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Optimizing Photovoltaic Operation Control for Community with CCHP under Economy Scales

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Abstract. With the rapid development of industry, carbon emissions and other environmental problems have become increasingly prominent due to the consumption of fossil fuels, which can be alleviated by changing the mode of energy utilization and utilizing renewable energy. Because of its high energy efficiency, less pollution and the ability to realize the cascade utilization of energy, the combined cooling heating and power (CCHP) system will become the development trend of the distributed energy supply system in the future. In this paper, solar energy refrigeration mode, photovoltaic power supply mode, and waste heat refrigeration technology are used to construct the control method of the power supply mode of CCHP system with solar energy in the park and establish two kinds of energy supply modes including fuel cost and electricity purchase cost respectively. Considering the deviation of solar power output prediction, the stochastic objective functions are described by α-super-quantile method and the optimization model is established. The simulation results are solar energy parameters. The economic benefit of CCHP system running in cooling mode is higher than that of power supply mode, which can provide new ideas for the efficient and rational utilization of renewable energy under the background of smart grid.

1. Introduction

With the deepening of the concept of energy saving and emission reduction, the use of renewable energy has become an effective way to solve the current serious fossil power crisis and environmental pollution problems [1-2]. The CCHP system has become the future development trend of distributed system [3-4].

On the basis of traditional CCHP, the solar energy participates in the system power supply in the form of heat energy and electric energy, and the utilization rate is improved remarkably [5]. A building in Spain is used to prove that the system can realize the savings of electricity and gas costs, and the waste heat absorption refrigerant plays a vital role in energy saving [6].

The former scholars simply recycled the waste heat from the CCHP gas turbine, without considering the use of solar energy. Considering that the solar irradiance is weak in winter and the environment temperature difference is too low, the heat dissipation of solar collector plate to the environment is large, the effect on building heating is not good, and the compensation amount of the traditional heating equipment is small. In summer, the solar irradiance is strong, sunshine time is long, and heat exchange
between collector and environment is small. Therefore, this paper takes the summer as the background, adopts the waste heat absorption refrigeration technology, and uses the solar heat to satisfy the summer refrigeration demand of the park. Its economy is also analyzed.

2. Solar energy supply mode and its control system

The system consists of a gas internal combustion engine, a solar photovoltaic generator set, a solar collector, an absorption refrigeration unit, and a heat exchanger. CCHP includes prediction module, decision module, information interaction and solar power generation system.

2.1 Solar energy supply mode

2.1.1 Solar cooling mode

The solar collector collects thermal energy and, together with the residual heat of the gas turbine, inputs the absorption chiller to meet the demand of the cold load. In this mode, gas turbines and urban power grids coordinate to meet the demand for electrical loads.

\[ Q_{AC,cool} = COP_{AC,cool} \cdot Q_{AC,heat,in} \]  \hspace{1cm} (1)

In Equations (1), cooling power for waste heat absorption chiller is \( Q_{AC,cool} \); Cooling energy efficiency coefficient is \( COP_{AC,cool} \); Input calorific value is \( Q_{AC,heat,in} \).

2.1.2 Solar power mode

The output of photovoltaics is determined by the intensity of light impinging on the photovoltaic array. In this mode, the cooling demand is provided by refrigeration appliances such as air conditioners. The specific calculation formula is as follows:

\[ P_{PV} = f_{pv} P_{PV,cap} \left( \frac{G}{G_{T,STC}} \right) \left[ 1 + \alpha_p (T_{cell} - T_{cell,STC}) \right] \]  \hspace{1cm} (2)

In the middle, \( f_{pv} \) is the power derating factor of photovoltaic array; \( P_{PV,cap} \) is the peak power of photovoltaic arrays under standard test conditions; \( G_T \) is the photovoltaic panel actual illumination.

2.2 Processing random function \( \alpha \)-super-quantile method

The CCHP power supply mode control system includes prediction module, decision module, information interaction and solar energy generation system. The prediction module includes the real-time prediction of the cooling, electric load and solar energy output [3].

Given the random function \( g(x, y) \) and its probability density function is expressed as \( P(y) \), then \( g(x, y) \) is less than the threshold \( y \) distribution function \( \Psi(x, y) \). \( \Psi(x, y) \) is a strictly monotone. For any given confidence level \( \alpha \), the corresponding minimum point value is \( U_\alpha(x) \). The expected value is \( U_\alpha(x) \).

According to the literature [6] it can be obtained:

\[ \begin{align*}
  & \text{a. b.} \\
  & \bar{U}_\alpha(x) = \min(y + \frac{1}{n(1-\alpha)} \sum_{i=1}^{n} y_i) \\
  & \text{s.t.} \\
  & y_i \geq g(x, y_i) - y; y_i \geq 0, i = 1, 2, \ldots, n
\end{align*} \]  \hspace{1cm} (3)

3. Models for optimization of energy supply models

3.1 Optimization model of solar thermal refrigeration model

3.1.1 Objective Function

Refrigeration optimization model takes the system production cost \( F_{p,h} \) as the objective function:

\[ F_{p,h} = \min \int_{q}^{t} (C_f(t) + C_s(t)) dt \]  \hspace{1cm} (4)
In Equation (4), $C_f(t)$, $C_g(t)$ are the fuel cost function and electricity purchasing cost function respectively.

