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Optimization Operation Research Based on CTS-DNFF Forecast for CCHP

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Abstract. For the process of scheduling, the method of combining dynamic fuzzy neural network and chaotic time series is proposed to be directed against uncertainties in cooling heating and power load and photovoltaic power generation output. The uncertainty in the system can be well reduced by the method. On the basis of each uncertainty can be forecasted, the scheduling model of considering economy and environmental protection is built, and the rationality of the scheduling is analysed in the light of simulation.

1. Introduction

Energy is the important material base of human survival and sustainable development of the world economy. With the high-speed development of science and technology in the 21st century, human's demand for energy is growing. With the increase of energy consumption, the supply capacity of traditional fossil energy is facing a huge challenge, and the unreasonable energy structure that relies mainly on coal and oil makes the atmosphere environment suffering so much. Therefore, the security and the rational utilization of energy are becoming more and more prominent, and it’s vital to find a reasonable energy solution.

To alleviate energy issues, changing energy structure and improving energy efficiency should be attached importance to [1]. Changing the energy structure mainly refers to the widespread introduce of distributed energy systems, including CCHP with high efficiency, on-site renewable energy system, and various energy-cyclic systems. These systems can provide electricity nearby the energy consumption. There are a variety of forms in distributed energy systems, such as micro gas power plant, wind power generation, fuel cells, photovoltaic, CCHP etc. this paper will mainly focus on the study of CCHP system.

CCHP is the main form of distributed energy system. In CCHP, the high grade energy (900 ~ 1200℃) that fuel releases can be turned into electricity by micro or small sized gas turbines, with the efficiency of 30% ~ 42%. Hot smoke (450 ~ 450℃) can be further converted and utilized by absorption refrigeration and heat pump. Waste heat of low temperature (250℃) can be used for heating water system, thus the can energy can be utilized in high efficiency. In addition, CCHP can make complementary use to the environment energy and renewable energy, realizing comprehensive utilization and high efficiency conversion of energy. Compared with the traditional power grid system, CCHP overcomes its shortcomings, and the combination of the two will become one of the main development directions of the future power system [2-4].

Nowadays, more and more countries have begun to research CCHP, and the CCHP technologies have gained international recognition. However, there are still some challenges in operation and energy management. Traditional power grid and CCHP system has obvious differences in optimization scheduling: Because of micro sized power generation possessing the characteristic of flexibility, there are some difficulties when dealing with optimization scheduling. There already have been some researches on stable operation and the optimization scheduling problems in CCHP and micro power grid which is mainly composed of photovoltaic system [5-19]. In [5], on condition that other devices in the system have certain generating capacities, the optimization energy storage capacity of wind-solar hybrid power generation system is researched, with the minimum equipment input number as the objective function, and their annual power loss rate as the constraint conditions. In [8], after micro power grid's running, the pipes satisfying hot and cooling load were included in the evaluation process. It designed a more specific method on investment and operation of micro power grid, but made it more complicated on scheduling process. In [9] and [10], reliability of the system and the minimum operation cost were evaluated by optimal spare analysis. Based on the reliability degree of uncertain unit combination, the transmission lines of space limitations, the uncertainty of load forecast and random power risk regulation were optimized.

It is of great significance to reduce the influence of uncertainty on the optimal scheduling of CCHP system. In [16], risks caused by uncertain factors were reduced by adding risk constraint factors before the uncertainties. The minimum system loss was made as the optimization objective, and feasibility of the method was proved by the analysis of the case, but this method only restrained the uncertainty, not actually conquering fundamental flaws of the uncertain factors. To make predictions, a data fitting model in the phase space is needed. BP neural network is widely used in data fitting[20].In order to solve the problems that BP neural network method is easy to fall into local optimal solutions and has a slow speed on studying historical parameters, a dynamic fuzzy neural network load forecasting method is proposed in this paper.

Uncertainties such as photovoltaic output and load characteristics are analysed in this paper. After short-term prediction which is in the way of model fitting, the general scheduling model which is based on predicted results is built. The content is arranged as follows: In the second part, the construction method of chaotic time series-dynamic fuzzy neural network prediction model is mainly introduced, and the uncertainties in CCHP are analysed by the aforementioned method. In the third part, the optimization scheduling model which satisfies load demand is put forward by analysing the weighing factors of environment and the influence of the thermal performance.

