Operation Mode of Integrated Energy System with Liquid Air Energy Storage

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Abstract. This paper takes the energy supply in the park as the research background, the integrated energy system as the research object and establishes the integrated energy system model including liquid air energy storage, distributed photovoltaic, gas turbines and other equipment. When the integrated energy system operates the mode of "ordering heat by power", the heat wasted as high as 14.647 MWh and the cold wasted as high as 24.13 MWh. When the system is not equipped with LAES, the output power of the CCHP unit increases by 21 MWh, the electricity purchase in power grid increases by 8.123 MWh, the heat waste increases by 21.696 MWh and the cold waste increases by 12.421 MWh. When the integrated energy system operates the mode of "ordering power by heat", heat energy of the system has been reasonably utilized. When the system is not equipped with LAES, the power output and heat of the CCHP unit in the system are the same, the thermal energy output results of the system are the same and the electricity purchased by the power grid increases by 32.14 MWh.

1. Introduction

At present, China is already the world’s largest and fastest growing country in renewable energy. By the end of 2019, the total installed capacity of renewable energy reached 79.4 GW, including 35.6 GW of hydropower, 21 GW of wind power and 20 GW of solar energy[1]. In order to effectively promote renewable energy consumptions and improve energy utilization efficiency, many scholars have proposed the main solutions to solve the imbalance between supply and demand of the power system as well as the consumption of renewable energy by combining renewable energy with the user-side integrated energy system.

Through the unified planning of integrated energy system, it can effectively make up for the shortcomings such as instability of renewable energy. In order to further solve the shortcomings of uncontrollable renewable energy generation, we add energy storage system to the integrated energy system. Among the many energy storage systems, compressed air energy storage system is developing rapidly. Compressed air energy storage uses abandoned wind and light to compress air in large storage tanks or natural caves for electrical energy storage, which can be combined with integrated energy system to solve some practical problems of renewable energy systems.

Yan[2] provided a parametric life-cycle assessment framework and studied an integrated energy system containing photovoltaic power and electrochemical energy storage. Yin[3] studied the economic benefits of applying advanced adiabatic compressed air energy storage in an integrated energy system and found that advanced adiabatic compressed air storage improves energy utilization efficiency and saves costs. Wang[4] studied an integrated energy micro-grid system with compressed
air energy storage and constructed an integrated energy micro-grid model with compressed air energy storage, gas turbine and cooling, heating and power trigeneration system. As an emerging energy storage method, liquid air energy storage (LAES) combines liquefaction technology, cold storage technology and original compressed air energy storage, which has the advantages of high energy storage density, low storage pressure, small floor space and can be moved etc. It perfectly solves the disadvantages of traditional compressed air energy storage site selection difficulties and is suitable for large cities, parks and other user sides.

This paper combines liquid air energy storage with user-side energy system, takes a park as an application scenario, establishes an integrated energy system model with LAES, distributed photovoltaic, gas turbine and other equipment, studies the load output characteristics of the park integrated energy system with LAES under two operation modes: "ordering power by heat" and "ordering heat by power", and analyses the output of three types of loads: cold, heat and electricity. The results are also compared with the load output results without LAES to analyse the improvement effect of LAES on the output characteristics of the park integrated energy system.

2. System Brief

The structure diagram of the park energy system is shown in Fig.1. The air-liquid energy storage system is added to the integrated energy system, which is divided into three parts: energy input, energy output, and energy conversion and storage. Among them, energy input includes external power grids, solar energy and natural gas; energy conversion and storage are the core of the system, including combined cooling heating and power (CCHP), electric refrigerator, electric boiler, and LAES system; Energy output includes electric load, heat load and cold load. The core device of the CCHP system is a gas turbine, which uses natural gas as a fuel energy source. In this system, the chemical energy of natural gas is first converted into electric energy in a gas turbine, and the remaining heat energy has a high utilization value, which can be converted into heat load and cold load by boiler and refrigerator.