① Fuel Cost Function

The mathematical expression of the fuel cost function of a gas turbine can be written as:

$$C_{pgu}(t) = \sum_{i=1}^{N_{pgu}} \left( \alpha_i + \beta_i P_{pgu,i}(t) + \sigma_i P_{pgu,i}^2(t) \right) + \delta H_{pgu,i}(t) + \epsilon_i H_{pgu,i}^2(t) + \theta_i P_{pgu,i}(t) H_{pgu,i}(t)$$

(5)

where $C_{pgu}(t)$ is the $i^{th}$ gas turbine unit, $H_{pgu,i}(t)$ is the heat power and $P_{pgu,i}(t)$ is the electric power. $\alpha_i$, $\beta_i$, $\sigma_i$, $\epsilon_i$, $\theta_i$ are production cost coefficient of the $i^{th}$ gas turbine unit. $N_{pgu}$ is the number of gas turbine units.

Only internal combustion engines in the system need fuel. Equation (6) is the mathematical expression of the total fuel cost function:

$$C_f(t) = C_{pgu}(t)$$

(6)

② Electricity Purchasing Cost Function

The switching power between the system and the grid is $P_{grid}(t)$. When considering the price of time-sharing electricity. Equation (7) is the mathematical expression of power exchange cost function between CCHP system and power grid:

$$C_s(t) = \frac{1}{2} \left[ C_{buy}(t) + C_{sell}(t) \right] P_{grid}(t) + \frac{1}{2} \left[ C_{buy}(t) - C_{sell}(t) \right] |P_{grid}(t)|$$

(7)

In Equation (7), $C_{buy}(t)$ is the unit price of purchasing electricity; $C_{sell}(t)$ is the unit price of selling electricity; When $P_{grid}(t)$ is a positive value, it indicates that the system buys electricity, and when it is a negative value, it indicates that it sells electricity to the urban grid.

3.1.2 The constraints

① Power Balance Constraint

$$P_i(t) = \sum_{i=1}^{N_{pgu}} P_{pgu,i}(t) + P_{grid}(t) + \sum_{k=1}^{N_{ch}} P_{ch,i}(t)$$

(8)

$$Q_i(t) = Q_s(t - \Delta t) + \int_{t-\Delta t}^{t} \left[ H_i(t) + H_{ch,i}(t) \right] dt - \left[ \sum_{i=1}^{N_{pgu}} H_{pgu,i}(t) + \sum_{i=1}^{N_{ch}} H_{ch,i}(t) \right] dt$$

(9)

Equation (8) is the real-time balance equation of electric power; equation (9) is the balance equation constraint in the thermal power stage (thermal, electrical and cold energy loss of the system is not considered temporarily). $\eta$ is the electric heating coefficient; $\Delta t$ is the thermal energy periodic equilibrium delay value, which can be decided by the decision-makers according to the heating quality and heating level. $\Delta t$ is the heat storage capacity of heat storage tank.

② Gas Unit Output

Gas turbine electrical and thermal output constraints should be set as:

$$P_{pgu,min}^{max} \leq P_{pgu,i}(t) \leq P_{pgu,max}^{max},$$

$$H_{pgu,min}^{max} \leq H_{pgu,i}(t) \leq H_{pgu,max}^{max}$$

(10)

The storage capacity range of the cooling tank should be set as:

$$0 \leq Q_s(t) \leq Q_s^{max}$$

(11)

The cooling power constraints provided by the system are as follows: During the operation of the waste heat absorption chiller, the outputs of heat power and cold power are limited by its rated power:

$$0 \leq Q_{AC_cool} \leq Q_{AC_cool,N}$$

(12)

where $Q_{AC_cool,N}$ is the rated refrigerating capacity of waste heat absorption chiller.
3.2 Optimization model of photovoltaic power supply mode

3.2.1 Objective Function
The mathematical expressions of target functions of photovoltaic power supply mode are the same as (4)~(7):

3.2.2 Constraint conditions
① Power Balance Constraints
\[ P_i(t) = \sum_{i=1}^{N_c} P_{ps_i}(t) + P_{grid}(t) + \sum_{k=1}^{N_s} P_{ss_k}(t) \] (13)
\[ Q_i(t) = Q_o(t - \Delta t) + \int_{t-\Delta t}^{t} [H(t) + H_{ch}(t)] \left[ -\sum_{i=1}^{N_c} H_{ps_i}(t) + \sum_{j=1}^{N_s} H_{ss_j}(t) \right] dt \] (14)

② Gas Unit Output
The mathematical expressions of output constraints of each unit are the same as (8)~(10).

