Research on optimal operation strategy of fuel cell vehicle charging-discharging-storage integrated station

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Abstract. The construction of energy supply facilities supporting fuel cell vehicles is the basis for the development of fuel cell vehicles. Aiming at the large-scale environmental protection supply of hydrogen energy for fuel cell vehicles, this paper proposes a construction idea and function setting for a fuel cell vehicle integrated station. Then, an optimized operation model of the fuel cell vehicle charging-discharging-storage integrated station is established. The model takes the total operating cost of the integrated station as the objective function, and considers the power balance and constraints of the electric-hydrogen system in the integrated station. Nonlinear programming tool is used to solve the model. It is verified by calculation examples that the integrated station proposed in this paper can effectively improve the power grid's peak and frequency modulation capabilities based on the total daily income of ¥25,431, and increase the renewable energy consumption rate from 48.0% to 84.6%.

1. Introduction

In recent years, the installed capacity of new energy power generation continues to increase, but the phenomenon of discarding wind power and photovoltaics is obvious. A large number of abandoned renewable energy electricity caused huge losses to the economy. The surplus electricity generated by new energy sources such as wind and solar energy can electrolyze water to produce hydrogen. This method has the advantages of low power generation cost and low-carbon environmental protection, which is considered to be the ideal way to realize large-scale hydrogen production and has been widely appreciated by the industry [1-3]. The product of hydrogen combustion is water, which is the cleanest energy source in the world. Hydrogen energy resources are abundant and sustainable. The rapid development of the hydrogen fuel cell vehicle industry has put forward requirements for the stable and reliable supply of hydrogen energy, which is therefore of great significance for the consumption of new energy.

Some progress has been made in the research on hydrogen energy and fuel cells recently. Literature [4] established an electric-thermal-hydrogen energy storage system to improve the regulation capacity of the grid; Literature [5] designed a predictive controller based on neural networks to control the voltage of fuel cells; Literature [6] briefly discussed fuel-based Battery electric vehicles and reviewed non-isolated multi-input boost converters for non-grid independent hybrid vehicles.

At present, the application of hydrogen energy is still in the exploration stage. The research on upstream hydrogen manufacturing and refueling services for the fuel cell vehicle industry is relatively insufficient. The Blue Paper on the Development of China's Hydrogen Energy Industry Infrastructure (2016) [7] put forward a roadmap for the development of China's hydrogen energy industry, and for
the first time proposes a plan for the development goals of China's medium-and-long-term hydrogen refueling stations and fuel cell vehicles. It can be seen that the hydrogen energy application scene oriented to the fuel cell vehicle industry has great research value.

This paper proposes an integrated fuel cell vehicle charging-discharging-storage station construction scheme for new energy consumption under the high permeability power distribution network. A distribution network with a large number of renewable energy sources was taken as an example and the integrated station is oriented to the hydrogen energy supply of large-scale fuel cell vehicles. The trading strategy of the integrated station under various market trading scenes is analyzed, and a multi-objective optimization model of the fuel cell vehicle charging-discharging-storage integrated station is proposed by establishing an electricity-hydrogen energy conversion model of the system. Finally, the economics of the integrated station and the improvement of the new energy absorption capacity of the power grid are verified through simulation.

2. Structure and function of charging-discharging-storage integrated station

The fuel cell vehicle charging-discharging-storage station is an intelligent integrated station that integrates the hydrogen production station with electrolysis tank, hydrogen storage station and fuel cell power station. While the station provides basic fuel cell vehicle hydrogen refueling service, the fuel cell power generation system in the station realizes the functions of participating in the market of Frequency Modulation (FM) auxiliary service of the power grid and supporting the voltage stability of the distribution network. The integrated station consists of the following five parts: dispatching center, hydrogen generation station with electrolyzed water, hydrogen storage system, fuel cell power station and hydrogen filling station, as shown in Figure 1.

**Figure 1.** Overall structure of the charging-discharging-storage integrated station.

The dispatching center is responsible for the stable and safe operation of the integrated station. The hydrogen production system is the core module of the integrated station, which can produce hydrogen and absorb the fluctuating "low quality" power in the grid. The hydrogen storage station uses a high-pressure hydrogen storage method and has the function of transferring and storing hydrogen energy. The fuel cell power generation system is the energy conversion system and power source in the integrated station. The hydrogen stored in the station is supplied to the power grid through the fuel cell power generation system to support the task of frequency regulation and peaking of the power grid and improve the reliability and efficiency of the power grid operation. The compression system realizes the conversion of hydrogen at different pressure levels. The compressed hydrogen can be stored in the high-pressure hydrogen storage system or supplied directly to the filling station. The filling station is a window for users to realize the secondary conversion of air pressure.
In the integrated station, the energy conversion system can flexibly control the operating conditions, and with the control of the main control system, the multifunctional and multi-objective optimized operation of the integrated station can be realized. The integrated station has the functions of cutting peaks and filling valleys, consuming renewable energy and supplying hydrogen to fuel cell vehicles.

