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LETTER TO THE EDITOR

An Optimal Control Strategy for Offshore Community with Considering Demand Response

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With the increase of installed renewable capacity in offshore areas, the uncertainty and randomness of wind speed and solar radiation have a significant impact on the power system. Therefore, it is necessary to study the offshore multi-energy system. A traditional offshore community with hybrid energy storage system (HESS) installation usually participates in demand response program to improve system economy. However, due to the high price and low discharge power of the HESS, it cannot response to the loads effectively. This paper introduces water electrolysis and on-board hydrogen storage technologies to an offshore community, so as to effectively optimize the operation of system. Subsequently, to analyze the impact of climate change on system operation, the concept of loads matching degree is firstly defined. Results show that compared with the traditional offshore multi-energy system, the improved system can significantly reduce system operation costs and carbon emissions by 23.02% and 48.43%, respectively.

water electrolysis technology; demand response;

1. Introduction

With the over-exploitation of fossil energy, environmental pollution is becoming more and more serious. Building a clean, economic and efficient energy system has become an important issue all over the world (Gu et al., 2014; Song et al., 2015). Reasonable development and utilization of clean energy such as wind, sunlight and hydrogen are effective measures to alleviate energy and environmental problems. However, due to the uncertainty of wind speed and solar radiation, the output power of renewable energy power generation system has strong fluctuation, which eventually leads to wind and sunlight abandonment (Li et al., 2019). Considering the remarkable advantages of hydrogen, such as high calorific value, convenient storage and fast response, how to apply water electrolysis technology to the demand response in offshore multi-energy system efficiently and economically has become a research hotspot.

In the study of operation optimization of multi-energy system, how to improve the consumption rate of wind and solar power has become a major difficulty. In order to suppress the output fluctuation of wind and solar power, Ekren and Ekren (2008), optimized the capacity of the battery by response surface methodology (RSM). However, due to the short life and large environmental pollution, the battery is difficult to apply on a large scale. The three-branch RC model of the supercapacitor was used in the photovoltaic energy storage system (Fathallah et al., 2018). However, the purchase cost of the supercapacitor is high and the storage capacity is small, and it is impossible to completely consume the wind and photovoltaic power. He et al. (2017) proposed a robust day-ahead scheduling model to optimize the coordinated operation of integrated energy systems, which used P2G (Power to Gas) technology to consume renewable energy. But it only considered the use of converting electricity into natural gas. Obviously, this is not very helpful in reducing carbon emissions. Andrijanovit, A et al. introduced the water electrolysis technology to the system and used hydrogen buffer as a new energy storage technology to improve the instability of wind power generation (Andrijanovit et al., 2010). However, the application scenario is too single, which is not conducive to improving the system economy. In view of the shortcomings in the above research, this paper introduces the water electrolysis technology, which converting surplus electricity to hydrogen and stores it in on-board hydrogen storage devices to participate in the demand response. The hydrogen can be used as fuel for hydrogen fuel vehicles and hydrogen generators. In addition, the stored hydrogen can react with carbon dioxide to produce methane for other units in the system during peak load period, and reduce the operation cost of the system.

1.1 The Structure of Multi-energy System

The offshore multi-energy system could connect its input and output by coupling different energy carriers to realize the transmission, conversion and storage of various energy sources. Compared with the traditional power system, the improved offshore multi-energy system increases the ways of energy supply, and improves the economy, flexibility and security of the energy system. Figure 1 shows the diagram of an offshore multi-energy system with water electrolysis technology.