2. Problem Statement and Preliminaries

Chaotic time series is a kind of nonlinear time series. Data and internal relationships are recorded in the reconstruction of phase space. According to the history record of the time series data, to establish an appropriate mathematical model, which can fit the data change rule, and can predict future data by the recent data is one of the most mature short-term forecasting methods [21]. The weather factors need to be considered in traditional time series forecasting model, which depends much on the accuracy of weather forecasts, thus bringing so much risks in the short-term prediction [22]. Chaotic time series can transfer the research on strong random factors to the research on the effect of model itself, so as to realize a better prediction.

2.1. Constructing chaotic time series including uncertainties

A single variable in the raw data can build a new phase space by means of delaying coordinates, and proper embedding dimensions can restore the rule of chaotic attractor, thus help predicting chaotic time series data in the future. For time series $\{x_i, i = 1, 2, ..., n\}$, assume delay time being τ, then the load time series becomes $\{x_{i+\tau}, i = 1, 2, ..., n\}$. Extend one dimensional time series into a phase space with m dimensional phase.

$$\begin{bmatrix} x_1 & x_{1+\tau} & x_{1+2\tau} & \cdots & x_{1+(m-1)\tau} \\ x_2 & x_{2+\tau} & x_{2+2\tau} & \cdots & x_{2+(m-1)\tau} \\ . & . & . & . & . \\ x_{n\text{-}(m-1)\tau} & x_{n+1\text{-}(m-1)\tau} & x_{n+2\text{-}(m-1)\tau} & \cdots & x_n \end{bmatrix} \tag{1}$$

Where the selection of delay time τ and embedding dimension m directly depend on the characteristics of the refactoring space.

The best delay time can be obtained by the mutual information function method. Assume that the probability of x_k in $\{x_i, i=1,2,...,n\}$ is $p(x_k)$, the probability of $x_{k+\tau}$ in $\{x_{i+\tau}, i=1,2,...,n\}$ is $p(x_{k+\tau})$, the joint probability of x_k and $x_{k+\tau}$ appearing at the same time in their own sequence is $p(x_k, x_{k+\tau})$, and joint probability $p(x_k, x_{k+\tau})$ can obtained by calculating the number of the frames in plane $(x_k, x_{k+\tau})$. The mutual information function is shown as follows:

$$I(\tau) = \sum_{k=1}^{N} P(x_k, x_{k+\tau}) \ln \frac{P(x_k, x_{k+\tau})}{P(x_k)P(x_{k+\tau})} \tag{2}$$

The best value of τ is the first minimum of mutual information function.

2.2. The forecasting model that based on DFNN chaotic time series.

The steps of the prediction model to be established are as follows:

1) Set delay time of the refactoring space by mutual information function method. Calculate the embedding dimension of the space by the Cao's method [23], so as to reconstruct phase space $X_i = (x_i, x_{i+\tau}, ..., x_{i+(m-1)\tau})$.
2) Select k points which nearest the reference point as preparatory training input samples of dynamic fuzzy neural network:

$$f(\begin{bmatrix} x_{1(n-(m-1)\tau)} & x_{1(n-m\tau)} & \cdots & x_{1(n)} \\ x_{2(n-(m-1)\tau)} & x_{2(n-m\tau)} & \cdots & x_{2(n)} \\ . & . & . & . \\ x_{k(n-(m-1)\tau)} & x_{k(n-m\tau)} & \cdots & x_{n(n)} \end{bmatrix}) \Rightarrow \begin{bmatrix} x_{1(n+1)} \\ x_{2(n+1)} \\ . \\ x_{n(n+1)} \end{bmatrix} \tag{3}$$

Set $Y_{\text{n}} = \{Y_n(1), Y_n(2), ...Y_n(m)\}$ as the reference point, the nearest k points to Y_n are $Y_{\text{n}} = \{Y_n(1), Y_n(2), ...Y_n(m)\}$.

3) Take the training samples and the target samples as the training sample set, and traindynamic fuzzy neural network.

