Robust Scheduling Optimization Model for Combined Cooling, Heating and Power System in Industrial Parks

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Abstract: The multi energy complementary system is a new power energy technology. Firstly, we studied renewable energy and load uncertainties of an operation optimization system, and established the industrial park energy system, which includes wind power, photovoltaic power, a combined cooling, heating and power system, and an energy storage tank. Secondly, given the renewable energy uncertainties of unit output and load, we introduced a robust multi-objective operation optimization method for industrial park energy supply systems while considering conservative system operation. Thirdly, we examined the synergetic and game relationship among multiple objectives. The particle swarm optimization algorithm is used to optimize the system operation scheme, reduce the feasible domain, and improve the efficiency of the solution. Finally, the simulation results show that the operation optimization method effectively uses the demand response to optimize economic and environmental objectives and ensure the optimal operation efficiency of the system under multiple uncertainties.

1. Introduction

Industrial park energy systems are integrated with renewable energy units, Combined Cooling, Heating and Power (CCHP), and other systems, which is the main direction of the development of energy systems to fully explore the energy saving potential by multiple-coordination. These systems are the most effective means to achieve energy conservation, emission reduction, and energy structure optimization. Industrial park energy systems are being increasingly used in projects in China.

In terms of the simulation of renewable energy output uncertainty, it is necessary to simulate the uncertainty of clean energy generation scheduling. In [1], reviewed the internal and external uncertainties of wind power plant, and analyzed the influence and mechanism of uncertainty on the system, Corresponding countermeasures were recommended. In [2], discussed the influence of randomness and volatility of wind power on the system, and considered the impact of renewable energy and load random disturbance on system operation. However, due to the distributed energy exists random problems such as randomness, volatility and uncertainty [3], the structure and operation control methods of traditional power system also need to be changed.

According to the above literature, the researches on the optimization and use of clean energy in China, considering the random disturbance of renewable energy and load, the optimization of multi-energy complementary system operation considering economic, environmental and energy consumption targets is the frontier of current research.

2. Industrial Park CCHP System Operation Performance Evaluation Indexes

The industrial park energy supply system is driven by distributed energy, which consists of electricity subsystem, Combined Cooling Heating and Power (CCHP) subsystem, and auxiliary subsystem.
2.1. Energy Performance Indexes
For the CCHP system energy rate can be calculated as

\[ ER = \frac{Q_{h_{load}} + Q_{c_{load}} + E_{load}}{g_{CGT} + g_{WPP} + g_{PV}} \]  

where \( Q_{h_{load}} \), \( Q_{c_{load}} \), and \( E_{load} \) are the system load demands for heating, cooling and electricity, respectively; \( g_{CGT} \), \( g_{WPP} \), and \( g_{PV} \) are natural gas turbine power output, wind power output, and photovoltaic power output of the system, and \( ER \) is the energy rate of the industrial park CCHP system.

2.2. Economic Performance Indexes
For CCHP system, the total operation cost includes electricity purchasing cost, gas consumption cost and other operation costs, which is calculated in Equation (2).

\[ TOC = C + Q(t) \times P(t) + C_{o_{th}} \]  

Where in \( Q(t) \) is the system purchases electricity from public grid; \( P(t) \) is the price of the system purchases electricity from public grid; \( C_{o_{th}} \) is other operational cost, \( C \) is the operating cost of the system gas turbine. The operating cost of the system gas turbine is shown in the formula (13-14):

\[ C = \sum_{i=1}^{T} \sum_{t=1}^{I} \left[ [1 - u_i(t)] SU_i + u_i(t) G_i(g_i(t)) \right] \]  

\[ G_i(g_i(t)) = a_i(g_i(t))^2 + b_i g_i(t) + c_i \]  

Where in \( u_i(t) \) is the 0–1 integer state function of unit \( i \) at time \( t \), \( SU_i \) is the start and stop cost of unit \( i \), \( G_i(g_i(t)) \) is the gas consumption function of the unit \( i \), \( g_i(t) \) is the power of gas turbine, \( a_i \), \( b_i \) and \( c_i \) are the gas turbine consumption coefficient, the coefficients are 6.63E-05, 0.306 and 3.5, respectively.

2.3. Environmental Performance Indexes
The CE can be calculated as (5).

\[ CE = C_e + \varphi \times Q_p \]  

where in, \( C_e \) is the total carbon emissions cost of the CCHP system; \( \varphi \) is the per unit electricity carbon dioxide emissions of public grid, and \( Q_p \) is the electricity of the system purchases from public grid, and the specific relationship is as follows:

\[ C_e = \sum_{i=1}^{T} \sum_{i=1}^{I} \sum_{k=1}^{K} P_e \times \left[ f_2(g_i(t)) \right] \]  

\[ f_2(g_i(t)) = \alpha_i + \beta_i g_i(t) + \gamma_i g_i(t) \]  

where in \( f_2(g_i(t)) \) is the carbon emissions from unit \( i \); \( \nu \) is the carbon emission quota for generator \( i \); \( P_e \) is the price of \( \text{CO}_2 \); and \( \alpha_i \), \( \beta_i \) and \( \gamma_i \) are the carbon emission coefficients of generator \( i \), the coefficients are 9.82E-05, 0.877 and 12.8, respectively.
3. Multi-objective Optimization Model for Industrial Park CCHP System

The performance evaluation indexes and the operation effect of the CCHP system can be evaluated to optimize system performance. Therefore, the operation strategy of the CCHP system should be optimized. Therefore, we choose energy rate (ER), Total Operating Costs (TOC), and carbon emissions (CE) as the optimization objectives.

