IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received September 17, 2018, accepted October 15, 2018, date of publication October 25, 2018, date of current version December 27, 2018.

Digital Object Identifier 10.1109/ACCESS.2018.2878044

Intelligent Scheduling Optimization of Seasonal CCHP System Using Rolling Horizon Hybrid Optimization Algorithm and Matrix Model Framework

WANG YANAN, WU JIEKANG, (Member, IEEE), AND MAO XIAOMING
[1]School of Automation, Guangdong University of Technology, Guangzhou, China

Corresponding author: Wu Jiekang (wujiekang@163.com)

This work was supported in part by the National Natural Science Foundation of China under Grant 51567002 and Grant 50767001, in part by The National High Technology Research and Development of China (863 Program) under Grant 2007AA04Z197, in part by the Specialized Research Fund for the Doctoral Program of Higher Education under Grant 20094501110002, in part by the Natural Science Foundation of Guangdong under Grant S2013010012431 and Grant 2014A030313509, in part by the Guangxi Natural Science Foundation under Grant 2011jjA60017, in part by the Guangdong Special Fund for Public Welfare Study and Ability Construction under Grant 2014A010106026, in part by The Guangdong Applied Science and Technology Research Foundation, China, under Grant 2016B020244003, in part by The Talent Introduction Special Foundation Project of Guangdong High School, and in part by The Disciplinary Construction Special Foundation Project of Guangdong High School under Grant 2012KJCX0045.

ABSTRACT The optimal operation of a combined cooling, heating and power (CCHP) system depends on its structure and adopted energy dispatch strategies. This paper proposes a matrix modeling method for the CCHP system structure, in which multi-energy supply is regarded as the input of system, and cooling, heating, electric load as the output of the system. The energy flow from the system input to output includes the scheduling matrix, the efficiency matrix, and the energy conversion matrix model. Adopt mixed rolling-horizon and particle swarm optimization algorithm to allocation the system scheduling factor to promote optimal operation of CCHP systems. According to the characteristics of input and output energy flow in different seasons of a certain area, the system is simulated and calculated. The results show that the adoption of rolling-horizon optimization for the thermal-electric load in winter can fully calculate the three scheduling strategies and select the optimal strategy in the rolling window. Compared to other methods, the optimization of scheduling factors in summer highlights the low-cost benefits.

INDEX TERMS CCHP system, rolling horizon, matrix model framework, intelligent scheduling.

I. INTRODUCTION

Combined cooling, heating and power (CCHP) system, also called trigeminy system, which is an important part of the Energy Internet system [1]. CCHP system has the characteristics of reducing environmental contamination, improving utilization of primary energy and decreasing cost of energy utilization [2], [3]. Therefore, it has been widely concerned by scholars from all over the world.

With sustainable development of distributed energy, including development and utilization of wind energy [4], solar energy [5] and biomass energy [6], the single energy supply CCHP system has gradually developed into a multi-energy supply CCHP system [7], [8]. While the integration of distributed energy provides great benefits for a CCHP system [9], [10], unification of renewable energy and non-renewable energy systems is also confronted with many challenges [11].

Research on different CCHP systems has unique design structures, and the common CCHP system structure is composed of equipment that produces power, thermal energy, and cold energy[12], [13]. The generation of electric energy includes renewable energy generation (wind turbines, solar photovoltaic) and non-renewable energy generation (gas turbines, internal combustion engines, etc.) [14], [15]. The equipment of producing thermal energy has an electric heater that converts electricity into thermal energy [16], and has a gas boiler that generates thermal energy through fuel and combustion [17]. Equipment of producing cold energy consists of an electric chiller that converts electric energy into cold energy [18] and an absorption chiller that converts thermal energy into cold energy [19]. A CCHP system composed of the above components generates cold, heat and electrical energy output through external energy input to meet all loads. From the point of view of mapping matrix, a CCHP system can be regarded as the focus area is provided with a plurality of energy vectors in the input and output terminals [20]. Therefore, CCHP system can establish a matrix model of the input and output relationships and analyze and optimize system operation a using matrix model.

There are many uncertainties in CCHP system, including energy input [21], selling price [22] (the price of electricity and fuel at different time periods), and load [23], all of which have a great effect on the operation of CCHP. In order to put the system in an optimal environment, including the minimum operating cost [24], [25], the minimum pollutant discharge [26] and the most efficient energy utilization [27], the uncertain factors of CCHP system should be dealt with reasonably. Generally speaking, the methods of dealing with CCHP that contains uncertain factors often are reactivity and precaution. The reactivity method includes rolling-horizon method [28] and model predictive control [29]. The precaution method includes stochastic programming and robust optimization.

The rolling-horizon optimization method appeared in the 1970s. It is a method to solve the computational difficulty of large-scale optimization decision problems, and can obtain complex and dynamic environment information in timely and effectively to make optimal decisions. The essence of the rolling horizon method is to supersede the static large-scale optimization problem solving process with a series of small-scale optimization problems solving processes repeated over time to achieve the goal of reducing the amount of calculation and adapting to the uncertainty under the premise of optimization. The work [30] considers the time-varying load and other uncertain variables, and uses the rolling-horizon algorithm to optimize the operation state of CCHP system. The work [31] aims at minimizing costs, combines rolling horizon and stochastic operating methods on the basis of mixed integer linear programming, and performs optimal energy management for uncertain supply and demand in the microgrid. The work [32] is considering the multi-level transportation cost problem, formulating transportation capacity and transportation volume to achieve minimum expected cost, and using the rolling horizon optimization algorithm to analyze the worst case to adjust the transportation plan.

Combined with the background of the above topics, this work sets up efficiency matrix, scheduling matrix and energy conversion matrix model on the structure of the multi-energy CCHP system, which can visually understand the relationship between modules and distribute energy flexible and reasonably. Using rolling horizon optimization algorithm can quickly respond to a CCHP system with dynamic variables and propose solutions. An example analysis is made for different seasons in a certain area, and CCHP system cost is reduced by optimizing the scheduling factor. The simulation illustrates show that rolling horizon algorithm has good adaptability to the uncertain information in dynamic scheduling environment, and the reasonable adjustment of rolling window can effectively improve the quality of energy scheduling.

II. SYSTME MATRIX MODELLING

In this section, an intuitive matrix model is built according to the structure of CCHP system. The use of three matrixes for calculation and optimization are: efficiency matrix, scheduling matrix and energy transformation matrix.

A. STRUCTURE COMPOSITION OF CCHP SYSTEM

The work [33] combines wind energy with traditional CCHP system to improve environmental protection capability of traditional CCHP system by utilizing clean and renewable characteristics of wind power. The work [34] adds solar energy to traditional CCHP system and uses solar energy to collect heat and photovoltaic power to reduce consumption of disposable energy. Based on both situations, this work proposes a scheme to add both wind and solar energy to a CCHP system, which not only increases development and utilization of renewable energy, but also reduces consumption of disposable energy and the output of polluting gases.

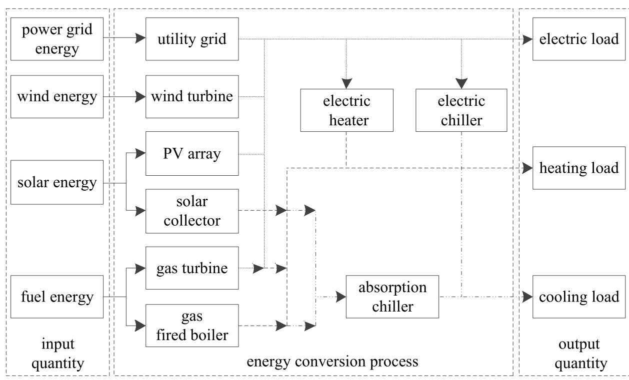


FIGURE 1. CCHP system structure and energy flow diagram.

A CCHP system structure and energy flow as showed in Fig. 1. It is not difficult to see from the figure that CCHP energy input includes grid energy, wind energy, solar energy and fuel. In which wind energy is used by wind turbines and outputs electrical energy; there are two forms of solar energy utilization, one is used by photovoltaic cell and generates electrical energy, and the other is used by solar collector and generates heat energy; gas turbines and gas boilers, both of them require fuel. Gas turbine can produce heat and electricity simultaneously, and Gas boiler can be used to make up for thermal load of CCHP; there are three types of energy conversion components: electric heaters, electric chillers, and absorption chillers; CCHP system outputs energy in the form of electricity, heat, and cold. Energy conversion process in Fig. 1 can correspond to three matrix models.