![Figure 1. The structure diagram of integrated energy system](image)

3. Model

3.1 Liquid Air Energy Storage

Assume that the liquid air is an incompressible fluid, the cycle efficiency of the energy storage system $\eta$ is [5]

$$\eta = \frac{W_c}{W_c + W_p} \quad (1)$$

where, $W_c$ is the power consumption of compression process in the LAES, J/s; $W_e$ is the output work of the expansion process, J/s; and $W_p$ is the power consumption of cryogenic liquid pump, J/s.
3.2 CCHP

The CCHP system involves the conversion of three types of loads: cold, heat, and electricity. The equations of the three types of loads are listed separately[6]. The consumption of natural gas is

$$ M = \frac{PT}{\eta_g Q_L} $$

where, $M$ is the consumption of natural gas in the CCHP system, m$^3$; $P$ is the output electric power of the system, kW; $T$ is the working time of the CCHP system, h; $\eta_g$ is the power generation efficiency; and $Q_L$ is the calorific value of natural gas, kWh/ m$^3$.

The total heat load of the system is

$$ H_Z = \frac{P}{\eta_g} (1 - \eta_{t_e} - \eta_{r_h}) $$

where, $H_Z$ is the total heat load, kW; and $\eta_{r_h}$ is the self-dissipation rate of heat energy.

The cooling load of the system is

$$ U = \frac{H_Z \eta_{r_e}}{\eta_U + \eta_{r_h}} $$

where, $U$ is the cold load, kW; $\eta_{r_e}$ is the cooling efficiency of the refrigerator; and $\eta_{r_h}$ is the heating efficiency of the electric boiler.

The heat load of the system is

$$ H = H_Z - U $$

where, $H$ is the heat load of the system, kW.

3.3 Electric Refrigeration and Heating

The electric heating conversion power is

$$ H_t = \eta_t P_t $$

where, $H_t$ is the output heat power of electric heating, kW; $P_t$ is the power consumption of electric heating, kW; and $\eta_t$ is the conversion efficiency of electric heating.

The electric refrigeration conversion power is

$$ U_b = COP \times P_b $$

where, $U_b$ is the output cooling power of electric refrigeration, kW; $P_b$ is the power consumption of electric refrigeration, kW; and $COP$ is the coefficient of electric refrigeration.

4. Results and Discussion

The park consumed 40.1GWh of electricity and has a total annual heat load of 20.1GWh in 2019. In order to ensure that the research results are representative, the energy load of the two typical days of the great cold day in 2019 and the great heat day in 2019 are selected for analysis. With 24 hours a day as the dispatch cycle, the energy dispatch load ratio of each period is improved on the basis of Ref.[6], and the establishment of dispatch load is shown in Fig.2.
The operating parameters of the integrated energy system equipment are shown in Table 1. The photovoltaic power generation system uses the solar panels on the top of the park building to convert sunlight into electrical energy. The equipment parameters of CCHP system, electric refrigerator and electric boiler are referred to literature [6]. The rated power of the liquid air energy storage system is 6.5MW and the coefficient of refrigeration in electric refrigerator is 3.2 [6].

| Equipment           | Power/MW  | Efficiency/% | Self-dissipation efficiency, % | Natural gas calorific, kWh/m³ |
|---------------------|-----------|--------------|--------------------------------|-------------------------------|
|                      | Min   | Rated | Power generation | Energy storage | Refrigeration | Heating |                                      |                                |
| Photovoltaic         | 0     | 5     | -                | -              | -             | -       |                                      |                                |
| CCHP                 | 5     | 10    | 0.35             | -              | 0.2           | 0.4     | 0.05                                 | 10.08                          |
| Electric refrigerator| 0     | 1     | -                | -              | -             | -       |                                      |                                |
| Electric boiler      | 0.4   | 1     | -                | -              | -             | -       | 0.98                                 | -                              |
| Energy storage       | 0     | 6.5   | -                | 0.6            | -             | -       |                                      | -                              |

This paper designs two kinds of integrated energy system configuration cases for comparative analysis. Case 1 operates in the mode of "ordering heat by electricity", while Case 2 operates in the mode of "ordering electricity by heat". In order to study the effect of LAES on the integrated energy system, the LAES subsystem in Case 1 and Case 2 is removed and compared with the original system. Among them, "ordering electricity by heat" is based on the demand of heat load to determine the power output of the system; "ordering heat by electricity" is based on the demand of electricity load to determine the heat load demand output of the system.

