The analysis of the optimal operation of integrated energy microgrid with multi-energy supply and energy storage

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Abstract. The technology of multi-energy supply and energy storage can both improve the efficiency of energy use and the renewable energy absorption capacity of system, in which way they have wide application prospects. Based on the actual data of a park in East China, an integrated energy microgrid containing CCHP system and energy storage was modelled, in which the nonlinear characteristics of each equipment in the CCHP system, the investment cost and the maintenance cost were taken into consideration. With the objective function to minimize the total cost, an optimal economic operation model of the integrated energy microgrid was established. Finally, an example was given to demonstrate the economic benefits and the effect of improving the renewable energy absorption capacity brought by the introduction of multi-energy supply and energy storage.

1. Introduction

With the progress of the global energy structure revolution, the main energy consumers migrate from the non-renewable energy sources to renewable energy sources gradually. During this period, the regional Energy Internet centered on multi-energy supply has attracted the attention of a great number of researchers for its features of effectively improving the comprehensive energy efficiency and renewable energy absorption capacity [1]. A typical regional Energy Internet uses CCHP system as an energy hub to achieve multi-energy supply and introduces the energy storage equipment to further enhance the ability to adjust of system.

The multi-energy supply further utilizes the waste heat generated after power generation to achieve the cascade utilization of energy, in which way the comprehensive energy efficiency can be improved significantly [2], and the level of renewable energy consumption also increases by its multi-energy complementary advantages [3]. Literature [4] studied the optimization of the microgrid with CHP system operation under the fluctuation of renewable energy output from an economic perspective; Literature [5] made an optimization for a microgrid with CCHP system with the minimum cost as an objective function, and the sensitivity of the results to the price of the natural gas was analyzed. The effect of the application of heat pump in the CHP microgrid on the absorption of wind power was considered in the literature [2].

The installation of energy storage equipment is significant for improving the renewable energy absorption capacity of system. Literature [6] established the optimal configuration model of the electricity storage system and analyzed the stability of the microgrid with electricity storage equipment. Literature [7-8] discussed the effect of applying heat storage on the improvement of wind
power absorption in a CHP microgrid system. Literature [9] optimized the energy storage capacity in the cogeneration microgrid and analyzed the effect.

The above literatures have made some progress in the optimization of integrated energy microgrid. However, through reading and comparing the relevant literatures, it can be found that there are following two problems in the current literature.

1) The modeling of CCHP system is general, and the relationship between power, heat and cold supply is directly given according to the linear relationship. The coupling relationship between the equipment in the CCH system is omitted, and the simplified linear relationship is different from the actual unit characteristics sometimes.

2) When exploring the impact of energy storage on the renewable energy absorption and operation benefit, the storage capacity is usually directly specified without optimization, which limits significance in guiding the construction of energy storage in practical microgrids.

In view of above problems, this paper first established a detailed CCHP system model with independent equipment model, in which way the coupling relationship between the equipment of CCHP system was clarified, and the capacity of energy storage equipment was also put into the model as a decision variable to form the optimal economic operation model of an integrated energy microgrid with multi-energy supply and energy storage. After the formation of the planning model, a non-linear planning method was used to solve it. With the result of planning model, the improvement of operational benefit and renewable energy absorption brought by the introduction of multi-energy supply and energy storage could be quantificationally analyzed.

2. The model of equipment in the integrated energy microgrid

The equipment of an integrated energy microgrid often includes CCHP system, electrical refrigeration unit, energy storage equipment, etc. This section models these devices.

2.1. The model of CCHP system

The traditional CCHP system modeling usually gives the output expression of power supply, heating and cooling directly according to the linear relationship. In this paper, the specific composition of CCHP system including gas turbine, waste heat boiler, extraction condensing turbine and lithium bromide unit was modeled independently, and the non-linear characteristics of the monomer was taken into account.