A CCHP system cannot meet load demand only with uncontrollable new energy. The most important power support is a gas turbine which converts fuel energy into useful mechanical energy by burning coal, carbon etc. The residual heat in the combustion chamber can be absorbed by a heat recovery boiler. Electric chillers and absorption chillers simultaneously absorb electricity and heat generated by the second stage of energy to meet regional cooling load. Electric heater is used as backup heating equipment to provide heat energy. In the whole energy dispatching process, fuel allocation, thermal energy absorption ratio of absorption refrigerators, electric energy absorption ratio of electric refrigerators and electric heater need to be coordinated with each other, and combined with working characteristics of equipment and output characteristics of energy to achieve goal of reducing costs.

B. COEFFICIENT MATRIX

Efficiency is the amount that expresses energy conversion capability of a system component and is the ratio of useful power to drive power [35]. Here are some statements, the input vector is $\mathbf{Z}_{\mathrm{i}} = [v_{\mathrm{i}}, S_{\mathrm{i}}, F_{\mathrm{i}}, E_{\mathrm{grid}}, Q_{\mathrm{hi}}, Q_{\mathrm{ci}}]^{\mathrm{T}}$ and the output vectors is $\mathbf{Z}_{\mathrm{o}} = [v_{\mathrm{o}}, S_{\mathrm{o}}, F_{\mathrm{o}}, E_{\mathrm{user}}, Q_{\mathrm{ho}}, Q_{\mathrm{co}}]^{\mathrm{T}}$ of CCHP system. The subscript i and o represent input and output of CCHP system; v, S, F, Q_{h} and Q_{c} represent wind speed, solar intensity, fuel, heat energy and cold energy, respectively; E_{grid} and E_{user} represent power from grid and load demand, respectively. The input-output relationship of CCHP system can be represented by efficiency matrix $\mathbf{Z}_{\mathrm{eff}}$.

$$\mathbf{Z}_{\mathrm{o}} = \mathbf{Z}_{\mathrm{eff}}\mathbf{Z}_{\mathrm{i}} \tag{1}$$

According to the input-output relationship of wind turbines, efficiency of wind turbines **Z**W eff can be expressed as the following matrix form:

$$\mathbf{Z}_{\mathrm{o}}^{\mathrm{W}} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ P_{\mathrm{W}} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ \eta_{\mathrm{W}} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} v_{\mathrm{i}}^{\mathrm{W}} \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} = \mathbf{Z}_{\mathrm{eff}}^{\mathrm{W}} \cdot \mathbf{Z}_{\mathrm{i}}^{\mathrm{W}} \tag{2}$$

Efficiency matrix generation process of other components is similar to wind turbine. The efficiency matrix of photovoltaic cell is $\mathbf{Z}_{eff}^{PV}$; the efficiency matrix of the solar collector is $\mathbf{Z}_{eff}^{SC}$; the power generation efficiency matrix and thermal efficiency matrix of gas turbine generator are $\mathbf{Z}_{eff}^{GP}$ and $\mathbf{Z}_{eff}^{GQ}$ respectively; the efficiency matrix of gas boiler, electric heater, electric chiller and absorption chiller are $\mathbf{Z}_{eff}^{B}$, $\mathbf{Z}_{eff}^{EH}$, $\mathbf{Z}_{eff}^{EC}$ and $\mathbf{Z}_{eff}^{AC}$ respectively; they can be expressed in sequence in the form of following matrix.

$$\begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \eta_{\mathrm{PV}} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \eta_{\mathrm{SC}} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \eta_{\mathrm{GP}} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$\begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \eta_{\mathrm{GQ}} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \eta_{\mathrm{B}} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \eta_{\mathrm{EH}} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$\begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \eta_{\mathrm{EC}} & 0 & 0 \end{bmatrix} \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \eta_{\mathrm{AC}} & 0 \end{bmatrix}$$

C. DISPATCH MATRICES

Dispatch matrix represent the distribution and circulation of energy in CCHP system. The fuel supply will be separated into two parts: one for the gas turbine and the other one for the auxiliary boiler. α_{GT} and β_{B} represent dispatch factors for gas turbine and auxiliary boiler.

$$\begin{cases} F_{\mathrm{GT}} = \alpha_{\mathrm{GT}} \cdot F_{\mathrm{i}} \\ F_{\mathrm{B}} = \alpha_{\mathrm{B}} \cdot F_{\mathrm{i}}, \end{cases} \quad \alpha_{\mathrm{GT}} + \alpha_{\mathrm{B}} = 1 \tag{3}$$

The fuel input for gas turbines and auxiliary boilers can be represented by scheduling matrices ZGT dis and ZB dis:

$$\mathbf{Z}_{\mathrm{i}}^{\mathrm{G}} = \begin{bmatrix} 0 \\ 0 \\ F_{\mathrm{i}}^{\mathrm{G}} \\ 0 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \alpha_{\mathrm{G}} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} 0 \\ 0 \\ F_{\mathrm{i}} \\ 0 \\ 0 \\ 0 \end{bmatrix} = \mathbf{Z}_{\mathrm{dis}}^{\mathrm{G}} \cdot \mathbf{Z}_{\mathrm{i}} \tag{4}$$

$$\mathbf{Z}_{\mathrm{i}}^{\mathrm{B}} = \begin{bmatrix} 0 \\ 0 \\ F_{\mathrm{i}}^{\mathrm{B}} \\ 0 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \alpha_{\mathrm{B}} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} 0 \\ 0 \\ F_{\mathrm{i}} \\ 0 \\ 0 \\ 0 \end{bmatrix} = \mathbf{Z}_{\mathrm{dis}}^{\mathrm{B}} \cdot \mathbf{Z}_{\mathrm{i}} \tag{5}$$

In the process of refrigeration, electrical chillers absorption electric energy is converted into cold energy, and absorption chillers absorption heat energy is converted into cold energy. Finally, two kinds of cold energy flow gather to meet the cold load demand. In the process of heating, besides heat generated by gas turbines and auxiliary boilers, electric heaters can be used to convert electric energy into heat energy to meet load demand.

The percentage of electricity absorbed by an electric refrigerator and electric heater are α_{EC} and α_{EH}, respectively. The percentage of heat absorbed by the absorption chiller is α_{AC}. The equality relation can be expressed as:

$$\alpha_{\mathrm{Euser}} + \alpha_{\mathrm{EH}} + \alpha_{\mathrm{EC}} = 1 \tag{6}$$

$$\alpha_{\mathrm{Huser}} + \alpha_{\mathrm{AC}} = 1 \tag{7}$$

The scheduling matrix can be represented in turn as:

$$\mathbf{Z}_{\text{dis}}^{\text{EH}} = \alpha_{\text{EH}} \cdot \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ \eta_{\text{W}} & \eta_{\text{PV}} & \alpha_{\text{GT}} \cdot \eta_{\text{GT}} & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{8}$$

$$\mathbf{Z}_{\text{dis}}^{\text{EC}} = \alpha_{\text{EC}} \cdot \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ \eta_{\text{W}} & \eta_{\text{PV}} & \alpha_{\text{GT}} \cdot \eta_{\text{GT}} & 1 & 0 & 0 \end{bmatrix} \tag{9}$$

$$\mathbf{Z}_{\text{dis}}^{\text{AC}} = \alpha_{\text{AC}} \cdot \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \eta_{\text{SC}} & L & 0 & 0 & 0 \end{bmatrix} \tag{10}$$

Where, $L = \alpha_{\text{GT}} \cdot (1 - \eta_{\text{GT}}) + (1 - \alpha_{\text{GT}}) \cdot \eta_{\text{B}}$.

D. CONVERSION MATRIX

Energy conversion matrix of CCHP system describes the whole process of component efficiency and energy flow, as well as operating strategy of CCHP system. According to a CCHP system structure of Fig. 1, and the input and output vectors of CCHP can be represented as follows:

$$\begin{aligned} \mathbf{Z}_{\text{i}} &= [v_{\text{i}}, S_{\text{i}}, F_{\text{i}}, E_{\text{grid}}, Q_{\text{hi}}, Q_{\text{ci}}]^{\text{T}} \\ &= [v_{\text{i}}, S_{\text{i}}, F_{\text{i}}, E_{\text{grid}}, 0, 0]^{\text{T}} \end{aligned} \tag{11}$$

$$\begin{aligned} \mathbf{Z}_{\text{o}} &= [v_{\text{o}}, S_{\text{o}}, F_{\text{o}}, E_{\text{user}}, Q_{\text{ho}}, Q_{\text{co}}]^{\text{T}} \\ &= [0, 0, 0, E_{\text{user}}, Q_{\text{ho}}, Q_{\text{co}}]^{\text{T}} \end{aligned} \tag{12}$$

It can be seen from equations (11) and (12) that the input elements of CCHP system include wind speed, sunlight intensity, fuel and power grid energy, and both thermal energy and cold energy are zero. The output elements include cold, heat, electricity corresponding to a CCHP system load, wind speed, sunlight intensity, and fuel output are zero.