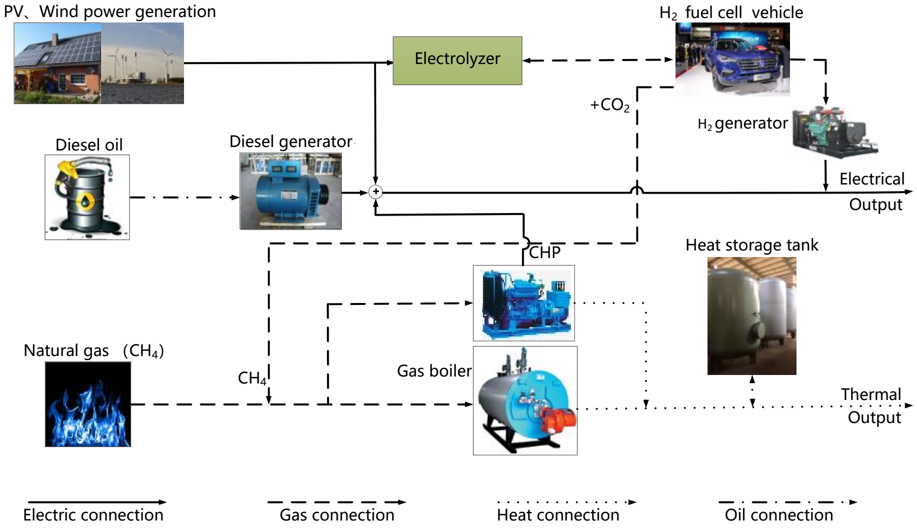

Figure 1. System structure diagram of an improved offshore multi-energy system with water electrolysis technology

1.2. Output Power Modeling of Each Unit

As shown in Figure 1, the offshore multi-energy system with hydrogen energy includes: wind and photovoltaic generators, diesel generators, CHP, electrolyzers, gas boilers, hydrogen generators, water tanks, hydrogen fuel cell vehicles and other energy conversion devices. This section will introduce the output model of each component.

1.2.1. Wind Power Generation System Output Power Modeling

Wind power is widely used in offshore multi-energy systems due to its no pollution and renewability characteristics. In this paper, the off-grid wind turbine is used to supply electric loads. Its output power PW is determined by its rated power, cut-in wind speed, cut-out wind speed and rated wind speed. Therefore, the output power of wind turbines PW (t) can be expressed as follows:

$$P_W(t)=\begin{cases}0 & 0\le v(t)<v_{in}\ \text{ or }\ v(t)>v_{out}\\ \dfrac{v(t)^3-v_{in}{}^3}{v_r{}^3\text{-}v_{in}{}^3}\cdot P_{Wr} & v_{in}\le v(t)<v_r\\ P_{Wr} & v_r\le v(t)\le v_{out}\end{cases} \tag{1}$$

1.2.2. Photovoltaic Generation System Output Power Modeling

Photovoltaic generation has the advantages of high reliability, no noise and no pollution, it is not limited by the geographical distribution of resources and its construction cycle is short. This paper adds photovoltaic generation to supply electric loads. The output power of photovoltaic generation system is closely related to the solar radiation (Datta et al. 2010), and it can be expressed as follows:

$$P_{PV}(t)=P_{PVr}\cdot\eta_{PV}\cdot\frac{\mu(t)}{\mu_{ref}} \tag{2}$$

1.2.3. Diesel Generator Output Power Modeling

Diesel generator is a kind of small power generation equipment, which uses diesel as fuel to generate electricity. It has the advantages of easy operation and fast generation, which makes it widely used in multi-energy system. In this paper, diesel generator is used as a supplement to power generation system to improve the reliability of power supply. The output of diesel generator can be expressed as:

$$P_{DG}(t)=\eta_{DG}P_{DGin}(t) \tag{3}$$

1.2.4. CHP Output Power Modeling

CHP is composed of gas turbine and waste heat boiler. It generates electricity by burning natural gas to drive gas turbine. Moreover, CHP can recover high temperature flue gas through waste heat boiler and convert it into thermal energy to supply heat loads. The application of CHP can not only improve the energy efficiency, but also reduce environmental pollution. Formula (4) is the output model of CHP:

$$\begin{cases} P_{ECHP}(t) = \eta_E P_{in}(t) \\ P_{HCHP}(t) = \eta_H P_{in}(t) \end{cases} \tag{4}$$

1.2.5. Electrolyzer Output Power Modeling

The electrolyzer is a device that decomposes water into hydrogen and oxygen by electrolysis technology. According to Faraday's law, the volume of hydrogen produced by the electrolyzer is closely related to the input power and voltage of electrolyzer. Therefore, it can be expressed as follows:

$$V_{H_2}(t) = \eta_{EL} \cdot \frac{N_{EL} \cdot P_{EL}(t)}{m \cdot F \cdot U_{EL}(t)} \tag{5}$$

$$\eta_{EL} = a_1 EXP[\frac{a_2 + a_3 \cdot T_{EL} + a_4 \cdot T_{EL}{}^2}{i_{EL} / \mathrm{S}} + \frac{a_5 + a_6 \cdot T_{EL} + a_7 \cdot T_{EL}{}^2}{(i_{EL} / \mathrm{S})^2}] \tag{6}$$