3.3 Stochastic optimization Models of two kinds of energy supply modes
The optimization model of solar refrigeration and power supply is an optimization problem with integral, which can be used in the discrete algebraic processing method. Using T-samples to calculate the integral value in \( \Delta t \) period.

3.3.1 Stochastic optimization model of solar refrigeration mode
The stochastic effect of PV on the economic operation of the system is to accurately characterize and solve the function model with stochastic PV output, and to take the limit state function:
\[ g(P_{ps}, P_r) = \int_0^{T} C_f(t) dt \] (15)

The stochastic optimization model with PV output can be written as:
\[ \begin{align*}
\text{o.b.} \quad & \min \sum_{i=1}^{n_c} (C_g(t) + z_0 + \frac{1}{n(1-\alpha)} \sum_{i=1}^{n} y_i) \\
\text{s.t.} \quad & z_i \geq g(P_{ps}, P_r) - z_0 \\
& y_i \geq 0, i = 1, 2, ..., n \end{align*} \] (16)

3.3.2 Stochastic optimization model of photovoltaic power supply mode.
Take limit state function:
\[ g(P_{ps}, P_r) = \int_0^{T} [C_f(t) + C_s(t)] dt \] (17)
the corresponding stochastic optimization model can be written as:
\[ \begin{align*}
\text{o.b.} \quad & \min \sum_{i=1}^{n_c} (y_0 + \frac{1}{n(1-\alpha)} \sum_{i=1}^{n} y_i) \\
\text{s.t.} \quad & y_i \geq g(P_{ps}, P_r) - y_0 \\
& y_i \geq 0, i = 1, 2, ..., n \end{align*} \] (18)

4. Numerical simulation and result analysis

4.1 Examples and parameters
The simulation analysis of the typical day of a certain district is carried out. The output of the photovoltaic unit is obtained by the prediction method proposed in [8]. The prediction deviation is obeyed by \( \Delta P_W \sim N(0, \sigma^2) \) and \( \sigma = 0.01 P_W^0 \). The typical daily cooling, heat and electric load demand curves are shown in Figure 1. The time-sharing electricity price [1] is shown in Table 1. The parameters of each power supply unit are shown in Table 2. The electric heating coefficient \( \eta \) is 0.98, \( \Delta t \) is 0.25h.

![Figure 1. Cold, heat, electrical load demand and PV output forecast](image)

| price (¥/kWh) | [6:00—21:00] | [22:00—5:00] |
|---------------|---------------|---------------|
| Buy           | 0.13          | 0.09          |
| Sell          | 0.10          | 0.05          |

4.2 Simulation results and analysis
1) Solar cooling mode.

For the stochastic optimization model of solar cooling mode, the system operating cost curve is shown in Figure 2 under different confidence levels. During the [7:00, 11:00] period, as the cold and electric load rises sharply, the slope of the operating cost curve increases in this section, and the requirements for the unit's climbing ability are higher; at different confidence levels. [22:00, 7:00] During the period, due to the low solar power and load level, the operating costs under the three confidence levels are basically equal; the operating costs increase with the increase of the confidence level in the remaining periods.
Table 2. Parameters of each power unit

| Power | α/($) | B/($/kW) | σ/($/kW²) | δ/($/kW) | θ/($/kW²) | P max/ kW | P min/ kW | Q max/ kW | Q min/ kW |
|-------|-------|---------|-----------|---------|---------|-----------|---------|----------|----------|
| 1     | 2650.03 | 14.50  | 0.035     | 4.20    | 0.03    | 0.05      | 247.00  | 5        | 160.00   | 0        |
| 2     | 1250.04 | 136.00 | 0.044     | 0.60    | 0.03    | 0.04      | 125.80  | 5        | 115.60   | 0        |
| 3     | 950.00  | 0       | 0         | 2.01    | 0       | 0         | 0       | 0        | 200.00   | 0        |

2) Photovoltaic power supply mode

The confidence level is α=0.99, and the operating cost comparison curve between the solar cooling mode and the photovoltaic power supply mode is shown in Fig. 3. The analysis shows that the operating cost of the system in the power supply mode is higher than that of the cooling mode, which is mainly determined by the current high cost of cooling of electrical equipment such as domestic air conditioners and the different pricing mechanism of electricity price, that is, for the parks with CCHP in summer. The access of solar energy to the cooling mode helps to further enhance its economy.

Figure 2. Operating cost curve of different confidence level systems in PV cooling mode

Figure 3. Comparison of operating cost of different modes of system (cooling and power supply)

5. Conclusions

In order to reduce the impact of solar randomness on the grid-connected system, it is proposed that solar energy participates in the CCHP system for cooling and power supply, which can effectively solve the problems caused by the randomness of solar grid-connected.

For the stochastic fluctuation of solar energy output prediction bias, a stochastic optimization model based on α-super-quantile method is established in two energy supply modes. The simulation results
show that the efficiency of the solar cooling mode is higher than that of the power supply mode during the total scheduling period; as the confidence level increases, the operating cost of the system will increase.

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