Energy transformation matrix of CCHP system can be expressed as:

$$\mathbf{Z}_{\text{o}} = \mathbf{Z}_{\text{con}} \mathbf{Z}_{\text{i}} \tag{13}$$

The power balance matrix of CCHP system is as follows:

$$\begin{aligned} E_{\text{user}} &= (P_{\text{W}} + P_{\text{PV}} + P_{\text{GT}} + E_{\text{grid}})\alpha_{\text{Euser}} \\ &= (\eta_{\text{W}} \cdot v_{\text{i}} + \eta_{\text{PV}} \cdot S_{\text{i}} + \alpha_{\text{GT}} \cdot \eta_{\text{GT}} \cdot F_{\text{i}} + E_{\text{grid}})\alpha_{\text{Euser}} \\ &= [\eta_{\text{W}}, \eta_{\text{PV}}, \alpha_{\text{GT}} \cdot \eta_{\text{GT}}, 1, 0, 0] \\ &\quad \cdot [v_{\text{i}}, S_{\text{i}}, F_{\text{i}}, E_{\text{grid}}, 0, 0]^{\mathbf{T}} \alpha_{\text{Euser}} \end{aligned} \tag{14}$$

The heat balance matrix of CCHP system is as follows:

$$\begin{aligned} Q_{\text{h}} &= (Q_{\text{SC}} + Q_{\text{GT}} + Q_{\text{B}})\alpha_{\text{Huser}} \\ &\quad + (P_{\text{W}} + P_{\text{PV}} + P_{\text{GT}} + E_{\text{grid}})\alpha_{\text{EH}} \\ &= [0, \eta_{\text{SC}}, [\alpha_{\text{GT}}(1 - \eta_{\text{GT}}) + (1 - \alpha_{\text{GT}})\eta_{\text{B}}], 0, 0, 0] \\ &\quad \times [v_{\text{i}}, S_{\text{i}}, F_{\text{i}}, E_{\text{grid}}, 0, 0]^{\mathbf{T}} \alpha_{\text{Huser}} \\ &\quad + [\eta_{\text{W}}, \eta_{\text{PV}}, \alpha_{\text{GT}} \cdot \eta_{\text{GT}}, 1, 0, 0] \\ &\quad \times [v_{\text{i}}, S_{\text{i}}, F_{\text{i}}, E_{\text{grid}}, 0, 0]^{\mathbf{T}} \cdot \alpha_{\text{EH}} \end{aligned} \tag{15}$$

The cold balance matrix of CCHP system is as follows:

$$\begin{aligned} Q_{\text{c}} &= Q_{\text{ec}} + Q_{\text{ac}} \\ &= (P_{\text{W}} + P_{\text{PV}} + P_{\text{GT}} + E_{\text{grid}})\alpha_{\text{EC}} \\ &\quad + (Q_{\text{SC}} + Q_{\text{GT}} + Q_{\text{B}})\alpha_{\text{HC}} \\ &= [\eta_{\text{W}}, \eta_{\text{PV}}, \alpha_{\text{GT}} \\ &\quad \cdot \eta_{\text{GT}}, 1, 0, 0] \cdot [v_{\text{i}}, S_{\text{i}}, F_{\text{i}}, E_{\text{grid}}, 0, 0]^{\text{T}} \cdot \alpha_{\text{EC}} \\ &\quad + [0, \eta_{\text{SC}}, [\alpha_{\text{GT}}(1 - \eta_{\text{GT}}) + (1 - \alpha_{\text{GT}})\eta_{\text{B}}], 0, 0, 0] \\ &\quad \times [v_{\text{i}}, S_{\text{i}}, F_{\text{i}}, E_{\text{grid}}, 0, 0]^{T} \alpha_{\text{HC}} \end{aligned} \tag{16}$$

The transformation matrix of CCHP system can be derived from formula (11) - (16).

$$\mathbf{Z}_{\text{o}} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ \alpha_{\text{Euser}}\eta_{\text{W}} & V_{42} & V_{43} & \alpha_{\text{Euser}} & 0 & 0 \\ \eta_{\text{W}}\alpha_{\text{EH}} & V_{52} & V_{53} & \alpha_{\text{EH}} & 0 & 0 \\ \eta_{\text{W}}\alpha_{\text{EC}} & V_{62} & V_{63} & \alpha_{\text{EC}} & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} v_{\text{i}} \\ S_{\text{i}} \\ F_{\text{i}} \\ E_{\text{grid}} \\ 0 \\ 0 \end{bmatrix} = \mathbf{Z}_{\text{con}} \cdot \mathbf{Z}_{i}$$

$$\begin{aligned} &V_{42} = \alpha_{\text{Euser}}\eta_{\text{PV}}, \quad V_{52} = \eta_{\text{PV}}\alpha_{\text{EH}} + \eta_{\text{SC}}\alpha_{\text{Huser}} \\ &V_{62} = \eta_{\text{PV}}\alpha_{\text{EC}} + \eta_{\text{SC}}\alpha_{\text{HC}}, \quad V_{43} = \alpha_{\text{Euser}}\alpha_{\text{GT}} \cdot \eta_{\text{GT}} \\ &V_{53} = \alpha_{\text{GT}} \cdot \eta_{\text{GT}} \cdot \alpha_{\text{EH}} \\ &\qquad + [\alpha_{\text{GT}}(1 - \eta_{\text{GT}}) + (1 - \alpha_{\text{GT}})\eta_{\text{B}}] \cdot \alpha_{\text{Huser}} \\ &V_{63} = \alpha_{\text{GT}} \cdot \eta_{\text{GT}} \cdot \alpha_{\text{EC}} \\ &\qquad + [\alpha_{\text{GT}}(1 - \eta_{\text{GT}}) + (1 - \alpha_{\text{GT}})\eta_{\text{B}}] \cdot \alpha_{\text{HC}} \end{aligned} \tag{17}$$

III. OPTIMIZATION

Evaluating operation quality of CCHP system includes three indexes: operation cost, environmental cost and system benefits. In this section, the constraints and objective functions of CCHP system are described in detail and transformed into a matrix model for analysis.

A. OBJECTIVE FUNCTION MATRIX

The operation cost, environmental costs and system profit of CCHP system can be expressed as follows:

$$C_1 = \sum_{i=1}^{N} C_{i,\text{om}} \sum P_{\text{GT}} \cdot \Delta t + C_{\text{fuel}}(V_{\text{GT}} + V_{\text{boiler}}) \tag{18}$$

$$C_2 = \mu_{\text{f}} k_{\text{ca}}(V_{\text{GT}} + V_{\text{boiler}}) \tag{19}$$

$$C_3 = C_{\text{grid}} - C_{\text{heat}} - C_{\text{cool}} \tag{20}$$

$$C = C_1 + C_2 + C_3 \tag{21}$$

$$\begin{cases} C_{\text{heat}} = Q_{\text{h}} C_{\text{h}} \\ C_{\text{cool}} = Q_{\text{c}} C_{\text{c}} \end{cases}$$

$$C_{\text{grid},1} = C_{\text{e}} \sum P_{\text{grid},t} \Delta t$$

$$C_{\text{grid},2} = \mu_{\text{e}} k_{\text{ca}} \sum P_{\text{grid},t} \Delta t$$

$$C_{\text{grid}} = \begin{cases} C_{\text{grid},1} + C_{\text{grid},2} & P_{\text{grid},t} \geq 0 \\ C_{\text{grid},1} & P_{\text{grid},t} \leq 0 \end{cases} \tag{22}$$

Where C_1, C_2 and C_3 are system operation and maintenance costs, environmental costs, system benefits, respectively. $C_{i,\text{om}}$ is the maintenance cost of i device; C_{fuel}, C_{e}, C_{h} and C_{c} are fuels, electricity, heat energy and cold energy prices, respectively; V_{GT} and V_{boiler} are the volume of fuel consumed by gas turbines and auxiliary boilers, respectively; μ_{f} and μ_{e} are the carbon conversion coefficient of fuel and electricity, respectively; k_{ca} is the rate of carbon emission; $C_{\text{grid},1}$ and $C_{\text{grid},2}$ are electric energy sale and purchase price and the environmental costs of consuming electrical energy.

B. CONSTRAINT CONDITION MATRIX

There are two aspects to be considered in the optimization of CCHP system: (1) scheduling factors; (2) Input value of electric energy and fuel.