In addition to direct use, hydrogen produced by electrolyzer can also react with CO2 in the air to produce methane. Methane can be transported to natural gas pipelines for use in CHP and gas boilers. The reaction process can be expressed as follows:

$$4H_2 + CO_2 = CH_4 + 2H_2O \tag{7}$$

1.2.6. Gas Boiler Output Power Modeling

Gas boilers produce steam and hot water by burning natural gas. They are widely used in multi-energy systems due to their low cost, high thermal efficiency and reliability characteristics. In offshore multi-energy systems, gas boilers are used as auxiliary heat generating equipment to supply heat loads. Thermal energy generated by gas boilers at time t Qth(t) can be expressed as:

$$Q_{th}(t) = 0.00278 \cdot G_{water}(t) \cdot (\mathrm{h}_{bo} - \mathrm{h}_{bi}) = V_{NG}(t) \cdot Q_S \cdot \eta_b \tag{8}$$

1.2.7. Hydrogen Generator Output Power Modeling

Hydrogen generator has obvious advantages such as easy maintenance, high reliability and low environmental pollution. The multi-energy system usually use hydrogen generators to consume parts of hydrogen generated by water electrolysis technology and response to electric loads rapidly. The mathematical expression of hydrogen generator output power is as follows:

$$P_{HG}(t) = \eta_{HG} V_{HGin}(t) \rho_{H_2} \theta_{H_2} \tag{9}$$

1.2.8. Hot Water Tank Modeling

In order to smooth the heat load curve and improve the thermal efficiency of the system, the offshore multi-energy system usually configures a hot water tank to store the waste heat generated by gas turbine and

CHP, and releases heat during the peak period of heat demand to alleviate the heat supply pressure. The total thermal energy HWT (t) stored in the hot water tank can be expressed as:

$$H_{WT}\left(t\right)=\left(1-\alpha\right)H_{WT}\left(t-1\right)+\left[H_{WT,s}\left(t\right)\varepsilon_{WT,s}-\frac{H_{WT,r}\left(t\right)}{\varepsilon_{WT,r}}\right]\Delta t \tag{10}$$

1.2.9. Hydrogen Fuel Cell Vehicles Modeling

Hydrogen fuel cell vehicles use hydrogen generated by water electrolysis technology as fuel to consume excess electricity generated by wind power and photovoltaic system. The total daily hydrogen consumption of hydrogen fuel cell vehicles in offshore multi-energy systems is related to the total vehicles amount, driving range and vehicle efficiency. Therefore, the total daily hydrogen volume consumed by hydrogen fuel cell vehicles V H2FE can be expressed as follows:

$$V_{H_2FE}=\frac{N\cdot L_{\mathrm{H}_2FE}\cdot Q_{\mathrm{H}_2U}}{\theta_{H_2}\cdot\eta_{H_2}} \tag{11}$$

At the same time, hydrogen fuel cell vehicles are equipped with hydrogen storage devices. Therefore, hydrogen fuel cell vehicles can not only consume hydrogen, but also store hydrogen to participate in demand response. The hydrogen storage model can be expressed as follows:

$$V_{H_2}(t)=V_{H_2}(0)+\sum_{t=1}^{n}(\mathrm{V}_{H_2st}(t)-V_{H_2re}(t)) \tag{12}$$

Compared with fuel vehicles, hydrogen fuel cell vehicles do not produce CO2 during driving, and the reduced carbon cost CΔ is:

$$C_{\Delta}=N\cdot L_{\mathrm{H}_2FE}\cdot A_{CO_2}\cdot(\alpha_{CO_2}+\gamma_{CO_2}) \tag{13}$$

1.3. Objective Function

In order to realize the economic and environmental operation of the offshore multi-energy system, it is usually necessary to consider its operation cost and carbon emissions. On the basis of ensuring the stable operation of the system, this paper optimizes the method of power supply to reduce the system operation cost F. It is worth noting that compared with the traditional offshore multi-energy system, the improved offshore multi-energy system uses hydrogen instead of traditional fossil energy to provide power to cars, thereby reducing carbon dioxide emissions and carbon emissions costs.