3. The optimized operation model of the integrated station

3.1. Objective function

The operation of the fuel cell vehicle charging-discharging-storage integrated station involves two-way interaction with both the power grid and the gas grid, including competitive bidding for electricity, participation in the renewable energy market, and participation in the FM auxiliary services market. Meanwhile, the station is also required to provide hydrogen refueling services to fuel cell vehicles.

The total operating cost of the integrated station \( C \) is an objective function of the minimum total operating cost, which is calculated in Equation (1):

\[
\min C = \min \left( C_p + C_T \right)
\]  

where \( C_p \) denotes the cost of the integration station's participation in external electricity and hydrogen energy transactions, including transactions with the grid \( C_{\text{ele}} \) and the revenue received from the sale of hydrogen to fuel cell vehicle owners \( C_{\text{H}_t} \); \( C_T \) is the sum of the internal equipment operating costs of the integrated station, including water electrolysis tank \( C_{\text{EL}} \), fuel cell \( C_{\text{FC}} \), compressor \( C_{\text{Comp}} \), and hydrogen storage station \( C_{\text{Sto}} \). The cost expressions are shown in Equation (2).

\[
\begin{align*}
C_p &= C_{\text{ele}} + C_{\text{H}_t} \\
C_T &= C_{\text{EL}} + C_{\text{FC}} + C_{\text{Comp}} + C_{\text{Sto}}
\end{align*}
\]  

3.2. Constraints

3.2.1. Constraints on hydrogen power exchange. The Hydrogen production power \( E_{\text{EL}}^t \) is calculated in Equation (3):

\[
\begin{align*}
E_{\text{EL}}^t &= E_{\text{FC}}^t + E_{\text{HT}}^t + L_{\text{H}_t}^t, \quad 0 \leq E_{\text{EL}}^t \leq E_{\text{EL,max}}^t \\
0 \leq E_{\text{FC}}^t &\leq E_{\text{FC.max}}^t, \quad 0 \leq L_{\text{H}_t}^t &\leq L_{\text{H}_t,max}^t
\end{align*}
\]  

where \( E_{\text{HT}}^t \) is the transfer power of the hydrogen storage system, \( E_{\text{FC}}^t \) is the hydrogen consumption power of the fuel cell, and \( L_{\text{H}_t}^t \) is the hydrogen refueling power demand of the fuel cell vehicle load at time \( t \). \( E_{\text{EL.max}}^t \), \( E_{\text{FC.max}}^t \), \( L_{\text{H}_t,max}^t \) are the upper limits of the hydrogen production power of the electrolysis cell, the hydrogen consumption power of the fuel cell, and the hydrogen refueling power demand of the fuel cell vehicle load.

3.2.2. Constraints on hydrogen storage system. The hydrogen energy capacity \( \text{Vol}_{\text{HIT}}^t \) at time \( t \) is related to the hydrogen energy capacity \( \text{Vol}_{\text{HIT-1}}^t \) at time \( t-1 \) in the hydrogen storage system, which is calculated in Equation (4):

\[
\begin{align*}
\text{Vol}_{\text{HIT}}^t &= \text{Vol}_{\text{HIT}}^t + E_{\text{ET,in}}^t - E_{\text{ET,out}}^t \\
\text{Vol}_{\text{HIT, min}} &\leq \text{Vol}_{\text{HIT}}^t \leq \text{Vol}_{\text{HIT, max}} \\
0 &\leq E_{\text{ET}}^t \leq E_{\text{ET,max}}^t, \mu_{\text{ET,in}} = 1 \\
- E_{\text{ET,max}}^t &\leq E_{\text{ET}}^t \leq 0, \mu_{\text{ET,out}} = 1
\end{align*}
\]  

where \( \text{Vol}_{\text{HIT, max}} \) and \( \text{Vol}_{\text{HIT, min}} \) are the upper and lower limits of the hydrogen storage capacity of the hydrogen storage system, respectively; \( E_{\text{ET,max}}^t \) and \( E_{\text{ET,out,max}}^t \) are the maximum values of the input
power and output power of the hydrogen storage system, respectively; \( \mu_{\text{in}}^{H_2} \) and \( \mu_{\text{out}}^{H_2} \) are the auxiliary variables, \( \mu_{\text{in}}^{H_2} = 1 \) indicates that the hydrogen storage system is in hydrogen generation state, \( \mu_{\text{out}}^{H_2} = 1 \) indicates that the hydrogen storage system is in hydrogen release state.

