mixed Oxide	Proton exchange membrane
Operating temperature	60–90 °C	160–220 °C	600–1000 °C	50–100 °C
Efficiency	50–60%	55%	50–65%	50–60%
Life	10000 h	7000 h	15000 h	100000 h
Start time	Short	Long	Long	Short
Price	Low	High	Low	High

3 Access Scheme of Hydrogen Power Generation System

3.1 Topology

The electric energy in the traction substation supplies power to the train through the catenary network. In order to ensure the reliability of power supply, the number of stations along the railway is large, and the energy consumption is relatively concentrated, which facilitates large-scale use of various energy forms such as new energy and renewable energy [11]. When the hydrogen power generation system is connected to the traction power supply system side, there are two typical schemes for the access location. The first is to connect at the traction substation, and the second is to connect at the section post. There are two access methods to choose from [12]. The first is to adopt three-phase inverter for connection, convert the DC output from hydrogen power generation system into three-phase AC, and then connect it to the feeding sections through the three-phase two-phase transformer. The second is to adopt back-to-back single-phase converter for connection, and then connect it to the feeding sections through two single-phase transformers. The access topology is shown in Fig. 1.



(a)Scheme 1, Strategy 1 (b)Scheme 2, Strategy 1

(c)Scheme 1, Strategy 2 (d)Scheme 2, Strategy 2

Fig. 1. Access topology of scheme

3.2 Working Condition Classification

Based on the scheme of using back-to-back converters to access to power grid at traction substation, the typical working conditions can be summarized into 4 types:

1. Both feeding sections are in braking state;
2. Both feeding sections are in traction state;
3. One feeding section is in traction state, the other is in braking state, and the traction power is greater than the braking power;
4. One feeding section is in traction state, the other is in braking state, and the braking power is greater than the traction power.

4 Principle and Control Strategy of Negative Sequence Compensation

4.1 Principle of Negative Sequence Compensation

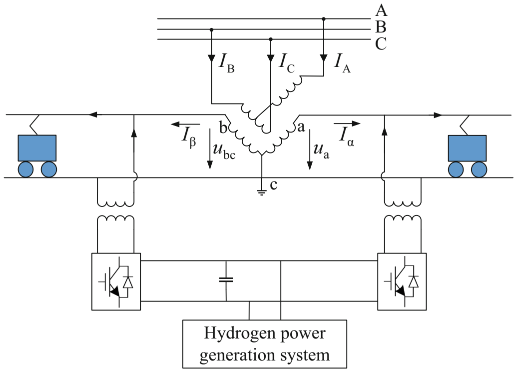


Fig. 2. Topology of hydrogen power generation system based on Scott traction transformer

For the topology shown in Fig. 2, consider that the power factor of the AC-DC-AC locomotive is 1, and the traction transformer adopts a Scott transformer. It is assumed that the base (M) of the transformer is connected to the BC phase of the power system, and the high block (T) One end of the primary side of the winding is connected to the midpoint of the base winding, and the other end is connected to the A phase of the power system. The high seat is connected to the α feeding section of the traction power supply system, and the base is connected to the β feeding section. Taking the phase A voltage as the reference, when only the fundamental wave is considered, the relationship between the high-voltage side current and the low-voltage side load current is

$$\begin{bmatrix} \dot{I}_A \\ \dot{I}_B \\ \dot{I}_C \end{bmatrix} = \frac{1}{\sqrt{3}K} \begin{bmatrix} 2 & 0 \\ -1 & \sqrt{3} \\ -1 & -\sqrt{3} \end{bmatrix} \begin{bmatrix} \dot{I}_\alpha \\ \dot{I}_\beta \end{bmatrix} \tag{1}$$

When the load current of the two feeding sections is the same, the three-phase current injected into the power system is balanced and $\dot{I}_A + \dot{I}_B + \dot{I}_C = 0$. As shown in Fig. 3.

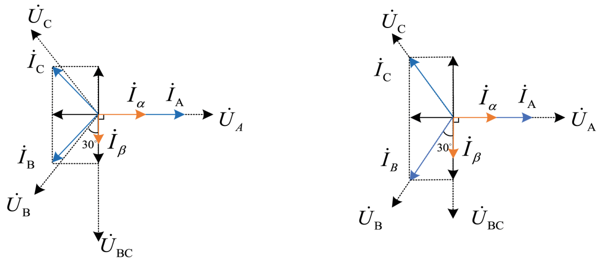


Fig. 3. Diagram of Scott primary and secondary side current phasor

4.2 Control Strategy

Assuming that the traction transformer is a Scott transformer, the power is positive when the traction load is in traction mode, the power is negative when it is in braking mode, and the discharge power of the hydrogen power generation system is negative.