2.1.1. The model of gas turbine. The gas turbine generates electricity by burning natural gas and discharges high-temperature and high-pressure exhausted gas after work. The gas turbine’s power output and the exhausted gas mass flow can be expressed as

\[ P_{gt,t} = V_{gas,t} \cdot LHV \cdot \eta_{gt,t} \quad (1) \]

\[ m_{eh,t} = \frac{V_{gas,t} \cdot \Delta H_{eh,t}}{\alpha} \quad (2) \]

\[ \eta_{gt,t} = \eta_{gt,e} \cdot \left( p_1 \cdot l d_{gt,t}^2 + p_2 \cdot l d_{gt,t} + p_3 \right) \quad (3) \]

where, \( V_{gas,t} \) is the intake volume flow of natural gas at time \( t \); \( LHV \) is the natural gas low thermal value; \( \Delta H_{eh,t} \) is the increase of enthalpy of the exhausted gas; \( \alpha \) is the proportion of natural gas combustion heat transfer to exhausted gas waste heat; \( \eta_{gt,t} \) is power generation efficiency at time \( t \); (3) is a quadratic fitting formula, in which \( \eta_{gt,e} \) is the rated power generation efficiency and \( p_1 \sim p_3 \) are dimensionless coefficients.

2.1.2. The model of waste heat boiler. A waste heat boiler can be considered as a heat exchanger that transfers the heat of exhausted gas to water steam. The mass flow rate of water steam can be expressed as

\[ m_{st,t} = \frac{m_{eh,t} \cdot \Delta H_{eh,2}}{\Delta H_{st} \cdot \eta_{bt,t}} \quad (4) \]

\[ \eta_{b,t} = \eta_{b,e} \cdot \left( q_1 \cdot l d_{b,t}^2 + q_2 \cdot l d_{b,t} + q_3 \right) \quad (5) \]
where \( m_{eb,t} \) is the mass flow rate of the exhausted gas entering the boiler at time \( t \); \( \Delta H_{eh,2} \) is the decrease of enthalpy of the exhausted gas; \( \Delta H_{st} \) is the increase of enthalpy of the water steam; \( \eta_{b,t} \) is the efficiency of the waste heat boiler at time \( t \); (5) is a quadratic fitting formula, in which \( \eta_{b,e} \) is the rated efficiency of the waste heat boiler and \( q_1 \sim q_3 \) are dimensionless coefficients.

### 2.1.3. The model of extraction condensing turbine

The high temperature and high pressure steam generated by the waste heat boiler is passed to the extraction condensing turbine for power generation. In the intermediate pressure stage of turbine, a part of the steam is extracted for the use of cooling and heating. The power output of the extraction condensing turbine can be expressed as

\[
P_{st,t} = (k_1 - k_2 \cdot \gamma) \cdot m_{st,t}
\]

where \( P_{st,t} \) is the power output of turbine; \( m_{st,t} \) is the mass flow rate of steam entering the turbine at time \( t \); \( k_1 \) and \( k_2 \) are two dimensionless coefficients; \( \gamma \) is the extraction ratio.

The temperature and pressure of the steam extracted from the turbine satisfy the standard of heat supply, so the steam can be used for heat supply directly. The heat supplied can be expressed as

\[
Q_{st,t} = m_{ex,1,t} \cdot \Delta H_{st,1}
\]

where, \( Q_{st,t} \) is the heat supplied by the steam extracted; \( m_{ex,1,t} \) is the mass flow rate of the steam extracted for heating and \( \Delta H_{st,1} \) is the decrease of the enthalpy of steam for heating.

### 2.1.4. The model of lithium bromide unit

The lithium bromide unit uses the extracted water steam to drive the chiller which converts the heat contained in the water steam into refrigerating capacity. The refrigerating capacity can be calculated as

\[
C_{lb,t} = m_{ex,2,t} \cdot \Delta H_{st,2} \cdot COP_{lb}
\]

where, \( C_{lb,t} \) is the refrigerating capacity of the lithium bromide unit at time \( t \); \( m_{ex,2,t} \) is the mass flow rate of the steam extracted for cooling; \( \Delta H_{st,2} \) is the decrease of the enthalpy of the steam for cooling and \( COP_{lb} \) is the coefficient of performance of lithium bromide unit.

### 2.2. The model of energy storage equipment

The integrated energy microgrid realizes the coupling of electricity, heat and cold, so the heat storage and power storage can both achieve the effect of adjustment.

