Operation optimization of a CCHP system including wind renewable energy resources using matrix modeling approach

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Abstract. This paper designs combined cooling heating and power systems with wind power generation (CCHP-Wind) system, and establishes the optimal operation model of the system. The optimal operation mode of matrix modeling is set up and the comprehensive indicator including energy, environment and economy index is used as the measurement standard compared with the traditional power determined by heat (FHL) mode and heat determined by power (FEL) mode. Establishing the optimization operation mathematical model in system, sequential quadratic programming methods and genetics algorithm are used to solve the optimization model, determine the optimal operation mode of the system. Taking a hotel in Wuhan as the research object, the typical days of the four seasons of the year are selected, according to the different cooling heating and power demands and the wind energy sources of four seasons, the CCHP-Wind system optimal operation is empirically analyzed. The results show that the set matrix optimization operation mode compared with the traditional operation mode can reasonably distribute the energy flow of the system, satisfying the demands of the system and effectively avoid energy waste.

1. Introduction

Compared with the traditional separation system, the CCHP(combined cooling heating and power) system is more efficient and less polluting. It can realize the energy ladder utilization. CCHP system can also provide users with cooling, heating and electricity demands. Energy efficiency can be increased from 40% of traditional energy supply to more than 70%[1]. At present, people pay more attention to environmental and energy problems. Developing renewable energy, such as wind energy, can solve environmental pollution. And the problems posed by the fossil energy crisis[2]. Wind energy is one of the green energy which develops vigorously in recent years. From the perspective of energy, environment and sustainable development, the development of wind energy has great value[3-4]. In [5] designed a heat and power co-supply system with renewable energy, in the traditional cogeneration of heat and electricity, wind turbines, photovoltaic cells and batteries are added to meet the load. The application of wind energy in CCHP system is presented in [6], but it is different from the structure in this paper. The operating mode of its system is more dependent on wind energy. In this paper, the optimal operation mode of the combined cooling and heating power supply system with wind power is designed based on matrix modelling, and compared with the two traditional operation modes.
2. Structure of the CCHP-Wind system design

The structure of the CCHP-Wind system designed in this paper is shown in figure 1. In figure 1, \( E_{\text{grid}}, E_{w}, E_{t}, E_{u}, E_{c} \) are separately represent grid power supply, wind turbine power supply, gas turbine power supply, system electric load and electric chiller consumption; \( F_{u}, F_{t}, F_{b} \) are separately represent the total consumption of natural gas, the consumption of natural gas by gas turbine and the consumption of natural gas by gas boiler. \( Q_{c}, Q_{h}, Q_{w}, Q_{u}, Q_{c} \) are separately represent heat supply of gas boiler, heat energy of absorption chiller is shared, heat supply of heat recovery system, cooling capacity of absorption chiller, cooling capacity of electric chiller, system heating load and system cooling load.

When the system is running, gas turbines use natural gas as fuel to provide electricity to customers. The heat recovery system reclaims the residual heat generated by the gas turbine, and supplies some heat energy to the user to satisfy the user's heating load, and the other part of the heat energy to the absorption refrigerator. To meet the cooling load requirements of users. Gas boiler, as the reserve device of heat energy, starts work when the heat energy generated by gas turbine is not enough to produce heat energy. A portion of this heat energy is supplied directly to the heating load of the system, the other part is provided to the absorption chiller to meet the cooling load requirements of the users. When the electricity and heat provided by the gas turbine cannot meet the electricity and heat demands of the user, the insufficient electricity is provided by the wind turbine and the power grid.

![Figure 1. Structure of CCHP-Wind systems](image)

3. Matrix modeling of the system and Optimization of operation mode

3.1. Efficiency matrix of system equipment

Defining input vectors for system equipment \( k \), \( V_{k,i} = [F_{k,i}, E_{k,i}, Q_{k,e,i}, Q_{k,h,i}] \), the output vectors \( V_{k,o} = [F_{k,o}, E_{k,o}, Q_{k,e,o}, Q_{k,h,o}] \). Of which \( F_{i}, E_{i}, Q_{i}, Q_{o} \) are separately represent the consumption of natural gas, the consumption of electricity, the cooling capacity and the heating capacity.

Therefore, the relationship between input and output of equipment \( k \) is expressed as,

\[
V_{k,o} = H_{i}V_{k,i}
\]  

(1)

The relationship between input and output of a gas turbine can be expressed as a matrix

\[
\begin{bmatrix}
0 \\
0 \\
0
\end{bmatrix}
= 
\begin{bmatrix}
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0
\end{bmatrix}
\] 

\[
H_{i}V_{k,i}
\]  

(2)
In the same way, the efficiency matrix of gas boiler, heat recovery unit, electric chiller and absorption chiller can be obtained.