3.2.3. Constraints on electric power exchange. At time \( t \), the relationship between the transmission power \( P_{\text{Grid}}^{t} \) of the grid, the power consumption \( P_{\text{EL}}^{t} \) of the electrolysis cell, the output power \( P_{\text{FC}}^{t} \) of the fuel cell, and the operating power \( P_{\text{Comp}}^{t} \) of the compressor is determined by Equation (5):

\[
\begin{align*}
0 & \leq P_{\text{Grid}}^{t} \leq P_{\text{Grid,max}}^{t}, \mu_{\text{Grid,boy}}^{t} = 1 \\
- P_{\text{Grid,max}}^{t} & \leq P_{\text{Grid}}^{t} \leq 0, \mu_{\text{Grid,sell}}^{t} = 1 \\
0 & \leq P_{\text{FC}}^{t} \leq P_{\text{FC,max}}^{t}, 0 \leq P_{\text{Comp}}^{t} \leq P_{\text{Comp,max}}^{t}
\end{align*}
\]

where \( P_{\text{Grid,max}}^{t}, P_{\text{FC,max}}^{t}, P_{\text{EL,max}}^{t}, P_{\text{Comp,max}}^{t} \) are the upper limits of power transmission between the grid and the integrated station, output power of the fuel cell, power consumption of the electrolysis cell and operating power of the compressor.

3.2.4. Constraints on energy transfer. The hydrogen production power \( E_{\text{EL,H}_2}^{t} \) of the electrolysis cell is calculated in Equation (6):

\[
E_{\text{EL,H}_2}^{t} = \eta_{\text{EL}} P_{\text{EL,ele}}^{t}
\]

where \( \eta_{\text{EL}} \) is the hydrogen cell efficiency and is a fixed value; \( P_{\text{EL,ele}}^{t} \) is the electrical power input to the hydrogen cell.

According to the literature [8], the simplified output power \( P_{\text{FC,ele}}^{t} \) of a hydrogen fuel cell is calculated in Equation (7):

\[
P_{\text{FC,ele}}^{t} = \eta_{\text{FC}} E_{\text{FC,H}_2}^{t}
\]

where \( E_{\text{FC,H}_2}^{t} \) is the amount of hydrogen input by the hydrogen fuel cell, \( \eta_{\text{FC}} \) is the electrical efficiency of the hydrogen fuel cell.

The compressor energy consumption is related to the amount of hydrogen input to the hydrogen storage tank, so that the compressor energy consumption \( P_{\text{Comp}}^{t} \) is calculated in Equation (8):

\[
P_{\text{Comp}}^{t} = \eta_{\text{Comp}} E_{\text{Comp,i}}^{t}
\]

where \( \eta_{\text{Comp}} \) is the conversion efficiency of compressor \( i \) for different variable pressure levels; \( E_{\text{Comp,i}}^{t} \) is the amount of hydrogen injected into the compressor in time period \( t \), which can be divided into different options depending on the source and destination of the hydrogen transfer.

4. Simulation and analysis

4.1. Basic data of the integrated station

Taking the actual operation data of a certain distribution network as an example, the data comes from literature [4]. The key equipment configuration is shown in Table 1. The time-of-day tariff for the region and the daily demand curve for fuel cell vehicles is shown in Figure 2, and the forecast renewable energy generation is shown in Figure 3. Besides, the price of hydrogen energy is ¥37/kg, the price of new energy is ¥0.29, and the price of the FM service market is ¥4/kWh. The time horizon of the optimization is 24 hours in one day. The operation optimization model of the integrated station is modeled in the Matlab environment by applying the Yalmip toolbox and calling the CPLEX optimization tool to solve the problem.
Table 1. Related parameters of the calculation example device.

| Type            | Parameter Name                  | Parameter    | Type            | Parameter Name                  | Parameter    |
|-----------------|---------------------------------|--------------|-----------------|---------------------------------|--------------|
| Electrolysis    | efficiency                      | 0.85         | Compressor      | efficiency                      | 0.95         |
| cell            | hydrogen produced/kWh           | 0.25Nm³      | or hydrogen     | capacity                        | 1000kg       |
|                 | capacity                        | 5MW          | storage mass    | efficiency                      | 0.95         |
|                 | operating cost                  | ¥18/MW       | daily filling   | efficiency                      | 0.95         |
|                 | efficiency                      | 0.65         | limit           | capacity                        | 750kg        |
| Fuel cell       | hydrogen required/kWh           | 0.28Nm³      | filling pressure| operating cost                  | ¥28.5/t      |
|                 | capacity                        | 5MW          | pressure        | efficiency                      | 0.85         |
|                 | operating cost                  | ¥20/MW       | operating cost  | efficiency                      | 0.85         |
|                 |                                 |              |                 |                                 |              |

Figure 2. Time-of-day tariff and hydrogen fuel cell vehicle demand forecast curve.