3. CCHP optimization scheduling model based on data prediction

3.1. Composition and structure of typical distributed CCHP

Because of the complex actual structure of CCHP and its various ways of composition, the research of CCHP is usually based on the fixed structure. Figure 1 is the energy flow relationships of multiple energies in general CCHP systems.

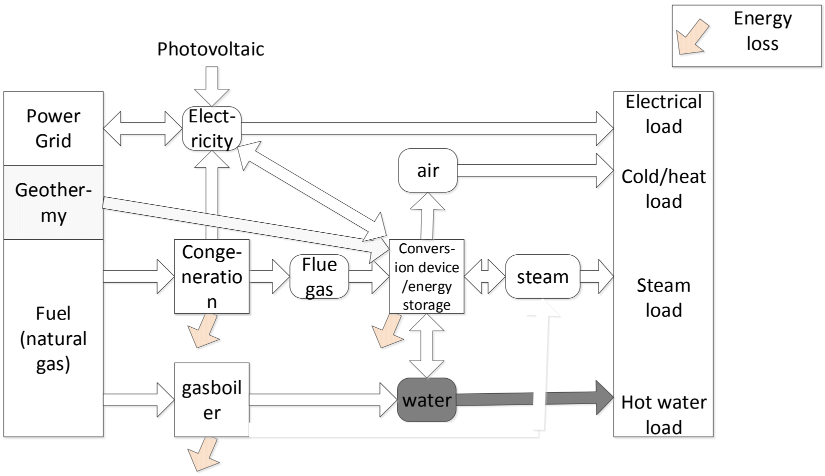


Figure 1. The power flow diagram of general CCHP

3.2. Constraint conditions and the established optimization goal

3.2.1.Equality constraint conditions. The energy balance constraints of CCHP scheduling model can be listed based on the composition and structure of the system. The inflow instantaneous energy of the electric bus is consists of photovoltaic output $P_{PV}(t)$ and output power of CCHP system $P_{PGU}(t)$; Outflows of electric bus are electricity load $L_E(t)$, devices supplying cool storage $P_{CS,C}(t)$, devices powering the heat pump $P_{HP}(t)$ and devices used for electric refrigeration $P_{EC}(t)$. Devices switching power with electric bus are power grid $P_{grid}(t)$ and electric energy storage device $P_{ES,C}(t)$. According to the electric bus energy exchange relationship at time t, the following electric bus balance equations are obtained:

$$P_{grid}(t)+P_{PGU}(t)+P_{PV}(t)+P_{ES,D}(t)= \\ L_E(t)+P_{EC}(t)+P_{HP}(t)+P_{CS,C}(t)+P_{ES,C}(t) \tag{4}$$

There is only flue gas from CCHP generator in flue gas bus input $Q_{PGU,smoke}(t)$ ($\lambda_{PGU,smoke}$ is the ratio of thermoelectric and electricity of CCHP). The output end consists of the gas that flow into temperature machine $Q_{CH,smoke}(t)$,the gas provided for absorption refrigerants $Q_{AC,smoke}(t)$,the gas recovered by waste heat $Q_{WH,smoke}(t)$, and the gas that flow into the heat exchange device $Q_{HX,smoke}(t)$.

Equation of flue gas bus at time t is as follows:

$$\lambda_{PGU,smoke}\ \ Q_{PGU,smoke}(t)=Q_{AC,smoke}(t)+Q_{HX,smoke}(t)+Q_{WH,smoke}(t)+Q_{CH,smoke}(t) \tag{5}$$

The steam recovered by waste heat $Q_{WH,steam}(t)$ ($\beta_{WH,smoke}$ is the recovery efficiency of waste heat) and the steam produced by gas boiler $Q_{GB,steam}(t)$ is input of steaming bus. Input of steaming bus consists of steaming heat load that can be directly used $L_{TS}(t)$, $Q_{AC,steam}(t)$ that supply absorption chiller, $Q_{HS,C}(t)/Q_{HS,D}(t)$ that flow into the heat storage device, and $Q_{HX,steam}(t)$ that is used by heat exchange device.