3.2. Scheduling matrix
Figure 1 shows that the total amount of natural gas $F_m$ is divided into two parts, which are supplied to gas turbine and gas boiler respectively. Thus, $\alpha_i$ and $\alpha_s$ are the dispatching factors of gas turbine and gas boiler, respectively. Then there are $F_i = \alpha_i F_m$, $F_s = \alpha_s F_m$. Thus can be obtained that $\alpha_i + \alpha_s = 1$. We can also see that the power input of the system is provided jointly by the power grid and the wind turbine, then there are $E_{net} + E_c = E_c$. $E_c$ is the total power input for the system.

In order to facilitate the optimization of the following calculation, the input vector of each device is rewritten to the form associated with the total input vector of the system. Input vector for gas turbine is

$$V_{t} = \begin{bmatrix} \alpha_i & 0 & 0 & 0 \\ 0 & \alpha_i & 0 & 0 \\ 0 & 0 & \alpha_s & 0 \\ 0 & 0 & 0 & \alpha_s \end{bmatrix} F_m = D_t V_i.$$  

Similarly, the scheduling matrix of gas boiler, heat recovery unit, electric chiller and absorption chiller $D_b, D_r, D_{ec}, D_{ac}$ can be obtained.

3.3. Transformation matrix of CCHP-Wind system
From figure 1, the input to the system can be represented as

$$V_{i} = \begin{bmatrix} F_m \\ E_c \\ Q_{c,d} \\ Q_{h,c} \end{bmatrix} = \begin{bmatrix} F_m \\ E_c \\ 0 \\ 0 \end{bmatrix}.$$  

As can be seen from the second equation in formula (4), the system does not have the input of cooling capacity and heat energy, the two elements are retained in the input vector. The aim is to unify the form of a matrix. Therefore, the output of the system can be represented as

$$V_{o} = \begin{bmatrix} F_b \\ E_{c} \\ Q_r \\ Q_h \end{bmatrix}$$  

Therefore, the transformation matrix $H$ of CCHP system can be expressed as

$$V_{o} = H V_i.$$  

Assuming that there is no loss in the transmission of electrical energy, the electric load of the system can be expressed as

$$E_N = (E_c + E_i) \alpha_N = E_c \alpha_N + E_i \alpha_N.$$  

For system refrigeration, it can be obtained from figure 1

$$Q_r = Q_{c,r} + Q_{h,r} = \alpha_c E_c COP_{c,r} + \alpha_h COP_{h,r} + \alpha_r$$  

For system heating, it can be obtained from figure 1

$$Q_h = (Q_h + Q_r) \alpha_h = \eta_h (1 - \eta_l) \alpha_r + \eta_h \alpha_h \alpha_h F_m.$$  

The transformation matrix $H$ of the system can be obtained from the formula (7) ~ (9)

$$H = \begin{bmatrix} 0 & 0 & 0 & 0 \\ \alpha_c COP_{c,r} \eta_l & \alpha_c COP_{c,r} \eta_l & 0 & 0 \\ \alpha_h COP_{h,r} \eta_l & \alpha_h COP_{h,r} \eta_l & \alpha_h COP_{h,r} \eta_l & 0 \\ \eta_h (1 - \eta_l) \alpha_c + \eta_h \alpha_h \alpha_h \eta_l & \eta_h (1 - \eta_l) \alpha_c + \eta_h \alpha_h \alpha_h \eta_l & \eta_h (1 - \eta_l) \alpha_c + \eta_h \alpha_h \alpha_h \eta_l & 0 \\ \end{bmatrix}$$  

The main objective of this paper is to find out the appropriate scheduling factor and input vector of the system, so that the objective function value set by the system can be minimized.
3.4. Optimization of composite indicators

In order to compare operation more objectively, the comprehensive index is composed of different proportion of energy index, environmental index and economic index.

The energy indicator \( Y_{PEC} \) indicates the primary energy consumption of the power grid and natural gas consumed by the system as a uniform standard, that is
\[
Y_{PEC} = P_{Ec} + F_{m} \sigma_f
\] (10)

The environmental indicator \( Y_{CDE} \) indicates the total amount of CO2 emitted when electricity and natural gas are consumed in the grid, that is
\[
Y_{CDE} = P_{Ec} \mu_f + F_{m} \mu
\] (11)

The economic indicator \( Y_{COST} \) consists of the cost of purchasing primary energy for the system (including the cost of purchasing electricity in the power grid and natural gas), the fees required to discharge the CO2 from the system operation, and the maintenance costs required after the operation of the system equipment, that is
\[
Y_{COST} = P_{Ec} C_e + F_{m} C \sum_i P_i C_i
\] (12)

In this paper, the comprehensive indicator of energy, environment and economy \( Y_c \) is constructed, which is also the objective function to be studied, that is
\[
y_c = \omega_1 Y_{PEC} + \omega_2 Y_{CDE} + \omega_3 Y_{COST}
\] (13)

In formula (13): \( \omega_1, \omega_2, \omega_3 \) represent the proportional coefficients of energy, environmental and economic indexes, respectively. Their range of values is \( 0 \leq \omega_1, \omega_2, \omega_3 \leq 1 \) and \( \omega_1 + \omega_2 + \omega_3 = 1 \).