The input vectors of CCHP system include scheduling factors, and input values of electric energy and fuels:

$$\boldsymbol{x} = [\alpha_{\text{GT}}, \alpha_{\text{EH}}, \alpha_{\text{EC}}, \alpha_{\text{HC}}, F, E_{\text{grid}}]^{\text{T}} \tag{23}$$

In combination with the supply-demand relationship, the only equality constraint of CCHP system matrix model is relationship between the output vector and the input vector, and show by formula (13). The scheduling matrix $\boldsymbol{Z}_{\text{con}}$ can be expressed in vector $\boldsymbol{x}$:

$$\begin{aligned} &\boldsymbol{Z}_{\text{con}} \\ &= [h_{11}\boldsymbol{W}_{24} - h_{11}\boldsymbol{W}_{34} + h_{12}\boldsymbol{W}_{25} + h_{13}\boldsymbol{W}_{35} + h_{11}\boldsymbol{W}_{36} \\ &\quad + h_{14}\boldsymbol{W}_{56}]\boldsymbol{x}\boldsymbol{x}^{\text{T}}\boldsymbol{U}_{13} \\ &\quad + (-h_{22}\boldsymbol{W}_{24} - h_{22}\boldsymbol{W}_{34} + h_{22}\boldsymbol{W}_{25} + h_{22}\boldsymbol{W}_{36})\boldsymbol{x}\boldsymbol{Q}_{11} \\ &\quad + (-h_{33}\boldsymbol{W}_{24} - h_{33}\boldsymbol{W}_{34} \\ &\quad + h_{33}\boldsymbol{W}_{25} - h_{34}\boldsymbol{W}_{45} + h_{33}\boldsymbol{W}_{36} + h_{34}\boldsymbol{W}_{46})\boldsymbol{x}\boldsymbol{Q}_{12} \\ &\quad + (h_{11}\boldsymbol{W}_{14} + h_{11}\boldsymbol{W}_{16} - h_{31}\boldsymbol{W}_{25} - h_{31}\boldsymbol{W}_{35} + h_{31}\boldsymbol{W}_{46})\boldsymbol{x}\boldsymbol{Q}_{13} \\ &\quad + (-\boldsymbol{W}_{24} - \boldsymbol{W}_{34} + \boldsymbol{W}_{25} + \boldsymbol{W}_{36})\boldsymbol{x}\boldsymbol{Q}_{14} + \boldsymbol{U} \end{aligned} \tag{24}$$

The above equation is simplified for clarity, where the composition of letters and matrices are completed by the following formula.

$$h_{11} = \eta_{\text{GT}}, \quad h_{22} = \eta_{\text{W}}, \; h_{33} = \eta_{\text{PV}}, \; h_{34} = \eta_{\text{SC}}, \; h_{31} = \eta_{\text{B}}$$

$$h_{12} = 2\eta_{\text{GT}} - 1 + \eta_{\text{B}}, \quad h_{13} = \eta_{\text{GT}} - 1 + \eta_{\text{B}},$$

$$h_{14} = -\eta_{\text{GT}} - \eta_{\text{B}}$$

$$\boldsymbol{W}_{14} = \begin{bmatrix} 0&0&0&0&0&0 \\ 0&0&0&0&0&0 \\ 0&0&0&0&0&0 \\ 1&0&0&0&0&0 \\ 0&0&0&0&0&0 \\ 0&0&0&0&0&0 \end{bmatrix} \quad \boldsymbol{W}_{24} = \begin{bmatrix} 0&0&0&0&0&0 \\ 0&0&0&0&0&0 \\ 0&0&0&0&0&0 \\ 0&1&0&0&0&0 \\ 0&0&0&0&0&0 \\ 0&0&0&0&0&0 \end{bmatrix}$$

$$\boldsymbol{W}_{34} = \begin{bmatrix} 0&0&0&0&0&0 \\ 0&0&0&0&0&0 \\ 0&0&0&0&0&0 \\ 0&0&1&0&0&0 \\ 0&0&0&0&0&0 \\ 0&0&0&0&0&0 \end{bmatrix} \quad \boldsymbol{W}_{25} = \begin{bmatrix} 0&0&0&0&0&0 \\ 0&0&0&0&0&0 \\ 0&0&0&0&0&0 \\ 0&0&0&0&0&0 \\ 0&1&0&0&0&0 \\ 0&0&0&0&0&0 \end{bmatrix}$$

$$\boldsymbol{W}_{35} = \begin{bmatrix} 0&0&0&0&0&0 \\ 0&0&0&0&0&0 \\ 0&0&0&0&0&0 \\ 0&0&0&0&0&0 \\ 0&0&1&0&0&0 \\ 0&0&0&0&0&0 \end{bmatrix} \quad \boldsymbol{W}_{45} = \begin{bmatrix} 0&0&0&0&0&0 \\ 0&0&0&0&0&0 \\ 0&0&0&0&0&0 \\ 0&0&0&0&0&0 \\ 0&0&0&1&0&0 \\ 0&0&0&0&0&0 \end{bmatrix}$$

$$\boldsymbol{W}_{16} = \begin{bmatrix} 0&0&0&0&0&0 \\ 0&0&0&0&0&0 \\ 0&0&0&0&0&0 \\ 0&0&0&0&0&0 \\ 0&0&0&0&0&0 \\ 1&0&0&0&0&0 \end{bmatrix} \quad \boldsymbol{W}_{36} = \begin{bmatrix} 0&0&0&0&0&0 \\ 0&0&0&0&0&0 \\ 0&0&0&0&0&0 \\ 0&0&0&0&0&0 \\ 0&0&0&0&0&0 \\ 0&0&1&0&0&0 \end{bmatrix}$$

$$\boldsymbol{W}_{46} = \begin{bmatrix} 0&0&0&0&0&0 \\ 0&0&0&0&0&0 \\ 0&0&0&0&0&0 \\ 0&0&0&0&0&0 \\ 0&0&0&0&0&0 \\ 0&0&0&1&0&0 \end{bmatrix}$$

$$\boldsymbol{W}_{56} = \begin{bmatrix} 0&0&0&0&0&0 \\ 0&0&0&0&0&0 \\ 0&0&0&0&0&0 \\ 0&0&0&0&0&0 \\ 0&0&0&0&0&0 \\ 0&0&0&0&1&0 \end{bmatrix} \quad \boldsymbol{U} = \begin{bmatrix} 0&0&0&0&0&0 \\ 0&0&0&0&0&0 \\ 0&0&0&0&0&0 \\ \eta_{\text{W}}&\eta_{\text{PV}}&0&1&0&0 \\ 0&\eta_{\text{SC}}&0&0&0&0 \\ 0&0&0&0&0&0 \end{bmatrix}$$

$$\boldsymbol{Q}_{11} = [1 \; 0 \; 0 \; 0 \; 0 \; 0]$$

$$\boldsymbol{Q}_{12} = [0 \; 1 \; 0 \; 0 \; 0 \; 0]$$

$$\boldsymbol{Q}_{13} = [0 \; 0 \; 1 \; 0 \; 0 \; 0]$$

$$\boldsymbol{Q}_{14} = [0 \; 0 \; 0 \; 1 \; 0 \; 0]$$

In addition, the input of a CCHP system can be expressed in vector x:

$$\boldsymbol{Z}_i = \boldsymbol{p}\boldsymbol{x}$$

$$\boldsymbol{p} = \begin{bmatrix} 0&0&0&0&1&0 \\ 0&0&0&0&0&1 \\ 0&0&0&0&0&0 \\ 0&0&0&0&0&0 \\ 0&0&0&0&0&0 \\ 0&0&0&0&0&0 \end{bmatrix} \tag{25}$$

Equality constraints can be translated into:

$$\begin{aligned} &[h_{11}\boldsymbol{W}_{24} - h_{11}\boldsymbol{W}_{34} + h_{12}\boldsymbol{W}_{25} + h_{13}\boldsymbol{W}_{35} \\ &\quad + h_{11}\boldsymbol{W}_{36} + h_{14}\boldsymbol{W}_{56}]\boldsymbol{x}\boldsymbol{x}^{T}\boldsymbol{U}_{13}\boldsymbol{P}\boldsymbol{x} \\ &\quad + (-h_{22}\boldsymbol{W}_{24} - h_{22}\boldsymbol{W}_{34} + h_{22}\boldsymbol{W}_{25} + h_{22}\boldsymbol{W}_{36})\boldsymbol{x}\boldsymbol{Q}_{11}\boldsymbol{P}\boldsymbol{x} \\ &\quad + (-h_{33}\boldsymbol{W}_{24} - h_{33}\boldsymbol{W}_{34} + h_{33}\boldsymbol{W}_{25} - h_{34}\boldsymbol{W}_{45} \\ &\quad + h_{33}\boldsymbol{W}_{36} + h_{34}\boldsymbol{W}_{46})\boldsymbol{x}\boldsymbol{Q}_{12}\boldsymbol{P}\boldsymbol{x} \\ &\quad + (h_{11}\boldsymbol{W}_{14} + h_{11}\boldsymbol{W}_{16} - h_{31}\boldsymbol{W}_{25} \end{aligned}$$

$$- h_{31}\boldsymbol{W}_{35} + h_{31}\boldsymbol{W}_{46})xQ_{13}Px$$
$$+(-\boldsymbol{W}_{24} - \boldsymbol{W}_{34} + \boldsymbol{W}_{25} + \boldsymbol{W}_{36})\boldsymbol{xQ}_{14}\boldsymbol{Px} + \boldsymbol{UPx} - Z_o = 0 \quad (26)$$