According to different types of carriers, there are battery storage, compressed air storage, super capacitor storage, etc. This article uses the most widely used battery storage model. The battery state of charge (SOC) is a parameter which reflects the ratio of the remaining battery power to its total capacity. Generally, it is used with the battery charge and discharge power and capacity to build a battery model [10].

The charging process of battery can be expressed as

\[
SOC_{e,t} = SOC_{e,t-1} + \frac{P_{e,t} \cdot \eta_{cg,in} \cdot \Delta t}{E_m}
\]

while the discharging process can be expressed as

\[
SOC_{e,t} = SOC_{e,t-1} + \frac{P_{e,t} \cdot \Delta t}{E_m \cdot \eta_{cg, out}}
\]

where, \( SOC_{e,t} \) is the state of charge of battery at time \( t \); \( P_{e,t} \) is the charging power of battery at time \( t \) (positive for charge and negative for discharge); \( \eta_{cg, in} \) and \( \eta_{cg, out} \) are the efficiencies of charge and discharge; \( \Delta t \) is the duration of a period and \( E_m \) is the maximum capacity of battery.

The heat storage model is almost the same as the battery model, and the only difference is that the heat storage device needs to consider the heat loss.

The heat storage process of heat storage equipment can be expressed as

\[
SOC_{h,t} = (1 - \mu) \cdot SOC_{h,t-1} + \frac{P_{h,t} \cdot \eta_{h,in} \cdot \Delta t}{Q_m}
\]

while the heat release process of heat storage equipment can be expressed as

\[
SOC_{h,t} = (1 - \mu) \cdot SOC_{h,t-1} + \frac{P_{h,t} \cdot \Delta t}{\eta_{h, out} \cdot Q_m}
\]
where, \( SOC_{h,t} \) is the ratio of the remaining heat storage capacity to the maximum capacity at time \( t \); \( P_{h,t} \) is the heat storage power at time \( t \) (positive for storage and negative for release); \( \eta_{h,in} \) and \( \eta_{h,out} \) are the efficiencies of heat storage and heat release; \( Q_m \) is the maximum capacity of heat storage equipment and \( \mu \) is the dissipation rate of heat storage per unit time.

2.3. The model of electrical refrigeration unit

The refrigerating capacity of electrical refrigeration unit can be expressed as

\[
C_{ac,t} = P_{ac,t} \cdot COP_{ac}
\]

where, \( C_{ac,t} \) is the refrigerating capacity at time \( t \); \( P_{ac,t} \) is the electric power consumed at time \( t \) and \( COP_{ac} \) is the coefficient of performance of electrical refrigeration unit.

3. The structure of integrated energy microgrid

Based on the equipment above, a typical structure of integrated energy microgrid is shown in Figure 1.

4. The optimal economic operation of integrated energy microgrid

4.1. Objective function

Establish the objective function under the principle of minimizing the cost of operation and energy storage investment, which is expressed as

\[
W = \min (W_{gas} + W_{sto})
\]

\[
W_{gas} = \sum_{t=1}^{NT} V_{gas,t} \cdot \Delta t \cdot p_{gas}
\]

\[
W_{sto} = w_e \cdot P_{em} + (w_{e,inv} + w_{mt,e}) \cdot E_m + w_h \cdot P_{hm} + (w_{h,inv} + w_{mt,h}) \cdot Q_m
\]

where, \( W_{gas} \) is the cost of natural gas; \( W_{sto} \) is the cost of the investment of energy storage equipment; \( P_{gas} \) is the price of gas; \( P_{em} \) and \( P_{hm} \) are the maximum charge and discharge rate of power storage and heat storage equipment; \( w_e \) and \( w_h \) are the energy storage equipment unit power investment coefficients; \( w_{e,inv} \) and \( w_{h,inv} \) are the investment cost of power and heat storage equipment; \( T_e \) and \( T_h \) are the service lifetime of power and heat storage equipment; \( w_{mt,e} \) and \( w_{mt,h} \) are the maintenance cost of power and heat storage equipment.
4.2. Constraints