3.1. Objective Functions of System

For an industrial park CCHP system, a higher ER means better energy efficiency in system, a lower TOC means lower operation cost of system, and a lower CE means lower carbon dioxide emission in system. The detailed objective functions are (8-10).

\[
f_1 = ER = \max \left\{ \frac{Q_{\text{load}} + Q_{\text{load}} + E_{\text{load}}}{g_{\text{CGT}} + g_{\text{WPP}} + g_{\text{PV}}} \right\}
\]

\[
f_2 = TOC = \min \sum_{i=1}^{T} \{C + Q(t) \times P(t) + C_{\text{ob}}\}
\]

\[
f_3 = CE = \min \sum_{i=1}^{T} \{C_i \times \phi \times Q_p\}
\]

where \(t\) is the time index for system, \(T\) is the total operation time of system, and \(f_1\), \(f_2\), and \(f_3\) are the objective functions of the system for ER, TOC, and CE, respectively.

3.2. Unit Output Model

Constraints such as the randomness of the output of photovoltaic and wind power units are referred to in Reference [5]. The output curve of a photovoltaic power system generally accords with Beta distribution, and the specific formula of photovoltaic power output was published in [6]. The paper adopted an improved particle swarm optimization (PSO) algorithm to solve optimization problems.

4. Example Analysis

4.1. Basic Data

The Industrial park's integrated energy system is equipped with battery energy storage system, Gas Turbines and P2G system. The operation parameters are as follows Table 1:

| Equipment name                        | Parameters                      | Numerical value |
|--------------------------------------|---------------------------------|-----------------|
| **CCHP system**                      | Rated power (MW)                | 80              |
|                                      | Upper limit of climbing rate (kW/min) | 40              |
|                                      | Lower limit of climbing rate (kW/min) | 20              |
| **Battery energy storage system**    | Rated power (MW)                | 72              |
|                                      | Discharge efficiency            | 0.9             |
|                                      | Charge efficiency               | 0.9             |
| **Wind turbine**                     | Rated power (MW)                | 200             |
| **photovoltaic power**               | Rated power (MW)                | 40              |

The price of Natural gas is 2.4 ¥/m³, the peak and valley electricity price information is shown in Table 2:
Table 2. The peak and valley electricity price. (¥/kW·h).

| Period of time | Peak                  | flat                  | Valley             |
|----------------|-----------------------|-----------------------|--------------------|
| 8:30-11:30     | 1.2898                | 0.8443                | 0.4188             |
| 18:00-23:00    |                       |                       |                    |
| Price(yuan/kW·h) |                      |                       |                    |

The rated power of the gas turbine is 80 MW, the rated power of the storage tank is 72 MW. Figure 3 depicts the wind power output, photovoltaic power output, cooling, heating, and electrical load curves.

To verify the effectiveness of the proposed model in handling the conservatism of the system, the robust multi-objective model under different Γ values is obtained. We assume the following five scenarios as table 3:

Table 3. Scenarios setting of different Γ values

| Scenarios setting | The value of Γ           |
|-------------------|--------------------------|
| Scenario 1        | Γ_w=0, Γ_pv=0, Γ_C=0, Γ_HE=0, and Γ_c=0 |
| Scenario 2        | Γ_w=2, Γ_pv=2, Γ_C=4, Γ_HE=4, and Γ_c=4 |

4.2. Example Results

4.2.1. Operation Results in Scenario 1 and Scenario 2

In Scenario 2, the PSO algorithm can complete the search for the worst scenario set of all scheduling schemes. Figure 4 shows the energy supply system operation scheme for industrial park in Scenario 1.
Figure 2. The energy supply system operation scheme for industrial park in Scenario 2

In Scenario 2, assume that there is a random fluctuation in wind power and photovoltaic power output during 2:00–3:00 p.m. and there is random fluctuation in the heating, cooling, and electrical loads during 9:00 a.m.–12:00 p.m.

Due to the high electrical and cooling loads and low heating load, the heating energy produced by the recovery system and the boiler must satisfy the heating load of the industrial park. As the cooling load is very high, the electric refrigerator must work and absorb more heating energy from the absorption heat pump units and energy storage tank. The gas turbine, wind power, and photovoltaic power satisfy the electrical and cooling load demands of the industrial park. The comprehensive efficiency of the motor and boiler is high. The storage tank can satisfy the peak load and the power fluctuation caused by the prediction error of wind power and photovoltaic power.

Due to the coupling characteristics of the energy flow in the system, there is a certain contradiction between reducing the consumption of natural gas and operation cost, carbon emissions, and minimum fossil energy consumption. Under the guidance of economic objectives, the energy storage tank follows the change in time of use (TOU) price, charges the heating energy during the valley period, and then releases energy during the peak price period. Because of the low cost of power purchase, the system buys electricity from the public grid in the valley period, which reduces the cost of the industrial park.

5. Conclusions

An increasing $\Gamma$ value leads to an increase in uncertainties frequently appearing in the scheduling period; the randomness of wind power, photovoltaic power output, and the system load increasingly worsen. In this paper, we focus on the operational problems of multiple uncertainties, multiple optimization objects and demand response mechanisms in the system, and the system containing photovoltaic power generation, cogeneration, and storage batteries is the research object.

Renewable energy, such as wind power and photovoltaic power output, has randomness and volatility, which makes grid connection more difficult. In this paper, according to the characteristics of the changes in load fluctuation and renewable energy output, with the appropriate capacity of energy storage tank, the multi-energy complementary model improves the calculation accuracy of distributed generation energy flow in the CCHP system. The PSO algorithm, through setting a neighborhood factor of the solution to search the optimal solution, improves local searching ability. The algorithm has outstanding performance and good convergence effect. It can satisfy the economy of heating, cooling, and electric load supply under different robust coefficients.
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