$$\min F=Q_{NG}\cdot C_{NG}+Q_{D}\cdot C_{D}+W_{W}\cdot C_{W}+W_{PV}\cdot C_{PV}+Q_{CO_2}\cdot C_{CO_2}-C_{\Delta} \tag{14}$$

$$Q_{CO_2}=Q_{NG}\cdot\lambda_{NG}+Q_{D}\cdot\lambda_{D} \tag{15}$$

In the formula, QNG, QD and QCO2 are respectively the amount of natural gas and diesel oil purchased by the system and total carbon emissions; WW and WPV are the total electricity generated by wind power and PV respectively. CNG, CD and CCO2 are natural gas, diesel and carbon emission prices respectively; CW and CPV are the cost per kilowatt hour of the electricity generated by wind power and PV. λNG and λD are the carbon emission coefficient of natural gas and diesel, which are 0.4483 and 0.5921 respectively.

2. Optimization Algorithm

Genetic Algorithms (GA) is a global optimization algorithm, which is based on the viewpoint of biogenetics. The genetic algorithm continuously improves the individual's adaptability and obtains the optimal solution through the mechanisms of natural selection, inheritance, crossover and mutation. However, the crossover probability and mutation probability of traditional genetic algorithm is fixed. Therefore, when dealing with complex optimization problems, it has the disadvantages of long calculation time, slow convergence rate and easy to fall into local optimum. Adaptive genetic algorithm (AGA) is an improvement of traditional genetic algorithm. It adaptively adjusts the crossover probability and mutation probability, which greatly improves the convergence precision of genetic algorithm and accelerates the convergence speed. Figure 2 is a flow chart for optimizing the operation cost of the offshore multi-energy system based on adaptive genetic algorithm.

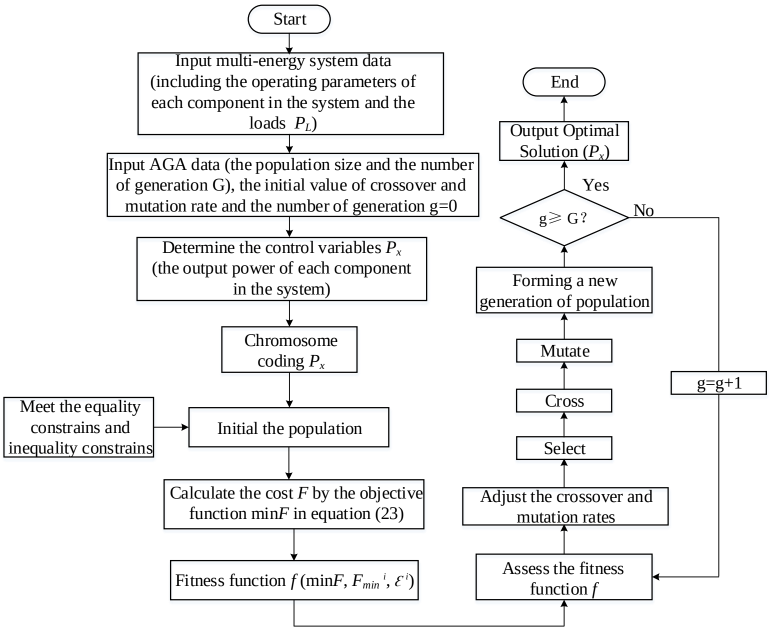

Figure 2. Adaptive genetic algorithm optimization flow chart

3. Case Study

In this paper, a typical offshore multi-energy system is taken as a case to simulate and verify the proposed optimal operation strategy. The energy supply, conversion and storage equipment included in the offshore multi-energy system is shown in Figure 2. In this system, the rated power of wind turbine and photovoltaic generator is 1 MW and 2 MW; the rated power and energy conversion efficiency of diesel engine is 1.2 MW and 40%; the rated power, electric conversion efficiency and heat-electricity ratio of CHP is 0.9 MW, 33% and 1:1.5, respectively. The CHP is used as the main heat supply equipment in the system because of its high overall efficiency. The rated power of electrolyzer is 1.7 MW, and the electrolysis efficiency is about 45% under standard conditions. The rated power of gas boiler is 1.6 MW, and the energy conversion efficiency is 88%. Considering the low installation cost of the water storage tank, this paper assumes that the water storage tank can fully collect waste heat to improve the comprehensive energy efficiency. In addition, hydrogen can be stored on a large scale by liquefaction or high-pressure compression. Therefore, all hydrogen produced by electrolyzer can be stored in vehicle hydrogen storage device, and participate in the demand response efficiently.