The optimization of the CCHP-Wind system should satisfy the following two aspects: 1) the optimization of the scheduling factor and 2) the optimization of the input vector of the system. The vector defining the scheduling factor is \( \alpha = [\alpha_1, \alpha_2, \alpha_3] \). In addition, system input vector can be defined as \( \beta = [F_m, P_{Ec} x N E E_k] \). Both \( \alpha \) and \( \beta \) are optimized vectors to be studied, so you can combine them into \( x = [\alpha^T, \beta^T]^T \). Function \( y_c \) can be represented as a function containing \( x \), that is
\[
y_c(x) = \omega_1 ax + \omega_2 bx + \omega_3(cx + e)
\] (14)

In the calculations below, \( \alpha_1, \alpha_2, \alpha_3 \) are \( 0.4, 0.1, 0.5 \). \( a = [0 0 0 \sigma_1 \sigma_2 \sigma_3]; b = [0 0 0 \mu_f \mu_e 0]; c = [0 0 0 C_f + \mu_f C_e + \mu_e C_e + C_e]; e = \sum_i P_i C_i \).

Equality constraint represents the balance of supply and demand between systems, including fuel, electricity, heating and cooling capacity. The unique nonlinear equality constraint in this paper is
\[
HV - V_o = 0
\] (15)

In this paper, there are no constraints on the input energy and system demand, and the required constraints are all included in the transformation matrix \( H \). The elements in the transformation matrix can be represented by matrix \( x \), is
\[
H = (d_{112}P_{22} + d_{113}P_{31} + d_{114}P_{41})xQ_{11} + d_{122}P_{23} + d_{131}P_{34} + d_{141}P_{44} + d_{113}P_{33} + d_{114}P_{41} - d_{113}P_{33} + d_{114}P_{41} - d_{113}P_{33} + d_{114}P_{41} - d_{113}P_{33} + d_{114}P_{41} 
\] (16)

In formula (16): \( P, T, Q \) are a matrix 01 satisfying the equation, \( d_{112} = \eta_1; d_{221} = 1; d_{412} = \eta_b; d_{312} = \eta_b \text{ COP}_a; d_{313} = -\eta_1 \text{ COP}_a; d_{314} = \eta_1 \text{ COP}_a; d_{321} = -\text{ COP}_a; d_{331} = (\eta_1 - \eta_1 \eta_b \eta_h) \text{ COP}_a; d_{411} = \eta_1 - \eta_1 \eta_h \eta_h \).

At the same time, the system input \( V_i \) can also be represented by \( x \), that is \( V_i = S \cdot x \). Therefore, the nonlinear equality constraint is
\[
(d_{112}P_{22} + d_{113}P_{31} + d_{114}P_{41})xQ_{11} + d_{122}P_{23} + d_{131}P_{34} + d_{141}P_{44} + d_{113}P_{33} + d_{114}P_{41} - d_{113}P_{33} + d_{114}P_{41} - d_{113}P_{33} + d_{114}P_{41} - d_{113}P_{33} + d_{114}P_{41} - d_{113}P_{33} + d_{114}P_{41} 
\] (17)

Inequality constraints mainly focus on the parameter characteristics, including the rated power (upper bound) and the lower bound of the device output. The scheduling factor \( \alpha \) should be no less than 0 and not greater than 1. At the same time, the input of the system only flows into the system, but
no energy flows out of the system. \( F_n, E_{grid}, E_n \) should be not less than 0, we can get
\[ 0 \leq \alpha \leq 1 \]
and \[ \beta \geq 0. \]

The output upper limit of each equipment is set as the rated power of the equipment. Therefore, the output upper bounds of gas turbine, gas boiler, heat recovery system, electric chiller, absorption chiller and wind turbine are given as follows

\[
\begin{align*}
V_{t,o} &= \begin{bmatrix}
0 \\
\overline{E}_{t,o} \\
\overline{\eta}_{t,o}
\end{bmatrix}
\quad V_{b,o} = \begin{bmatrix}
N_t \eta_t \\
0 \\
0
\end{bmatrix},
V_{h,o} = \begin{bmatrix}
N_t (1 - \eta_t) \\
0 \\
0
\end{bmatrix},
V_{r,o} = \begin{bmatrix}
0 \\
\overline{Q}_{r,h,o} \\
N_t \eta_t
\end{bmatrix},
V_{e,c,o} = \begin{bmatrix}
0 \\
\overline{\eta}_{e,c,o} \\
0
\end{bmatrix},
V_{w,o} = \begin{bmatrix}
0 \\
\overline{E}_{w,o} \\
N_w
\end{bmatrix},
\end{align*}
\]

In this paper, \( V_{t,o}, V_{b,o}, V_{h,o}, V_{r,o}, V_{e,c,o} \) and \( V_{w,o} \) are respectively the output lower bounds of gas turbine, gas boiler, heat recovery unit, electric chiller and absorption chiller. Normally, the output lower bound is set to 0.