Equation of steaming bus at time t:

$$\beta_{WH,smoke}Q_{WH,smoke}(t)+Q_{GB,steam}(t)+Q_{HS,D}(t)= \\ L_{TS}(t)+Q_{AC,steam}(t)+Q_{HX,steam}(t)+Q_{HS,C}(t) \tag{6}$$

Flue gas pipe and hot water pipe flow into the hot water bus after the heat exchange, including output of heat exchange device $Q_{HX,steam}(t)$ and $Q_{HX,smoke}(t)$ ($\beta_{HX,steam}$ and $\beta_{HX,smoke}$ are efficiency of heat exchange device), output of gas boiler $Q_{GB,water}(t)$,output of CCHP generator $P_{PGU,water}(t)$; The hot water that absorption chiller uses $Q_{AC,water}(t)$, the hot water that temperature machine uses $Q_{CH,water}(t)$ and hot water load $L_{TW}(t)$ are the other side of balance.

Equation of hot water bus at time t is as follows:

$$\begin{aligned}&\lambda_{PGU,water}P_{PGU}(t)+\beta_{HX,smoke}Q_{HX,smoke}(t)+Q_{GB,water}(t)\\&+\beta_{HX,steam}Q_{HX,steam}(t)=L_{TW}(t)+Q_{AC,water}(t)+Q_{CH,water}(t)\end{aligned} \tag{7}$$

Due to supplying cooling and heating load in practical system is generally not in the same time, the two parts (cold and warm) adopt unified air bus. Input side of air bus consists of the following parts: $Q_{CS,D}(t)$ that cool storage devices generate, $COP_{HP,cool}P_{HP,cool}(t)$ （ $COP_{HP,heat}P_{HP,heat}(t)$ ） that pumps produce, $COP_{CH,cool}Q_{CH,cool}(t)$ （ $COP_{CH,heat}Q_{CH,heat}(t)$ ） from the chiller, $\beta_{AC}Q_{AC}(t)$ from the absorption refrigerating machine and $COP_{EC}P_{EC}(t)$ from the electric refrigerator. Output side of air bus consists of cooling load $L_{CA}(t)$, and the heating load $L_{TA}(t)$.

Equation of single bus at time t is as follows:

$$\begin{cases}COP_{EC}P_{EC}(t)+COP_{HP,cool}P_{HP,cool}(t)+Q_{CS,D}(t)+\beta_{AC}Q_{AC}(t)+COP_{CH,cool}Q_{CH,cool}(t)=L_{CA}(t)\\COP_{HP,heat}P_{HP,heat}(t)+COP_{CH,heat}Q_{CH,heat}(t)=L_{HA}(t)\end{cases} \tag{8}$$

3.2.2.Inequality constraints. Energy balance equations in the bus need to be satisfied in scheduling system, and the impact of constraints on the device itself is also need to be analysed, including storage constraints and charging and discharging of energy storage equipment, upper and lower bounds of power equipment. Constraints of equipment are as follows:

The equations that satisfy upper and lower bounds of equipment power:

$$\begin{cases}P_{i\min}\le P_i\le P_{i\max}\\Q_{i\min}\le Q_i\le Q_{i\max}\end{cases} \tag{9}$$

Where P_i is electric power of equipment i; Q_i is thermal power of equipment i; $P_{\min}$ and $P_{\max}$ are upper and lower limits on electric power of equipment i ; $Q_{\min}$ and $Q_{\max}$ are upper and lower limits on thermal power of equipment i.

For energy storage equipment, the constraints of storage energy and charging and discharging power should be satisfied at the same time. Take battery as an example:

- Constraints of battery discharging:

$$0\le P_{ES,D}\le Cap_{ES}\gamma_{ES,D} \tag{10}$$

Where $\gamma_{ES,D}$ is the maximum discharging power; Cap_{ES} is the battery capacity.

- Constraints of battery charging:

$$0\le P_{ES,C}\le Cap_{ES}\gamma_{ES,C} \tag{11}$$

Where $\gamma_{ES,C}$ is the maximum charging rate.

- Constraints of battery energy storage:

$$W_{ES,\min}\le W_{ES}\le W_{ES,\max} \tag{12}$$

Where $W_{ES,\min}$ is the minimum battery energy storage; $W_{ES,\max}$ is the biggest battery energy storage.