The hydrogen energy power generation system adopts weak reaction power generation, which is mainly composed of a DC/DC converter and a hydrogen fuel cell. The schematic diagram and power output control flow chart of the hydrogen fuel cell power generation system are shown in Fig. 4 and Fig. 5.

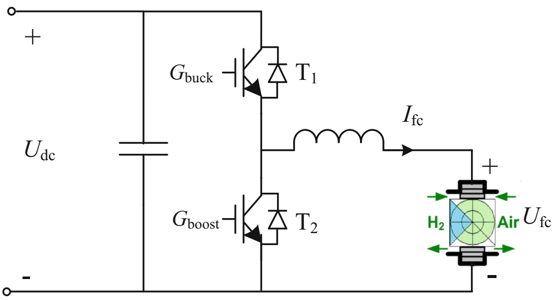


Fig. 4. Schematic diagram of hydrogen power generation system

Assuming that the instantaneous power of the two feeding sections are

$$\begin{cases} P_a = u_a i_a = U_a I_a + U_a I_a \cos(2\omega t) \\ P_b = u_b i_b = U_b I_b + U_b I_b \cos(2\omega t - \pi) \end{cases} \tag{2}$$

Wherein, I_a and I_b are the effective values of the fundamental currents of the two feeding sections; U_a and U_b are the effective values of the fundamental voltages of the two feeding sections.

The DC component obtained by low-pass filter is

$$\begin{cases} \overline{P_a} = I_a U_a \\ \overline{P_b} = I_b U_b \end{cases} \tag{3}$$

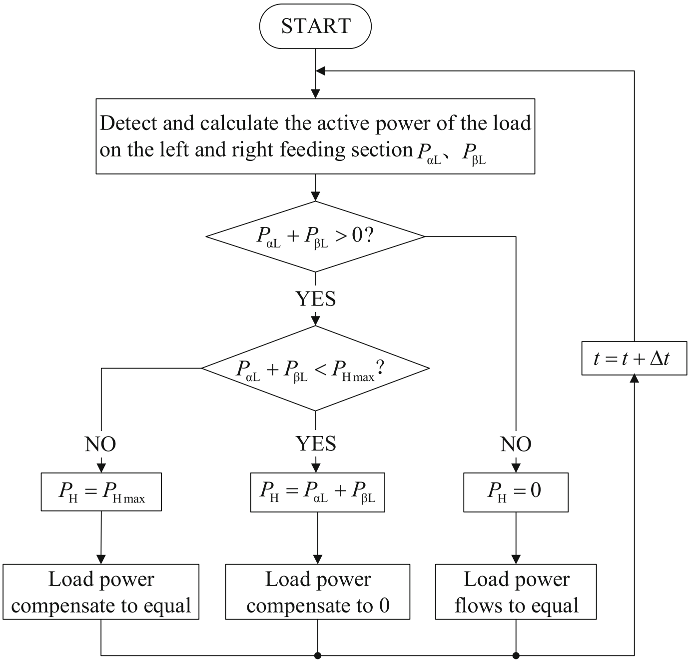


Fig. 5. Flow chart of power distribution

In order to provide active power and realize the power balance of load arm, the power distribution goal to be achieved is

$$P'_a = P'_b = \frac{\overline{P_a} + \overline{P_b} + P_h}{2} \tag{4}$$

Wherein, P'_a and P'_b are the active power when the load is balanced after the compensation of the two feeding sections; P_h is the active power provided for the hydrogen power generation system.

The signals $\cos(\omega t)$ and $\cos\left(\omega t - \frac{\pi}{2}\right)$ are obtained through PLL. Therefore, the reference value of the negative sequence compensation current provided by the two converters to the two feeding sections is

$$i_{ra} = K_R\left[\frac{\sqrt{2}P'_a}{U_a}\cos(\omega t) - \sqrt{2}I_a\cos(\omega t)\right] \tag{5}$$

$$i_{rb} = K_R\left[\frac{\sqrt{2}P'_b}{U_b}\cos\left(\omega t - \frac{\pi}{2}\right) - \sqrt{2}I_b\cos\left(\omega t - \frac{\pi}{2}\right)\right] \tag{6}$$

Where, K_R is the transformation ratio of the transformer at the grid connection of the hydrogen power generation system. i_{ra} and i_{rb} can realize the compensation of the negative sequence current of the traction power supply system.