After the upper and lower bounds of the output are determined, the inequality constraint is obtained
\[ V_{k,o} \leq H_k V_{k,i} \leq \overline{V}_{k,o} \]

And can be obtained

Similarly, \( D_k \) can also be represented by \( x \), that is
\[
\begin{align*}
D_t &= P_{t1}xT_{t1}, D_h = I_{11} - P_{t1}xT_{t1}, D_r = n_t P_{t1}xT_{t1}, \\
D_c &= I_{22} - P_{t2}xT_{t2}, D_a = r_c P_{t2}xT_{t2}, D_r = n_t P_{t1}xT_{t1},
\end{align*}
\]

In the formula: \( \eta_t = 1 - \eta_t, r_c = d_{411}; \eta_r = \eta_r \).

3.5. The running mode of matrix modeling and optimization algorithm

In the operation matrix modeling mode, the electric load \( E_N \), heating load \( Q_h \) and cooling load \( Q_c \) of the system are satisfied simultaneously. Only the input and output of the system are considered, the matrix model is carried out inside the system, the output is regarded as the known quantity, and the energy conservation is satisfied within the system. The numerical value of the input end of the system is obtained by calculating, and then the comprehensive index under the operation mode is obtained.

For this kind of problem, the sequential quadratic programming algorithm is selected, and the optimization simulation will be carried out on MATLAB.

Aiming at the two running modes of traditional CCHP system, the genetic algorithm is chosen to optimize the solution, and the objective function is the same as the set running algorithm.

4. Example analysis

In order to verify the reliability of the operation mode of the system, a hotel in Wuhan was selected as the research object, one day in spring, one day in summer, one day in autumn and one day in winter, with an interval of one hour. To facilitate calculation, the heat unit KJ is converted to kWh for calculation. According to the experimental data, the rated power of gas turbine is 30kW, and the rated power of gas boiler, electric refrigerator and absorption refrigerator is 120kW. Performing simulation operations based on given system parameters
The wind turbine with rated power of 100kW is selected in this paper. According to the weather conditions and the characteristics of the wind turbine, the rated output power \( P_r \) of each of the four seasons is obtained at different times in one day, as shown in Figure 2.

**Figure 2.** Output power of wind turbine in each time period

Because of the different seasons, the demand of electric, heating and cooling loads in the system is also quite different. In this experiment, the load of the system is selected as the experimental data in each of the four seasons. Through the MATLAB simulation, we can get the comprehensive index \( Y \) comparison of the three operation modes in spring, summer, autumn and winter, as shown in Figure 3.

**Figure 3.** Comparison of different operating modes in four seasons

It can be seen from figure 3 that the synthetic indexes of matrix modeling optimization are not higher than the other two traditional CCHP modes. Early and late in the spring and autumn, The composite index of matrix modeling optimization is the same as that of thermostatic operation mode, but at other times, the synthesis index is better under the operation mode of matrix modeling optimization. In summer and winter, The composite indexes under the optimized operation mode of matrix modeling are superior to those of the other two traditional CCHP modes at any time; in the
early morning and late night of summer and winter, there is a small difference between the synthetic index of matrix modeling optimization and the other two traditional CCHP operation modes, but there is a big difference in other time periods.

5. Conclusion
Both traditional CCHP modes waste part of their energy. When the system is in the mode of FEL, the CCHP system will first meet the power demand of the system, if the heat energy provided by the gas turbine cannot meet the heating demand of the system, the gas boiler will replenish the heat energy, but if the gas turbine provides more heat energy than the system requires, the excess heat energy will be wasted.

In the same way, this problem also exists in the operation mode of FTL. By matrix optimization, the input and distribution of system energy can be better managed. In order to eliminate the waste of system energy. It can be seen from formula 14 that the equality constraints at the output end of the CCHP system can be accurately matched with the demands of the user. Therefore, the optimal running mode of matrix modeling is better than that traditional CCHP.

The validity and feasibility of the system model and the system optimized operation mode are verified by the example analysis. Thus, the advantage of the proposed optimal operation mode is reflected.

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