4.2.1. Balance constraint

\[ P_{\text{st},t} + P_{\text{wp},\text{cont}} + P_{\text{pv},\text{cont}} = P_{\text{load},t} + P_{\text{act}} + P_{e,t} \]  
(17)

\[ Q_{\text{st},t} = Q_{\text{load},t} + P_{h,t} \]  
(18)

\[ C_{\text{st},t} + C_{\text{act},t} = C_{\text{load},t} \]  
(19)

where, \( P_{\text{wp},\text{cont}} \) and \( P_{\text{pv},\text{cont}} \) are the photovoltaic and wind power consumption at time \( t \); \( P_{\text{load},t} \), \( Q_{\text{load},t} \) and \( C_{\text{load},t} \) are the electrical load, heating load and cooling load at time \( t \).

4.2.2. Equipment constraint

\[ P_{\text{gt},\text{min}} \leq P_{\text{gt},t} \leq P_{\text{gt},\text{max}} \]  
(20)

\[ P_{\text{gt},\text{dn,min}} \leq P_{\text{gt},t} - P_{\text{gt},t-1} \leq P_{\text{gt},\text{up,max}} \]  
(21)

\[ m_{\text{ex},1,t} + m_{\text{ex},2,t} \leq m_{\text{gt},t} \cdot \gamma_{\text{max}} \]  
(22)

\[ 0 \leq \text{SOC}_t \leq 1 \]  
(23)

\[ 0 \leq H_t \leq 1 \]  
(24)

\[ |P_{\text{el}}| < P_{\text{em}} \]  
(25)

\[ |P_{\text{h}}| < P_{\text{hm}} \]  
(26)

4.2.3. Renewable energy consumption constraint

\[ P_{\text{pv},\text{cont}} \leq P_{\text{pv,t}} \]  
(27)

\[ P_{\text{wp},\text{cont}} \leq P_{\text{wp,t}} \]  
(28)

where, \( P_{\text{pv,t}} \) and \( P_{\text{wp,t}} \) is the maximum output of photovoltaic and wind driven generator at time \( t \).

5. Case study

5.1. Operational optimization of microgrid with multi-energy supply and energy storage

In order to verify the effect of optimal economic operation model and analyse the operation benefit and renewable energy brought by multi-energy supply and energy storage, this paper build an example based on an actual park. The system is optimized with LINGO according to the model proposed above. The optimization period is 24 hours and step is 15 minutes.

In this case, the constant mentioned above are listed here: \( \text{LHV}=35.99 \text{MJ/Nm}^3; \eta_{\text{gt},e}=36.5\%; p_1=-1.598; p_2=3.036; p_3=-0.438; \Delta H_{\text{ch,1}}=718.18 \text{MJ/t}; \alpha=61.88\%; P_{\text{gt, max}}=87 \text{Mw}; P_{\text{gt, min}}=26.1 \text{Mw}; P_{\text{gt, up, max}}=5 \text{Mw}/15 \text{min}; P_{\text{gt, up, min}}=5 \text{Mw}/15 \text{min}; \eta_{\text{h},e}=84.83\%; q_1=1.288; q_2=3.341; q_3=-0.51; \Delta H_{\text{ch,2}}=550 \text{MJ/t}; \Delta H_{\text{st}}=3345 \text{MJ/t}; k_1=0.3254; k_2=-0.2092; \gamma_{\text{max}}=0.6; \Delta H_{\text{st,1}}=2928 \text{MJ/t}; \Delta H_{\text{st,2}}=2552 \text{MJ/t}; \text{COP}_{\text{lb}}=1.5; \mu=-2\%; \text{COP}_{\text{ac}}=4.2; P_{\text{gas}}=2.21 \text{yuan/Nm}^3; w_e=100 \text{yuan/kw \cdot a}; W_{\text{e,inv}}=1000 \text{yuan/kwh}; T_e=15 \text{a}; w_{\text{mt, e}}=10 \text{yuan/kwh \cdot a}; w_h=50 \text{yuan/kw \cdot a}; W_{\text{h,inv}}=100 \text{yuan/kwh}; T_h=10 \text{a}; w_{\text{mt, h}}=10 \text{yuan/kwh \cdot a}. \) The load and max output of renewable energy are given by curves.