The battery energy storage quantity W_{ES} varies from the duration of the storage battery charging and discharging, the changing of efficiency and power. The following equation holds:

$$W_{ES}^{1} = W_{ES}^{0}(1-\sigma_{ES}) + \left(P_{ES,C}\beta_{ES,C} - \frac{P_{ES,D}}{\beta_{ES,D}} \right)\Delta t \tag{13}$$

Where σ_{ES} is self-discharge rate; $\beta_{ES,C}$ is the charging efficiency; $\beta_{ES,D}$ is the discharge efficiency; W_{ES}^{1} is the battery energy storage after charging and discharging, $kW \cdot h$; W_{ES}^{0} is the battery energy storage before charging and discharging, $kW \cdot h$; Δt is the simulation wavelength, h.

3.2.3.The optimization goal to be established. In order to satisfy the requirement of economy, energy saving and environmental protection, the CCHP system optimization scheduling mode makes maintaining the system operation cost as the starting point, and building dynamic economic dispatch model as the optimization goal. From an environmental point of view, the minimum emission of carbon dioxide is built as the optimization goal. From the viewpoint of energy saving, the minimum consumption of primary energy is built as the optimization goal.

- The dynamic economic objective function:

$$C = \min(C_{ae} + C_{tf}) \tag{14}$$

Where C_{tf} is the cost of purchasing natural gas, yuan; C_{ae} is the payment of purchasing electricity in total, yuan. C is the cost of system operation in total, yuan.

The formula of buying gas is shown as follows:

$$C_{tf} = c_{fc}\sum_{t=1}^{H}(F_{PGU}^{t} + F_{GB}^{t}) = c_{fc}\sum_{t=1}^{H}(\frac{P_{PGU}^{t}}{\beta_{PGU}} + \frac{Q_{GB}^{t}}{\beta_{GB}})\Delta t \tag{15}$$

Where H is the number of scheduling period, and 24 is chosen in this paper. c_{fc} is the calorific value unit price of natural gas in location of the system, yuan / $kW \cdot h$; F_{PGU}^{t} is the fuel gas calorific value of generators at duration t， $kW \cdot h$; F_{GB}^{t} is the fuel gas calorific value of gas boiler at duration t, $kW \cdot h$; P_{PGU}^{t} is the power generating power of generators at duration t, kW ; Q_{GB}^{t} is the thermal production power of gas boiler at duration t, kW ; β_{PGU} is the power generation efficiency of generators; β_{GB} is the thermal production efficiency of gas boiler.

The formula of the payment on purchasing electricity is shown as follows:

$$C_{ae} = \sum_{t=1}^{H}(c_{ec}^{t} P_{grid}^{t} \Delta t) \tag{16}$$

Where c_{ec}^{t} is the time-sharing electricity price, yuan / $kW \cdot h$; P_{grid}^{t} is the amount of electricity that is purchased from the grid at duration t, kW.

- Objective function on environmental benefits

To save oil, coal and other non-renewable energy and reduce emissions of greenhouse gas and harmful gas, the emissions of carbon dioxide is made as the measurement index of environmental protection and the minimum emissions of carbon dioxide is made as the objective function.

$$CDE = \min(CDE_{CCHP}) \tag{17}$$

$$CDE_{CCHP}=\begin{cases}P_{grid}\cdot\varphi_{grid}+P_{PGU}\cdot\varphi_{PGU}+P_{GB}\cdot\varphi_{GB}(P_{grid}>0)\\ P_{PGU}\cdot\varphi_{PGU}+P_{GB}\cdot\varphi_{GB}(P_{grid}\le 0)\end{cases}\tag{18}$$

- Objective function on energy saving index

$$PEC=\min(PEC_{CCHP})\tag{19}$$

$$PEC_{CCHP}=\begin{cases}P_{grid}\mu_{grid}+(P_{PGU}+P_{GB})\mu_f(P_{grid}>0)\\ (P_{PGU}+P_{GB})\mu_f(P_{\mathrm{grid}}\le 0)\end{cases}\tag{20}$$

Where μ_{grid} is the conversion coefficient of primary energy in the power grid; μ_f is the conversion coefficient of primary energy in natural gas.