In terms of CCHP system inequality constraints, there are the following parts: (1) output power constraints of CCHP system components; (2) fuel consumption constraints; (3) interaction constraints with the power grid. Taking output constraint of gas turbine as an example, the output constraint of other components has the same characteristics and matrix model.

$$\boldsymbol{Z}^{\mathrm{GT}}_{\mathrm{o,min}} \leq \left[0\ 0\ 0\ P^{\mathrm{GT}}_{\mathrm{o}}\ 0\ 0\right]^{\mathbf{T}} = \boldsymbol{Z}^{\mathrm{GT}}_{\mathrm{o}} \leq Z^{\mathrm{GT}}_{\mathrm{o,max}} \quad (27)$$
$$\boldsymbol{Z}^{\mathrm{GT}}_{\mathrm{o}} = \boldsymbol{Z}_{\mathrm{con}}\, Z^{\mathrm{GT}}_{\mathrm{dis}}\boldsymbol{Z}_{\mathrm{i}} \quad (28)$$
$$\boldsymbol{Z}^{\mathrm{GT}}_{\mathrm{dis}} = \boldsymbol{W}_{13}\boldsymbol{x}\boldsymbol{W}_{33} \quad (29)$$

IV. MIXED ROLLING-HORIZON AND PARTICLE SWARM OPTIMIZATION ALGORITHM

Rolling horizon scheduling strategy has two important components: prediction window and rolling window. A prediction window size, a scrolling window size, and a scrolling step size are three quantitative descriptions parameter of the rolling scheduling strategy.

Rolling-horizon algorithm is usually used to solve large-scale optimization problems caused by uncertainty of input data. This method has been used in financial research, energy management and many other fields. In the multi-energy-driven CCHP system, due to the intermittent and uncertainties of wind energy, solar energy and load, the difficulty in energy dispatching and distribution is increased. Uncertainty problems in dealing with energy systems usually have fuzzy and probability expression, and then use artificial intelligence algorithms(genetic algorithm and particle swarm algorithm) to manage multi-objective energy optimization problem. In this work, the matrix model of the CCHP system is established, and the rolling-horizon method is used to update the input (wind power, photovoltaic power, solar collector and cooling and heating load) information. At the same time, unit scheduling and energy allocation are optimized to reduce computational complexity and save computational time.

In order to realize the rational utilization and scheduling of energy in CCHP system, a matrix model is established for the components of CCHP system, which satisfies the power constraints within the scope of system dispatching capability, and keeps the real-time renewal of the input energy rolling optimization, and the particle swarm optimization algorithm is used to update the optimal dispatching of the system. An illustrative framework for energy scheduling is shown in Fig. 2.

A. ROLLING-HORIZON SCHEDULING STRATEGY

As a online predictive scheduling strategy, rolling horizon algorithm needs to predict part of future information at each scheduling time. A CCHP systems are jointly supplied by multiple distributed energy sources with dynamic uncertainty,

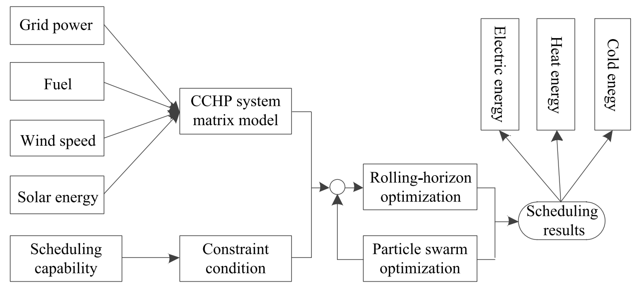


FIGURE 2. Scheduling model architecture.

and include four scheduling categories to meet load requirements: proportion of fuel distributed to gas turbine is α_{GT}; proportion of electrical energy to thermal energy is α_{EH}; proportion of electrical energy to cold energy is α_{EC}; proportion of thermal energy to cold energy is α_{HC}.

The proportion of know or predicted information contained in a prediction window represents the size of (time length) a prediction window, which can determine the degree of prediction of future dynamic information. When the prediction window size is zero, which means that the future information is completely unknown; when the prediction window is large enough, which means that the future information is completely mastered.

Forecast window lays the foundation for a local dispatch to be performed at the current moment. The amount of information in prediction window is relatively large, and the data need to be analyzed and selectively entered into the local scheduling process. Rolling window is defined as a combination of information in prediction window with certain characteristic conditions and size is a quantitative parameter.

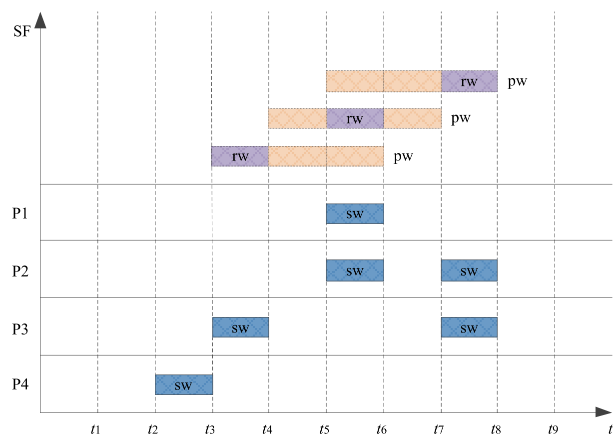


FIGURE 3. Scheduling task assignment diagram.

Scheduling task assignment is shown in Fig. 3. Abscissa represents time, and ordinate represents scheduling factor (SF). A CCHP system performs normal operation according to schedule tasks that have been scheduled. Forecast window is three times the length of schedule window, and scroll window is adjusted appropriately with the prediction information. The unit of time is 1 hour. Develop a scheduling plan based on the power and load information of prediction window. When there is a difference between predicted scheduling plans of the two adjacent periods, the latter time period is set as a rolling window, and prepares to change the schedule plan. When there is no difference between predicted scheduling plans of the two adjacent periods, the current running state is maintained.

Forecast window 1 set a rolling window in t_3 time period and send a task to P_3, which means that only P_3 changes a scheduling task at the time of t_3, and the other scheduling states remain unchanged at t_2. When the forecast window 2 information arrives, set a rolling window in t_5 time period, and the task is assigned to P_1 and P_3, which means that scheduling state of CCHP system is unchanged at the time of t_4, and scheduling state at t_5 time is properly adjusted as the task is reached.

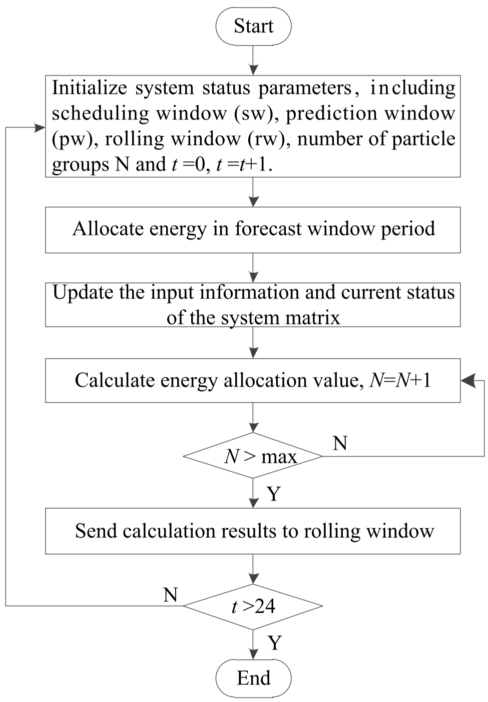


FIGURE 4. Flow chart of energy scheduling method based on the mixed rolling horizon and particle swarm optimization algorithm.

B. PARTICLE AWARM OPTIMIZATION ALGORITHM

Particle swarm optimization (PSO) is a new evolutionary algorithm [36], [37]. Because of the advantages of easy implementation, high precision and fast convergence, the method has attracted more and more attention from researchers. In this paper, PSO is used to calculate the energy scheduling problem. The basic principles and applications of PSO are not described here in detail. CCHP system scheduling calculation process is shown in Fig. 4.