Figure 3. Forecast of wind power and photovoltaics.

4.2. The operation model of the integrated station

According to the different operating states of the electricity price, hydrogen load, and hydrogen storage station, the integrated station will adopt different operating modes to ensure the optimal operating cost of the integrated station. The operating mode are divided into the following four modes:

(1) Power purchase and hydrogen storage mode

When the price of electricity is at a trough or when there is not enough hydrogen remaining in the hydrogen storage station, the integrated station needs to purchase electricity from the grid for hydrogen production. It takes into account the load profile of the fuel cell vehicles and the remaining capacity of the hydrogen storage station. Except for the current hydrogen load demand, the remaining hydrogen will be stored in the hydrogen storage station.

(2) Energy storage support mode

When the electricity price is at a peak or when there is a demand for frequency and peak regulation in the power grid, it is necessary to comprehensively consider the current hydrogen storage station capacity and speed regulation constraints. The power generation of the fuel cell in the station is controlled to achieve the frequency modulation of the bidding. At the same time, the remaining hydrogen in the hydrogen storage station of the integrated station should be available for the current and future hydrogen refueling of the fuel cell load.

(3) Dual supply mode

When the hydrogen load is in high demand and the hydrogen transmission rate of the energy storage station is insufficient, it is necessary to comprehensively consider the cost of hydrogen sales and the cost of electricity purchase. The proportion of the output of hydrogen production station and hydrogen storage station is configured so that both are in the state of hydrogen supply at the same time.

(4) Clean mode

When the hydrogen load and the grid load are at the same time in the waist load, the conventional power purchase cost is high. The integrated station only produces hydrogen by consuming the excess
renewable energy in the grid, so as to realize the energy saving operation and renewable energy consumption of the energy storage in the integrated station.

According to the real-time changes of grid electricity price, new energy generation capacity and hydrogen load demand, the optimization results of power trading between the integrated station and the grid are shown in Figure 4; the simulation results of power-to-hydrogen conversion and hydrogen storage device output optimization in the integrated station are shown in Figure 5.

From Figure 4 and Figure 5 we can get:

1) In 23:00-5:00 when the power grid is in the valley, the hydrogen load demand is small, and the integrated station operates in the power purchase and storage mode. Through the coordinated operation of the electrolysis cell, hydrogen storage station and compressor, it achieves efficient hydrogen storage while meeting the hydrogen load demand, and at 6:00, the hydrogen storage station reaches its peak.

2) In the 6:00-8:00 time period, electricity prices are at waist-high prices and the demand for hydrogen load is gradually increasing. Due to the presence of renewable energy generation in the grid, the integrated station operates in clean mode. At this time, the operation of the energy storage station is characterized by low-speed hydrogen energy output to save operating costs.

3) In the 12:00-16:00 time period, because the integration station needs to ensure the hydrogen load supply at the moment of peak tariff, it needs to purchase a certain amount of power to supplement the electricity at the usual tariff, so the integration station is in double supply mode at the same time.

4) In the 9:00-11:00, 18:00-22:00 time period the grid is at peak tariff, meanwhile the integration station provides peak service to the grid to gain income. At this time, the integration station is running in energy storage support mode, hydrogen storage station is in the state of high intensity discharge.

4.3 Results of the optimized operation

| Table 2. Daily operating cost of the integrated station. |
|--------------------------------------------------------|
| **Type of cost**                                       | **Type of sub-cost**                       | **Cost/¥**   |
| Energy transaction cost                                 | spot power trading                         | -17232.27    |
|                                                       | purchase of electricity from new energy sources | -4790.8     |
|                                                       | proceeds from sale of hydrogen             | 27591.43     |
|                                                       | proceeds from sale of electricity          | 22600        |
|                                                       | electrolysis cell                          | -847.56      |
|                                                       | fuel cell                                  | -226         |
| Equipment operating cost                                | compressor                                 | -1200        |
|                                                       | hydrogen storage equipment                 | -463.78      |
| Total proceeds of integrated station/¥                  |                                           | 25431.02     |
Using the integrated station operating state solution set in Section 4.2, combined with the objective function and constraints of the optimization model, the overall operating cost of the integrated station is shown in Table 2, and the abandoned wind and light ratio pair is shown in Table 3.