4.1 Electricity Output

Analyse the Cases of energy configuration on the great cold day, the electricity output results of integrated energy system in Case 1 and Case 2 are shown in Fig.3. The output power of photovoltaic power generation is the same. In order to meet the demand of electrical load, the output power of the CCHP unit in Case 1, which operates in the mode of "ordering heat by power", is 23.289MWh more than that in Case 2. In Case 1, the energy storage device stores 48.536MWh of electricity during the valley period of electricity price (23:00-06:00) and releases 29.123MWh of electricity during the peak period of electricity price (08:00-10:00, 18:00-22:00). In Case 2, the energy storage device stores 53.560MWh of electricity during the valley period of electricity price, and releases 32.140MWh of electricity during the peak period of electricity price. The electricity purchase in power grid of Case 2 is 20.472MWh more than that of Case 1.
According to calculation, when Case 1 is not equipped with LAES, the output power of CCHP unit increases by 21.000 MWh, and the electricity purchase in power grid increases by 8.123 MWh. Case 2 adopts the mode of “ordering power by heat”, whether the system is equipped with LAES or not has no influence on the output power of CCHP unit. The electricity output of the CCHP unit in the system of Case 1 and Case 2 is 39.510 MWh. When Case 2 is not equipped with LAES, the electricity purchased in power grid increases by 32.140 MWh.

In the same way, the analysis results of the energy allocation Cases on the great heat day are shown in Fig.4. The energy allocation mode of each period in the system is the same as that of the severe cold period. The difference is that the output power of the CCHP unit in Case 1 is 25.935 MWh more than that in Case 2. The energy storage system in Case 1 stores 65.392 MWh of electricity and releases 39.239 MWh of electricity. The energy storage system in Case 2 stores 65.464 MWh of electricity and releases 25.965 MWh of electricity. The electricity purchase in power grid of Case 2 is 39.210 MWh more than that of Case 1. According to calculation, when Case 1 is not equipped with LAES, the output power of CCHP unit increases by 11.000 MWh, and the electricity purchase in power grid increases by 8.560 MWh. In Case 2, the power output of CCHP unit is 44.065 MWh. Case 2 is not equipped with LAES, the electricity purchased in power grid increases by 32.140 MWh.

4.2 Heat Output

Analyse the Cases of energy configuration on the great cold day, the heat output results of integrated energy system in Case 1 and Case 2 are shown in Fig.5. The systems in Case 1 is operating in the “ordering heat by power” mode. While ensuring the power supply, heat energy is supplied. But the heat energy released is higher than the actual demand, which causes a lot of waste of heat energy. The output heat of the electric boiler and the output cold of the electric refrigeration are negative, which represents the wasted heat and cold of the CCHP unit. In Case 1, the heat wasted as high as 14.647 MWh and the cold wasted as high as 24.130 MWh. The systems of Case 2 are based on the heat demand to determine the power output of the system, so the heat energy of the system has been reasonably utilized.
When Case 1 is not equipped with LAES, the electricity output of the CCHP unit increases, so the output heat of the waste heat boiler and the refrigerator also increases. The heat waste increased by 21.696 MWh and the cold waste increased by 12.421 MWh compared with Case 1. The systems of Case 2 are based on the heat demand to determine the power output of the system, so there is no need to consider the impact of the energy storage device on the heat energy output.

In the same way, the analysis results of the energy allocation Cases on the great heat day are shown in Fig.6. The difference is that the heat wasted in Case 1 is as high as 26.042 MWh and the wasted cooling capacity is as high as 33.342 MWh. The heat wasted in Case 2 is 13.054 MWh, the cool wasted in Case 2 is 4.524 MWh.

5. Conclusions

(1) The energy release process of the energy storage system in Case 1 releases 3.017 MWh more electric energy than that in Case 2, the sum of power purchased in power grid and the power output of CCHP in Case 2 is 3.017 MWh more than that in Case 1 in the energy configuration Case of the great cold day. Because Case 1 uses the "ordering heat by power" mode, the heat released is higher than the actual demand. In Case 1, the heat wasted as high as 14.647 MWh and the cold wasted as high as 24.130 MWh. The systems of Case 2 are based on the heat demand to determine the power output of the system, so the heat energy of the system has been reasonably utilized.

(2) When Case 1 is not equipped with LAES, the output power of the CCHP unit increases by 21.000 MWh, the electricity purchase in power grid increases by 8.123 MWh, the heat waste increases by 21.696 MWh and cold waste increases by 12.421 MWh. When Case 2 is not equipped with LAES, the power output and heat of the CCHP unit are the same, the thermal energy output results of the system are the same and the electricity purchased by the power grid increases by 32.140 MWh. On the great heat day, except for the difference in specific data, the energy configuration mode of the system is the same as that on the great cold day. The integrated energy system operating in the mode of "ordering power by heat" has the minimum amount of heat and cold abandonment, which supports the above mentioned.
6. References

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