S1: Initializing system parameters;

S2: According to the predicted power and load information, particle swarm optimization algorithm is used to formulate the forecast scheduling plan;

S2-1: Sets the initialization particle size, and the individual optimal speed and location;

S2-2: Optimal and global optimum of particle is calculated according to the constraint condition and objective function;

S2-3: Determine whether the number of iterations N exceeds the maximum value of max. If N>max, then execute the step 3; if N<max, then iterate.

S3: Comparing the scheduling results calculated by the prediction window, selectively setting a part of the prediction window as a rolling window.

S4: When the operation is near the rolling window, should be ready to update the scheduling task.

C. PARAMETER SELECTION OF PSO

For the parameter selection of PSO, cognitive learning factor c_1 and social learning factor c_2 are set to the same value of 1.7, and the inertia weight coefficient ω decreases linearly with the number of iterations.

$$\omega(i) = \omega_{\max} - \frac{i(\omega_{\max} - \omega_{\min})}{I} \tag{30}$$

Where $\omega(i)$ is inertial weight value of i iterations; $\omega_{\max}$ and $\omega_{\min}$ are 0.9 and 0.4 respectively; I is the maximum iteration count.

V. EXAMPLE

In this paper, two typical seasons (winter and summer) in the same area are simulated. CCHP system equipment parameters, energy prices and other data are listed in Table 1.

TABLE 1. System coefficients.

symbol	variable	value
η_{GT}	efficiency of gas turbine	0.85
η_{B}	efficiency of boiler	0.8
η_{EH}	efficiency of electric heating	0.6
η_{AC}	efficiency of absorption chiller	1.15
η_{EC}	efficiency of electric chiller	3
C_{ca}	carbon tax rates (¥/g)	0.0002
μ_e	CO_2 emission conversion factor of electricity(g/kWh)	968
μ_f	CO_2 emission conversion factor of nature gas(g/kWh)	220
LHV	Low heat value of natural gas (kWh/m^3)	0.014
C_{grid}	electricity price (¥/kWh)	0.56
C_{fuel}	natural gas price (¥/m^3)	0.0035
C_{heat}	hot water price (¥/m^3)	0.2

A. TYPICAL DAILY SCHEDULE OPTIMIZATION IN WINTER

In winter, output power of a photovoltaic battery, output power of a wind turbine, and output heat energy of a solar thermal collector are shown in Fig. 5(a); electric and heat load shown in Fig. 5(b), where cold load demand is zero.

It can be seen from Fig.5 that solar energy can't be received at night, and wind resources are very rich, so we can make

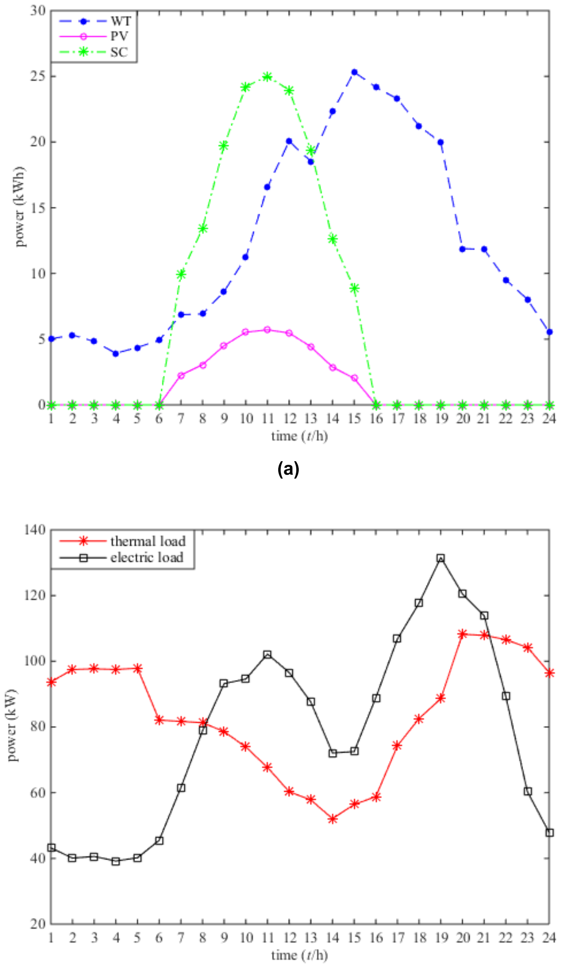


FIGURE 5. (a) is the output of energy data and (b) is a load energy data in winter.

full use of wind energy resources to meet the increased heat demand at night. Because the demand for cooling load is zero, the energy dispatch of CCHP system is the transformation of heat energy and electric energy.

First, prediction window is set to 3 hours, and rolling window is set to 1 hours. At the beginning of each run of scroll window, forecast window is re-adjusted to predict a CCHP system input and load requirements so that scroll window position can be adjusted in time. On this basis, three scheduling strategies are adopted to schedule a CCHP system.

The symbol WT, PV and SC in the figure are expressed as: wind turbine, photovoltaic and solar collector.

Strategy 1: Gas turbine is used to generate enough heat energy to meet requirements of heat users. When electrical energy is insufficient, and purchased electricity from the power grid. When electrical energy is surplus, electricity is sold and the total cost is calculated. Strategy 2: First, the amount of power output is calculated when gas turbine produces enough heat energy. When electrical energy is less than the electric load, it is converted into a strategy 1 operation system. When output power is larger than the electric load, the strategy 2 operation system and the total cost is calculated. Strategy 3: First of all, when gas turbine produces enough electricity, the heat and heat load are compared. If the heat energy is less than the heat load, gas turbine will need to be used to convert electricity into heat to satisfy the heat load. If thermal energy is greater than the heat load, excess heat will be sold.

According to the results of the three strategies, it can be seen that strategy 1 doesn't need information on the supply and demand in the future, so it can be called a rolling horizon scheduling method with a prediction window of zero. Strategy 2 and strategy 3 are the optimal scheduling strategy methods which are calculated through the prediction window. The position of rolling window and the size of scrolling step are reasonably designed. Eventually, energy is effectively scheduled when the time comes. From the experimental conclusion of Fig. 6, it can be seen that cost of the scheduling method with a prediction window of zero is much higher than that of a reasonable prediction window.

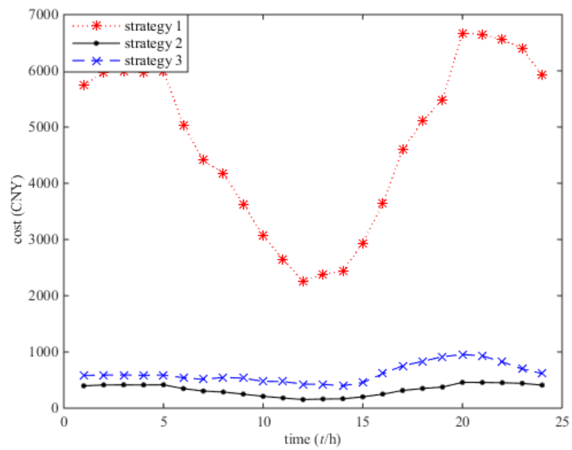


FIGURE 6. Analysis of scheduling results.

B. TYPICAL DAILY SCHEDULE OPTIMIZATION IN SUMMER

The supply and demand of typical days in summer and winter are slightly different. There are three kinds of load of cold, heat and electricity in summer typical days. Therefore, we need to consider the value of scheduling factor vector $\boldsymbol{x}$ in all aspects of simulation experiments. Output power of photovoltaic battery, wind turbine, and solar thermal collector are shown in Fig. 7(a), and electric and heat load shown in Fig. 7(b).