From Table 2, it can be seen that the daily operating cost of the integrated station is mainly concentrated in the power purchase consumption, and the new energy purchase cost is lower than the spot market purchase cost. Through the optimization algorithm in this paper, multiple operating modes of the integrated station can be obtained under different market conditions, thus achieving the optimal power purchase cost and equipment operating cost. Although there is a certain amount of energy loss in the process of energy conversion and storage, the higher cost of hydrogen energy and its storability enable the integrated station to achieve the goal of profitability and peak load reduction.

From Table 3, we can see that the wind power consumption of the integrated station reaches 12.27MW in a single day. Combined with the optimization results in Figure 4 and Figure 5, it can be seen that the integrated station uses excess wind power at night and unused photovoltaic power generation during the day to produce hydrogen, thereby reducing wind and light abandonment. From the changes in the utilization rate of new energy generation in the region before and after the configuration of the integrated station, the configuration of the integrated station can significantly improve the region's new energy consumption capacity. Therefore, the integrated station proposed in this paper can effectively reduce the phenomenon of regional wind and light abandonment on the basis of meeting the hydrogen demand of fuel cell vehicles.

| Type                                | Wind power | Photovoltaic | New energy |
|-------------------------------------|------------|--------------|------------|
| Daily consumption of electricity in integrated station/MW | 12.27      | 4.25         | 0.33       |
| Utilization of new energy without integrated stations | 45.5%      | 54.7%        | 48.0%      |
| Utilization of new energy with integrated stations | 82.8%      | 89.5%        | 84.6%      |

5. Conclusions
This paper discusses the optimized operation of the fuel cell vehicle charging-discharging-storage integrated station, and the following conclusions are obtained:

(1) The integrated station for fuel cell vehicles has the role of energy storage, which promotes the improvement of grid regulation capacity. At the same time, the station can improve the utilization rate of renewable energy and effectively reduce the phenomenon of regional wind and light abandonment.

(2) The main operating cost of an integrated station for hydrogen production through water electrolysis is concentrated in the purchase of electricity. The higher the proportion of renewable energy generation in the grid, the lower the operating cost of the integrated station. Therefore, it can be assumed that the integration station has a mutually beneficial effect on the high proportion of new energy sources connected to the grid.

(3) Due to the strong correlation between the prices of various energy sources and the operating costs of the integrated station, the increase in the price of a single energy source will lead to a sharp increase in the operating costs of the integrated station, which will help to encourage the integrated station to participate in the energy trading market, such as the natural gas market and heat energy supply, and will help to promote the anti-risk ability of the integrated station and the reduction of the total operating costs.

References
[1] L Carrette, K A Friedrich and U Stimming 2001 Fuel cells – fundamentals and applications Fuel Cells 1(1) 5-39
[2] M Qadrdan, M Abeyesekera, M Chaudry, J Z Wu and N Jenkins 2015 Role of power-to-gas in an integrated gas and electricity system in Great Britain International Journal of Hydrogen
Energy 40(17) 5763-5775

[3] S Clegg and P Mancarella 2016 Integrated electrical and gas network flexibility assessment in low-carbon multi-energy systems IEEE Transactions on Sustainable Energy 7(2) 718-731

[4] Teng Yun, Wang Zedi, Jin Hongyang, etc. 2019 A Model and Coordinated Optimization for the Multi-energy Storage System of Electricity Heat Hydrogen to Regulation Enhancement of Power Grid Proc Chin Soc Elect Eng, 39(24) 7209-7217 (in Chinese)

[5] A. Rezazadeh, M. Sedighizadeh, M. Karimi 2010 Proton Exchange Membrane Fuel Cell control using a Predictive control based on Neural Network International Journal of Computer and Electrical Engineering 2(1) 81-85

[6] Saikumar Bairabathina and Balamurugan S 2020 Review on non-isolated multi-input step-up converters for grid-independent hybrid electric vehicles International journal of hydrogen energy 45(41) 21687-21713

[7] National Development and Reform Commission, Ministry of Industry and Information Technology, National Energy Administration. Made in China 2025-Energy Equipment Implementation Plan [EB/OL]. (2016-06-20). http://www.gov.cn/xinwen/2016-06/20/content_5083796.htm. (in Chinese)

[8] Jin Hongyang, Teng Yun, Leng Ouyang, etc. 2020 Coordinated multi-energy energy storage model for waste-free cities based on source charge uncertainty state sensing J Transactions of China Electrotechnical Society, 35(13) 2830-2842 (in Chinese)