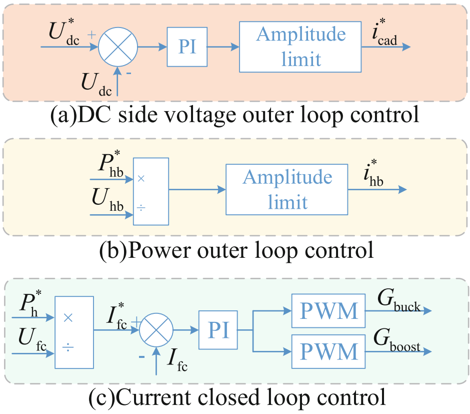


Fig. 6. Control block diagram of hydrogen fuel cell

In order to ensure the normal operation of the converter and the smooth connection of the hydrogen power generation system, the converter a adopts the DC voltage outer loop control to maintain the stability of the DC side capacitor voltage; The converter b adopts power outer loop control. According to the power command signal of the upper layer of the system, the d-axis current reference value is obtained through active power control to determine the power of a converter. The DC/DC converter connected to the hydrogen fuel cell adopts current closed loop control to control the power output of the hydrogen fuel cell. The control block diagram is shown in Fig. 6.

5 Simulation Analysis

5.1 Simulation Parameters

The traction power supply system adopts the direct power supply mode with return line, and the locomotive load is simulated by a controllable current source. The system simulation parameters and typical working condition settings are shown in Table 2.

Table 2. The parameters of typical operating

Working condition	Both in traction		One is in braking and the other is in traction		Both in braking	
Load power of feeding section a/MW	1	10	2	10	−2	−6
Load power of feeding section b/MW	0.5	0	−4	−2	0	−2
Total power/MW	1.5	10	−2	8	−2	−8

5.2 Simulation Results

Both in Traction

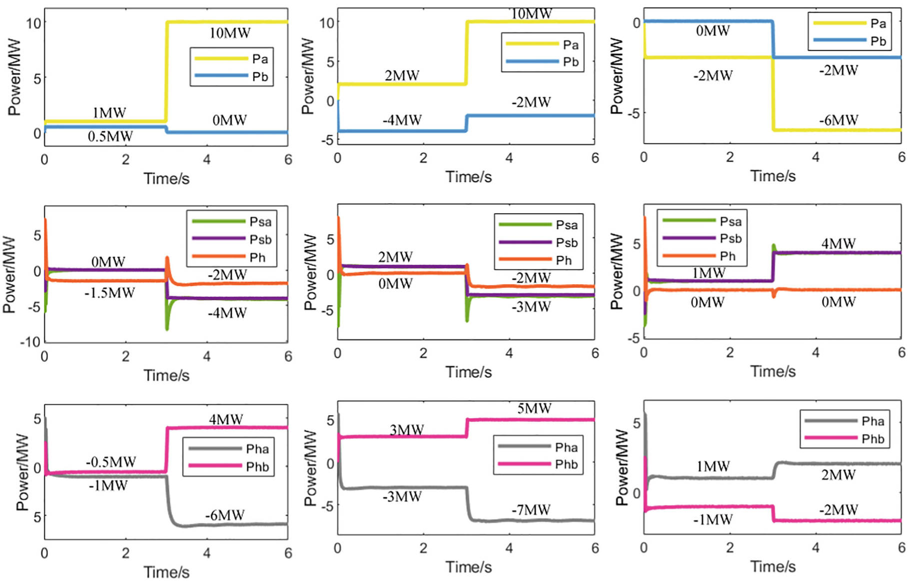
When the load power on the feeding section a and b are both traction power, 0–3 s is the working condition where the total load power is less than the maximum power of hydrogen power generation, and 3–6 s is the working condition where the load power is greater than the maximum power of hydrogen power generation. The simulation results Fig. 7(a) and Fig. 8(a) are available. From the simulation results, when the load power is less than the maximum power of the hydrogen power generation system, the hydrogen power generation system outputs the total load power, and the traction substation does not output power to the load. Under the same working conditions, compare the PCC point voltage unbalance before and after compensation, as shown in Fig. 8(a). During 3–6 s, without compensation, the three-phase voltage unbalance caused by the traction power supply system at the PCC point exceeds 1.3%. After compensation, the voltage unbalance is basically reduced to 0 due to the balance of the power of the two feeding sections, achieving a better negative sequence compensation effect.

One Is in Braking and The Other Is in Traction

When the load power of feeding section a is the traction power and the load power on feeding section b is the braking power, 0–3 s is a working condition where the traction power is less than the braking power, and 3–6 s is a working condition where the traction power is greater than the braking power. From the simulation results shown in Fig. 7(b) and Fig. 8(b), when the traction power is less than the braking power, the hydrogen power generation system does not output power to the system. Comparing the PCC point voltage unbalance before and after compensation under the same working conditions, during 3–6 s, the three-phase unbalance after compensation is reduced from 1.9% to about 0.05%, and the negative sequence compensation effect is significant.