In the process of scheduling, considering that cold load can't be generated directly, it needs to be converted from electric energy or heat energy. At this time, values of α_{EC} and α_{HC} need to be set. Heat energy can be transformed by electric energy in emergency, so the value of α_{EH} can be set. Finally, consider the condition of fuel allocation to set the value of the α_{B}. Through simulation experiments, it is found that the

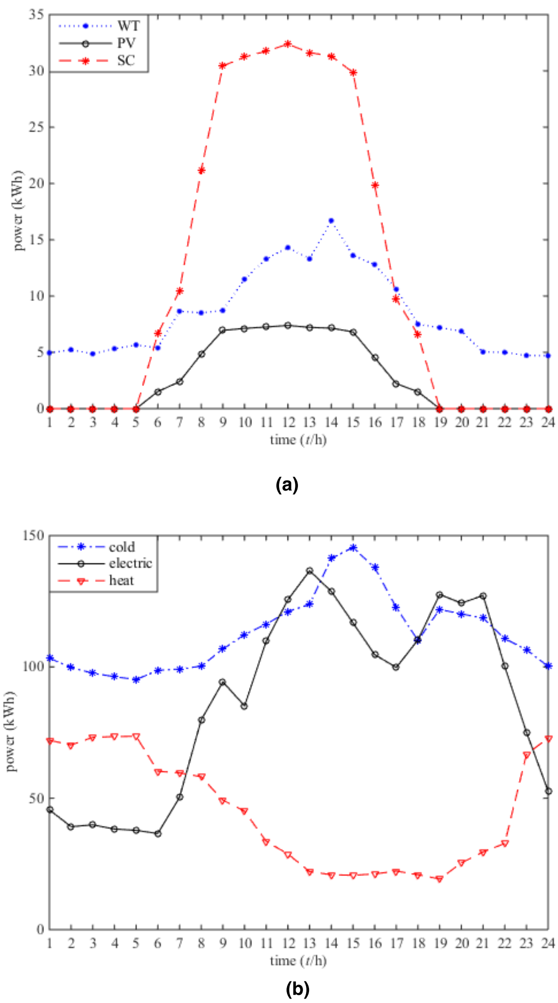


FIGURE 7. (a) is the output of energy data and (b) is a load energy data in summer.

cost of CCHP system increases with the increase of α_{EH} value without considering special circumstances.

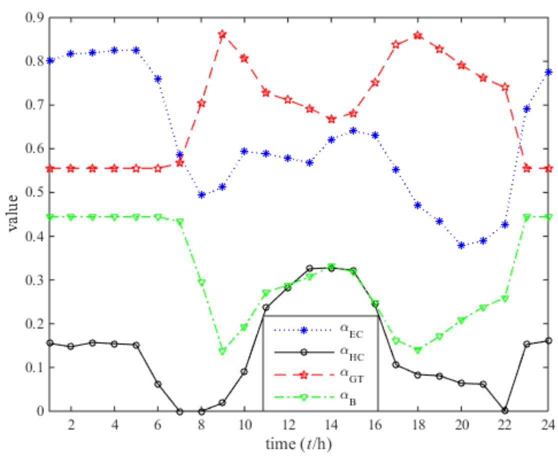


FIGURE 8. The best value of α_{EC}, α_{HC} and α_{B}.

The optimization of α_{EC}, α_{HC}, α_{B} and α_{GT} values per hour in a typical summer days is shown in Fig. 8. The results showed that demand for heating load decreased significantly in the time period of sufficient sunlight (10-18), and the value of α_{EC} decreased significantly. During periods of low sunlight (0-10, 18-24), heat load demand and the value of α_{HC} and α_{B} increases significantly.

The algorithm proposed in this work is compared with the improve particle swarm optimization (I-PSO) [38], differential evolution and particle swarm optimization (DE-PSO) combined algorithm [39], opposition-based learning and particle swarm optimization (OBL-PSO) combined algorithm [40]. Table 2 shows the results of optimal scheduling.

TABLE 2. Comparison of the experimental results of three methods.

time	I-PSO	DE-PSO	OBL-PSO	RH-PSO
1	397.9819	433.5186	402.3162	381.6244
2	425.1191	341.9320	433.5521	379.7314
3	497.5127	505.7619	477.9011	375.5534
4	402.3614	433.5211	463.0306	374.1634
5	398.1159	366.3289	402.3566	373.5120
6	512.0272	451.0020	500.5212	416.0490
7	503.3371	491.6626	521.3226	478.4913
8	556.8092	512.7710	493.7371	478.5718
9	466.1735	443.6652	451.6009	420.3729
10	370.5582	411.3361	313.5155	325.3474
11	323.2355	288.7357	302.7780	265.5040
12	306.9819	258.1665	288.7062	257.1632
13	298.5233	322.7006	273.6020	248.8861
14	313.2670	267.0015	233.3119	239.1969
15	232.1836	288.3355	226.1180	243.9802
16	309.9903	311.2561	313.7559	280.2553
17	358.7069	373.6099	434.6882	365.1077
18	411.2582	390.5328	377.1883	402.6053
19	422.5360	417.3310	457.5759	432.4985
20	511.3307	436.1150	493.5116	447.2369
21	500.0126	493.8008	466.7210	459.8560
22	516.8389	527.3091	507.7311	469.6179
23	451.0076	393.6788	422.0097	405.3091
24	463.7165	433.1072	413.5213	382.1369

TABLE 3. Experimental time comparison.

time	I-PSO	DE-PSO	OBL -PSO	RH-PSO
1-3	286.36	277.22	290.13	236.73
4-6	293.30	278.35	292.33	228.35
7-9	277.81	275.79	289.32	260.16
10-12	288.90	282.47	277.66	240.31
13-15	289.32	286.68	285.36	238.77
16-18	292.11	281.33	290.37	242.95
19-21	290.32	279.05	292.81	251.75
21-24	287.66	278.96	288.40	232.28

Table 3 lists the average scheduling runtime of the four algorithms in every 3 hours of the day, and time unit is 'ms.' By comparison, hybrid rolling horizon algorithm is slightly faster in calculation time than other algorithms, and the calculation time is relatively stable.

VI. CONCLUSION

Based on the structure of CCHP system, this work proposes a matrix modeling method that can intuitively express energy flow and energy conversion forms. In addition, the operation optimization of CCHP system is completed by meet the constraints of system supply and demand balance and component output power. In the process of using hybrid rolling optimization algorithm to complete energy scheduling, the following conclusions are drawn by analyzing the typical daily scheduling conditions in winter and summer seasons:

(1) Compared with the traditional mathematical models of multiple components, CCHP system matrix model is clearer and easier to understand.

(2) In the analysis of typical days in winter, the prediction window of rolling horizon algorithm has played a great advantage, and reducing the scheduling time and scheduling costs.

(3) The hybrid scrolling horizon algorithm has a good application and popularization to deal with random variables of a complex matrix. This method allows information to be updated and responds to plan deviations in time, and this feature is suitable for the supply and demand of the uncertainty calculation.

With the development of China's West-East Gas Transmission Project and offshore natural gas project, and CCHP system with natural gas as the main fuel can be developed and utilized on a large scale.

REFERENCES

[1] L. Cheng, C. Liu, Q. Wu, and S. Gao, "A stochastic optimal model of micro energy Internet contains rooftop PV and CCHP system," in *Proc. IEEE Int. Conf. Probab. Methods Appl. Power Syst.*, Beijing, China, Oct. 2016, pp. 1–5.

[2] E. Elsarrag and Y. Alhorr, "Green building practices: Optimisation of CCHP and biomass heating for maximum CO_2 reduction in a mixed-use development," *Int. J. Sustain. Built Environ.*, vol. 2, no. 1, pp. 99–108, Jun. 2013.

[3] I. B. Askari, M. O. Sadegh, and M. Ameri, "Effect of heat storage and fuel price on energy management and economics of micro CCHP cogeneration systems," *J. Mech. Sci. Technol.*, vol. 28, no. 5, pp. 2003–2014, May 2014.

[4] T. Stathopoulos *et al.*, "Urban wind energy: Some views on potential and challenges," *J. Wind Eng. Ind. Aerodyn.*, vol. 179, pp. 146–157, Aug. 2018.

[5] U. Akram, M. Khalid, and S. Shafiq, "An innovative hybrid wind-solar and battery-supercapacitor microgrid system—Development and optimization," *IEEE Access*, vol. 5, pp. 25897–25912, Oct. 2017.

[6] M. Caliano, N. Bianco, G. Graditi, and L. Mongibello, "Analysis of a biomass-fired CCHP system considering different design configurations," *Energy Procedia*, vol. 105, pp. 1683–1691, May 2017.

[7] Y. Jiang *et al.*, "Coordinated operation of gas-electricity integrated distribution system with multi-CCHP and distributed renewable energy sources," *Appl. Energy*, vol. 211, pp. 237–248, Feb. 2018.

[8] L. Wang, Q. Li, M. Sun, and G. Wang, "Robust optimisation scheduling of CCHP systems with multi-energy based on minimax regret criterion," *IET Gener., Transmiss. Distrib.*, vol. 10, no. 9, pp. 2194–2201, Jun. 2016.

[9] J. Wang, H. Zhong, Q. Xia, C. Kang, and E. Du, "Optimal joint-dispatch of energy and reserve for CCHP-based microgrids," *IET Gener. Transmiss. Distrib.*, vol. 11, no. 3, pp. 785–794, Feb. 2017.