The daily load data and meteorological data are recorded in the data center by monitoring the load and climate conditions in the offshore multi-energy system. The annual average daily load of the system and the distribution of wind speed and solar radiation data are shown in Figures 3 and 4. Because the fluctuation of energy prices such as diesel and natural gas is small, this study adopts constant prices of diesel and natural gas, which are 0.97 \$/L and 0.43 \$/m^3 respectively. In addition, in this study, the carbon emission coefficients of diesel and natural gas are 0.5921 and 0.4483, respectively. In order to simplify the calculation, the cost per kilowatt hour of the electricity generated by renewable energy (including installation cost, maintenance cost, etc.) is used to calculate the renewable energy generation cost. The costs per kilowatt hour of the electricity generated by wind power and photovoltaic generation are 10 US cents/kWh and 6 US cents/kWh, respectively.

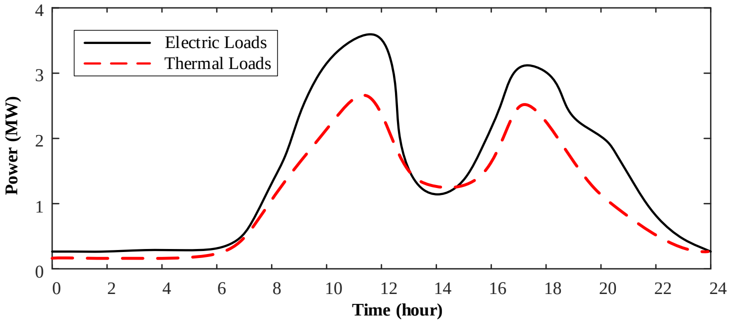

Figure 3. Annual average daily load curves

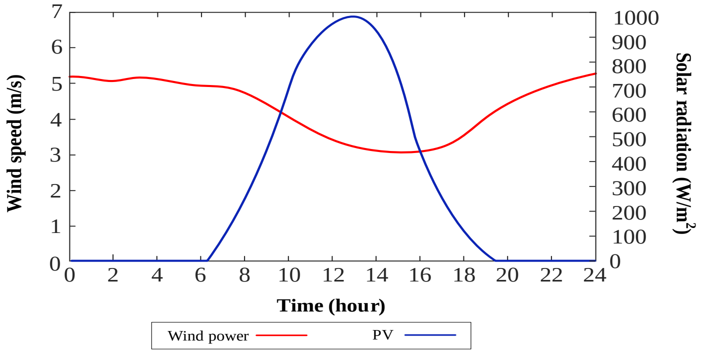

Figure 4. Annual average daily wind speed and solar radiation intensity data distribution

4. Results and Analysis

In order to compare the ability of the traditional offshore multi-energy system (battery/supercapacitor) and the improved offshore multi-energy system (including water electrolysis technology) to participate in demand response, Figure 5 shows the real-time energy interaction curves of energy storage system in the traditional offshore multi-energy system and the improved offshore multi-energy system (battery/supercapacitor and vehicle hydrogen storage device).

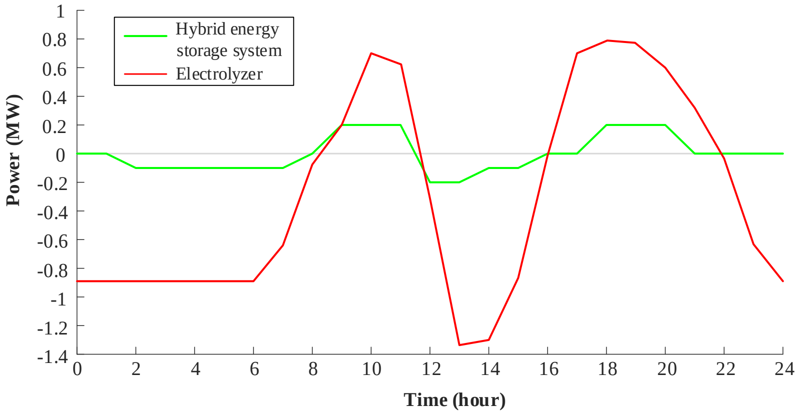

Figure 5. Real-time energy interaction curves of energy storage system in the traditional offshore multi-energy system and the improved offshore multi-energy system