After the optimization, the results are shown in the table.1.

| Power storage | Heat storage | Natural gas consumption | Renewable energy consumption rate | Total cost |
|---------------|--------------|------------------------|-----------------------------------|-----------|
| 8.01Mwh/4Mw  | 3.15Mwh/1Mw | 331209.21Nm$^3$        | 98.87%                            | 731972.37yuan |

Figure 2. and Figure 3. show the variation rules of operational parameters with given load and maximum output of renewable energy. It can be seen that from 8 to 12 o’clock, the maximum output of renewable energy begins to climb. In order to consume all renewable energy, CCHP system power output decreases, meanwhile the proportion of extraction of steam for heating increases to maintain the balance of heat load. On the other hand, the power storage equipment starts to...
discharge to prepare for the peak of renewable energy output. At the same time, the heat storage equipment begins to store heat to prepare for balancing the heat load when the renewable energy output reaches the peak and there is a further reduction in the output of CCHP system. From 12 to 15 o’clock, the output of the renewable energy reaches its peak. At this time, the power storage equipment starts to consume renewable energy as much as possible with an almost maximum charge rate and the output of CCHP system reaches a minimum value. In order to keep a balance of heat load, the proportion of extraction of steam for heating reaches the maximum value and the heat storage equipment begins to release the heat stored before. Through the coordinated control of multi-energy supply and energy storage, the entire system achieves optimal operational efficiency and maximum renewable energy absorption.

5.2. Contrastive analysis

To further clarify the operational benefit and renewable energy absorption brought by multi-energy supply and energy storage, this paper builds another three modes to make a contrastive analysis: mode 1 is expressed above; mode 2 is an operation mode without energy storage; mode 3 is an operation mode without multi-energy supply and mode 4 is without both multi-energy supply and energy storage. Optimized with LINGO and the results are shown in the table 2.

| mode | Power storage | Heat storage | Natural gas consumption | Renewable energy consumption rate | Total cost |
|------|---------------|--------------|-------------------------|----------------------------------|------------|
| 1    | 8.01Mwh/4Mw  | 3.15Mwh/1Mw | 331209.21Nm³           | 98.87%                           | 731972yuan |
| 2    | 0Mwh/0Mw     | 0Mwh/0Mw    | 334850.68Nm³           | 95.33%                           | 740020yuan |
| 3    | 7.21Mwh/6Mw  | 0Mwh/0Mw    | 400707.17Nm³           | 37.14%                           | 885563yuan |
| 4    | 0Mwh/0Mw     | 0Mwh/0Mw    | 441588.55Nm³           | 14.91%                           | 975911yuan |

From the table above, it can be seen that increasing the energy storage alone does increase the benefit and consumption of renewable energy, but it is constrained by its high cost. With the introduction of multi-energy supply and optimal planning, the advantage of multi-energy complementation can get full play and the effect is much better than energy storage. Therefore, when the energy storage technology is not yet fully mature and the cost is high, prioritizing the development of technology of multi-energy supply is more conducive to the improvement of economic efficiency.

6. Conclusion

In this paper, an integrated energy microgrid model containing multi-energy supply and energy storage was established based on the microgrid structure and operation data of an actual park, and independent modelling was performed for each equipment of CCHP system. On this basis, the nonlinear characteristic of the relevant equipment and the cost (including investment and maintenance) of energy storage equipment were considered in the model, which made the model more practical. Then based on the objective function of minimizing the cost of operation, the optimal economic operation
model came into being with the constrains of equipment, load balancing and renewable energy consumption. The feasibility of this model was verified by an example, and it also clarified the economic benefit and renewable energy absorption brought by multi-energy supply and energy storage. The internal mechanisms of these two methods to improve the system were analysed also, which could provide the support for the operation and decision-making of the actual integrated energy microgrid.

The model proposed above can be used for comprehensive optimization scheduling. If a more refined model is needed, further research can analyse the sensitivity of optimization results for the factors such as the price of natural gas, the parameters of CCHP system and the cost of energy storage equipment. The introduction of the start and stop of units, energy storage device life model and so on also deserve further research.

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