[10] Y. Tang, C. Luo, J. Yang, and H. He, "A chance constrained optimal reserve scheduling approach for economic dispatch considering wind penetration," *IEEE/CAA J. Autom. Sinica*, vol. 4, no. 2, pp. 186–194, Apr. 2017.

[11] E. Baranes, J. Jacqmin, and J.-C. Poudou, "Non-renewable and intermittent renewable energy sources: Friends and foes?" *Energy Policy*, vol. 111, pp. 58–67, Dec. 2017.

[12] B. Yu, C. Cao, W. Shu, and Z. Hu, "A new method for the design of optimal control in the transient state of a gas turbine engine," *IEEE Access*, vol. 5, pp. 23848–23857, Oct. 2017.

[13] A. Landelle, N. Tauveron, P. Haberschill, R. Revellin, and S. Colasson, "Organic Rankine cycle design and performance comparison based on experimental database," *Appl. Energy*, vol. 204, no. 15, pp. 1172–1187, Oct. 2017.

[14] A. Nourbakhsh, M. Bayareh, A. Mohammadi, and S. Jahantighi, "Effect analysis on boiling heat transfer performance of an internal combustion engine at the shutdown time," *Int. J. Thermal Sci.*, vol. 129, pp. 365–374, Jul. 2018.

[15] D. Liu *et al.*, "Improved efficiency of organic photovoltaic cells by incorporation of AuAg-alloyed nanoprisms," *IEEE J. Photovolt.*, vol. 7, no. 4, pp. 1036–1041, Jul. 2017.

[16] C. Hemmer, G. Polidori, and C. Popa, "Temperature optimization of an electric heater by emissivity variation of heating elements," *Case Stud. Thermal Eng.*, vol. 4, pp. 187–192, Nov. 2014.

[17] S. Shang, X. Li, W. Chen, B. Wang, and W. Shi, "A total heat recovery system between the flue gas and oxidizing air of a gas-fired boiler using a non-contact total heat exchanger," *Appl. Energy*, vol. 207, no. 1, pp. 613–623, Dec. 2017.

[18] A. W. A. Cavalcante, C. A. C. Dos Santos, and A. A. V. Ochoa, "Thermodynamic analysis of an energy high performance systems," *IEEE Latin Amer. Trans.*, vol. 15, no. 3, pp. 454–461, Mar. 2017.

[19] M. Salimi, H. Ghasemi, M. Adelpour, and S. Vaez-ZAdeh, "Optimal planning of energy hubs in interconnected energy systems: A case study for natural gas and electricity," *IET Gener. Transmiss. Distrib.*, vol. 9, no. 8, pp. 695–707, May 2015.

[20] W. Gu, Z. Wang, Z. Wu, Z. Luo, Y. Tang, and J. Wang, "An online optimal dispatch schedule for CCHP microgrids based on model predictive control," *IEEE Trans. Smart Grid*, vol. 8, no. 5, pp. 2332–2342, Sep. 2017.

[21] C. Wang, K. Zhou, and S. Yang, "A review of residential tiered electricity pricing in China," *Renew. Sustain. Energy Rev.*, vol. 79, pp. 533–543, Nov. 2017.

[22] K. Kpodar and C. Abdallah, "Dynamic fuel price pass-through: Evidence from a new global retail fuel price database," *Energy Econ.*, vol. 66, pp. 303–312, Aug. 2017.

[23] Y. Ding, Q. Zhang, T. Yuan, and F. Yang, "Effect of input variables on cooling load prediction accuracy of an office building," *Appl. Thermal Eng.*, vol. 128, no. 5, pp. 225–234, Jan. 2018.

[24] F. Fang, Q. H. Wang, and Y. Shi, "A novel optimal operational strategy for the CCHP system based on two operating modes," *IEEE Trans. Power Syst.*, vol. 27, no. 2, pp. 1032–1041, May 2012.

[25] Z. Han, J. Zhao, and W. Wang, "An optimized oxygen system scheduling with electricity cost consideration in steel industry," *IEEE/CAA J. Autom. Sinica*, vol. 4, no. 2, pp. 216–222, Apr. 2017.

[26] M. Fani and A. Sadreddin, "Solar assisted CCHP system, energetic, economic and environmental analysis, case study: Educational office buildings," *Energy Buildings*, vol. 136, pp. 100–109, Feb. 2017.

[27] F. Wu, Q. Guo, H. Sun, and Z. Pan, "Research on the optimization of combined heat and power microgrids with renewable energy," in *Proc. IEEE PES Asia–Pacific Power Energy Eng. Conf. (APPEEC)*, Hong Kong, Dec. 2014, pp. 1–5.

[28] R. Palma-Behnke *et al.*, "A microgrid energy management system based on the rolling horizon strategy," *IEEE Trans. Smart Grid*, vol. 4, no. 2, pp. 996–1006, Jun. 2013.

[29] L. Cavanini, G. Cimini, and G. Ippoliti, "Computationally efficient model predictive control for a class of linear parameter-varying systems," *IET Control Theory Appl.*, vol. 12, no. 10, pp. 1384–1392, Jul. 2018.

[30] W. Yang, Z. Lun, Z. Meng, and H. E. Zhaocheng, "Rolling-horizon optimization-based three-stage fuzzy logic controller for urban traffic signals," *J. Tongji Univ.*, vol. 42, no. 12, pp. 1846–1853 and 1867, Dec. 2014.

[31] J. Silvente, G. M. Kopanos, V. Dua, and L. G. Papageorgiou, "A rolling horizon approach for optimal management of microgrids under stochastic uncertainty," *Chem. Eng. Res. Des.*, vol. 131, pp. 293–317, Mar. 2018.

[32] L. Bertazzi and F. Maggioni, "A stochastic multi-stage fixed charge transportation problem: Worst-case analysis of the rolling horizon approach," *Eur. J. Oper. Res.*, vol. 267, no. 2, pp. 555–569, Jun. 2018.

[33] S. Soheyli, M. H. S. Mayam, and M. Mehrjoo, "Modeling a novel CCHP system including solar and wind renewable energy resources and sizing by a CC-MOPSO algorithm," *Appl. Energy*, vol. 184, pp. 375–395, Dec. 2016.

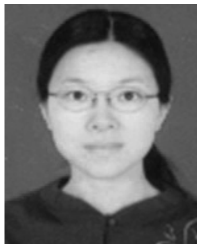
[34] I. B. Askari, M. O. Sadegh, and M. Ameri, "Energy management and economics of a trigeneration system Considering the effect of solar PV, solar collector and fuel price," *Energy Sustain. Develop.*, vol. 26, pp. 43–55, Jun. 2015.
[35] M. Geidl and G. Andersson, "Optimal power flow of multiple energy carriers," *IEEE Trans. Power Syst.*, vol. 22, no. 1, pp. 145–155, Feb. 2007.
[36] K. Mason, J. Duggan, and E. Howley, "Multi-objective dynamic economic emission dispatch using particle swarm optimisation variants," *Neurocomputing*, vol. 270, pp. 188–197, Dec. 2017.
[37] J. Li, J. Zhang, C. Jiang, and M. Zhou, "Composite particle swarm optimizer with historical memory for function optimization," *IEEE Trans. Cybern.*, vol. 45, no. 10, pp. 2350–2363, Oct. 2015.
[38] W. Dong and M. Zhou, "A supervised learning and control method to improve particle swarm optimization algorithms," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 47, no. 7, pp. 1135–1148, Jul. 2017.
[39] G. Tian, Y. Ren, and M. C. Zhou, "Dual-objective scheduling of rescue vehicles to distinguish forest fires via differential evolution and particle swarm optimization combined algorithm," *IEEE Trans. Intell. Transp. Syst.*, vol. 17, no. 11, pp. 3009–3021, Nov. 2016.
[40] Q. Kang, C. Xiong, M. Zhou, and L. Meng, "Opposition-based hybrid strategy for particle swarm optimization in noisy environments," *IEEE Access*, vol. 6, pp. 21888–21900, Mar. 2018.

WANG YANAN was born in China in 1991. She received the degree from the School of Automation, Guangdong University of Technology, Guangzhou, China. Her research topics lie at power system operation and analysis.

WU JIEKANG was born in China in 1965. He graduated from Zhejiang University.

His employment experience included as an engineer in power supply bureau, an engineer with the Electrical Engineering Designing Institute, a Professor with Zhejiang University, Guangxi University, Guangdong University of Technology, and an engineer in large enterprises. His special fields of interest included renewable power systems.

He received honorary degrees from institutions of higher learning, including Zhejiang University, South China University of Technology, and Guangxi University.



MAO XIAOMING is with the School of Automation, Guangdong University of Technology, Guangzhou, China. Her research topics lie at power system operation and analysis.