As can be seen from Figure 5, compared with the traditional energy storage system, the hydrogen storage system can store more energy, and it is more capable to participate in the demand response during peak hours. According to the data calculation, since the traditional electric energy storage system is limited by the charging and discharging power and capacity, it can only store 1.2 MWh of electricity in one day. However, the electrolyzer can completely convert excess energy 12.33 MWh into hydrogen and store it in the vehicle hydrogen storage system. This shows that the capacity of the improved offshore multi-energy system with on-board hydrogen storage device to participate in demand response is significantly better than that of the traditional offshore multi-energy system. In addition, the maximum output power of on-board hydrogen storage device is 0.81 MW when it participates in demand response, much larger than the maximum output power of the traditional energy storage system of 0.61 MW. This shows that compared with the traditional storage system, the offshore multi-energy system with on-board hydrogen storage device has a larger output power, which greatly improves the system's ability to participate in demand response at peak time.

In order to compare the influence of the traditional offshore multi-energy system and the offshore multi-energy system with on-board hydrogen storage device on the operation of standby power source (diesel engine), the daily output curve of diesel engine in two cases is shown in Figure 6.

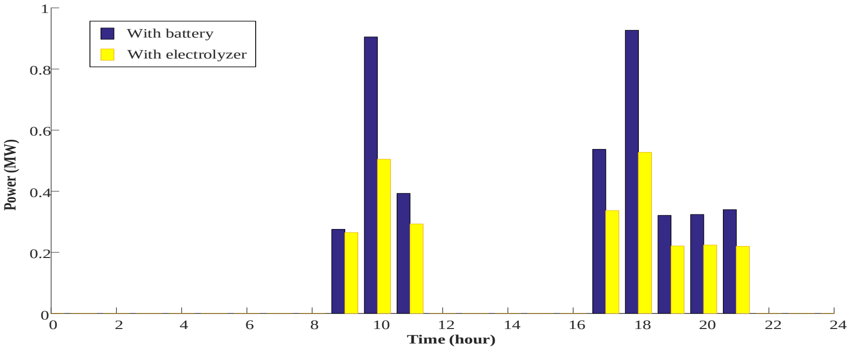

Figure 6. Daily output curve of diesel engine unit in the traditional offshore multi-energy system and the improved offshore multi-energy system

It can be seen from Figure 6 that for the traditional offshore multi-energy system, the output power of the diesel unit reaches a local maximum of 0.905 MW and 0.927 MW at 10:00 and 18:00 respectively. At this time, the peak-to-valley difference of the diesel engine output can reach 0.652 MW. For the offshore multi-energy system with on-board hydrogen storage, the diesel engine output reaches the local maximum of 0.514 MW and 0.533 MW at 10:00 and 18:00 respectively, which are 43.2% and 42.5% lower than the traditional offshore multi-energy system. For the improved offshore multi-energy system, the fundamental reason for the significant decrease in the maximum output of the diesel unit and the daily average energy cost of the system is that the battery energy storage system is limited by capacity and output power during the peak load period. The limitation of the storage system capacity makes the wind and sunlight abandoning, which eventually leads to the massive use of fossil energy and increases the carbon dioxide emissions. The output power of the storage system is limited, which makes the power generated by the standby power supply increase sharply during the peak load period, increases the peak-valley difference of the diesel engine output, and reduces the average utilization rate of the standby power supply capacity. Therefore, the offshore multi-energy system with on-board hydrogen storage improves the economy of the system, the average utilization rate of standby power supply, and reduces the carbon emissions of the offshore multi-energy system.

5. Conclusions

This paper firstly introduces the water electrolysis and on-board hydrogen storage technologies into a traditional offshore community to optimize the operation of multi-energy system. By comparing the demand response capability, it is proved that the improved system with on-board hydrogen storage devices is more economical and environmentally friendly. The results show that: by introducing the water electrolysis technology and the on-board hydrogen storage devices to participate in the demand response, the output power of on-board hydrogen storage devices can be rapidly increased at the peak demand time. Meanwhile, the installation of on-board hydrogen storage devices can reduce the installation capacity of the backup power source and make full use of backup generator. Results show that by installing hydrogen storage devices, the operation costs of system, carbon emissions and backup generator capacity are reduced by 23.02%, 48.43% and 42.5%.

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