Both in Braking

When the load power of feeding section a and b are braking power, 0–3 s, only feeding section a has train regenerative braking power, feeding section b has no train, 3–6 s, both feeding sections have braking power. It can be obtained from Fig. 7(c) and Fig. 8(c). When the power of the feeding section is braking power, the hydrogen power generation system does not emit power, and the power of the two feeding sections flows to balance through the back-to-back converter. After compensation, the three-phase unbalance at the PCC point drops significantly, which reduces the negative sequence at the PCC point where the traction power supply system is connected to the power grid.

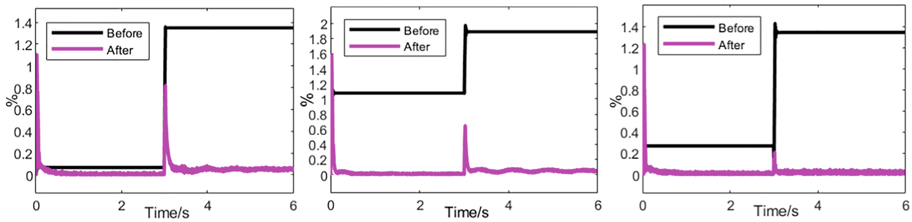


(a)Both in traction

(b)One is in braking and the other is in traction

(c)Both in braking

Fig. 7. Power of each port



(a)Both in traction

(b)One is in braking and the other is in traction

(c)Both in braking

Fig. 8. Voltage unbalance of PCC point

6 Conclusion

In order to increase the proportion of green energy in the energy consumption of the traction power supply system, such as hydrogen energy, the technology, topology and control strategy of hydrogen power generation system accessing to traction power supply system have been researched in this paper. The conclusions are as follows:

(1) In terms of technology, hydrogen fuel cell technology is more mature and the operation process is more environmentally friendly and efficient. High-power hydrogen

fuel cell power plants have been built and operated, but there are still technical problems that need to be solved for hydrogen-fired gas turbine power generation, such as tempering and thermal NO_x pollutant emissions, etc.

(2) The proposed topology and control strategy for traction power supply system with hydrogen power generation system have been verified by simulating typical operating conditions that voltage unbalance of PCC point can be effectively reduced and the negative sequence problem can be solved.

References

1. Ji, L., et al.: Status of hydrogen energy technology and its application in energy storage and power generation. Metall. Funct. Mater. **26**(6), 23–31 (2019). (in Chinese)
2. Kai, Z., Zhang, D.: Recent progress in alkaline water electrolysis for hydrogen production and applications. Prog. Energy Combust. Sci. **36**(3), 307–326 (2010)
3. Suman, D.: A review on production, storage of hydrogen and its utilization as an energy resource. J. Ind. Eng. Chem. **20**(4), 1148–1156 (2014)
4. Song, Y., et al.: International hydrogen energy policy summary and Chinese policy analysis In: 2020 IEEE 4th Conference on Energy Internet and Energy System Integration (EI2), pp. 3552–3557. IEEE Press, New York (2020)
5. Huang, N., Wu, Q., Su, L., Liu, J.: Study on the complementarity of hybrid power generation with gas turbine and new energy. Sino-Glob. Energy **25**(12), 10–15 (2020). (in Chinese)
6. Guo, Q., Zhou, Y., Liu, D., Wei, X., Fan, Z., Zheng, J.: Study on NOx emission from V94.3A gas turbine. Gas Turbine Technol. **31**(02), 56–59 (2018). (in Chinese)
7. Li, J., Li, G., Ma, S., Song, J.: Status of hydrogen energy storage and transportation technology and its typical application in power system. Mod. Power 1–12 (2021). (in Chinese). https://doi.org/10.19725/j.cnki.1007-2322.2021.0023
8. Song, X., Zheng, M., Xiao, J., Zhang, Z.: Development status and research progress of key materials for hydrogen fuel cell. Mater. Rep. **34**(S2), 1001–1005 (2020). (in Chinese)
9. Cheng, Y.: Application status and development trend analysis of hydrogen fuel cell technology. Green Petrol. Petrochem. **3**(2), 5–13 (2018). (in Chinese)
10. Brunet, Y.: Energy Storage Technology and Application. China Machine Press, Beijing (2018).(in Chinese)
11. Zhou, X.: Analysis on the potential of railway using new and renewable energy. Sino-Glob. Energy **21**(5), 29–34 (2016). (in Chinese)
12. Chen, W., Wang, X., Li, Q., Han, Y., Wang, W.: Review on the development status of PV power station accessing to traction power supply system for rail transit. Power Syst. Technol. **43**(10), 3663–3670 (2019). (in Chinese)