4. Case analysis

Data in this paper comes from a CCHP system which contains the photovoltaic. The CCHP system is nested within an office building, and consists of the following parts: photovoltaic components with peak capacity of 50KW, two micro gas turbine with maximum power of 55KW, an electric refrigeration system with maximum power of 300KW, a gas boiler with maximum power of 120KW, a steaming hot water exchanging device and a waste heat recovery unit with maximum power of 300KW, a battery with energy storage capacity of 200KW.h, and a set of heat storage system with power of 400KW·h. The specific parameter of these equipments are shown in table 1.

Table 1. The parameters of system equipments.

Parameters	Values	Parameters	Values
Electric refrigerator COP_{EC}	4	Efficiency of battery discharging $\eta_{ES,D}$	0.95
Efficiency of gas boiler $\eta_{GB,water}$	0.9	Maximum rate of battery charging $\gamma_{ES,C}$	0.2
Efficiency of steaming hot water exchanging device $\eta_{WH,smoke}$	0.9	Maximum rate of battery discharging $\gamma_{ES,D}$	0.4
Absorption chiller η_{AC}	0.7	Battery self-discharge rate σ_{ES}	0.04
Efficiency of gas turbine η_{PGU}	0.6	Maximum energy storage of battery $W_{ES,\max}$	0.9 Cap_{ES}
Efficiency of waste heat boiler $\eta_{GB,smoke}$	0.73	Minimum energy storage of battery $W_{ES,\min}$	0.1 Cap_{ES}
Efficiency of battery charging $\eta_{ES,C}$	0.95		

The energy flow relationship of all the equipment is shown in figure 2, and it's a structure diagram in bus style. The coupling relationship and the connection relationship in each equipment can be figured out directly, and the process of energy flow and conversion between different media can be seen distinctly, too.

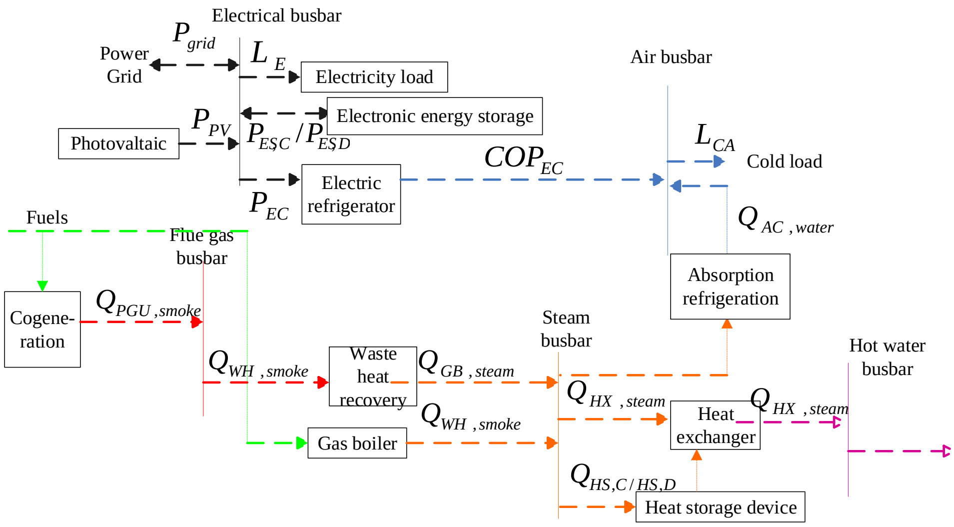
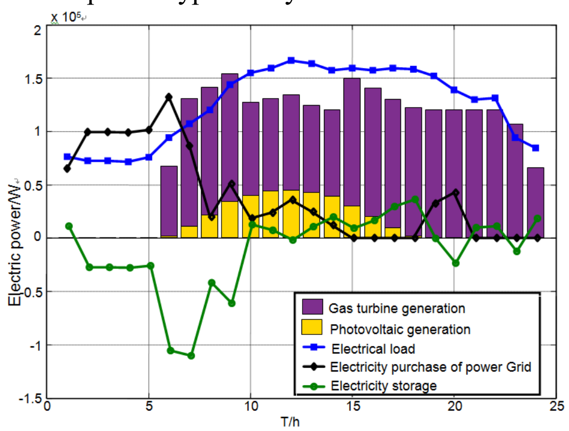
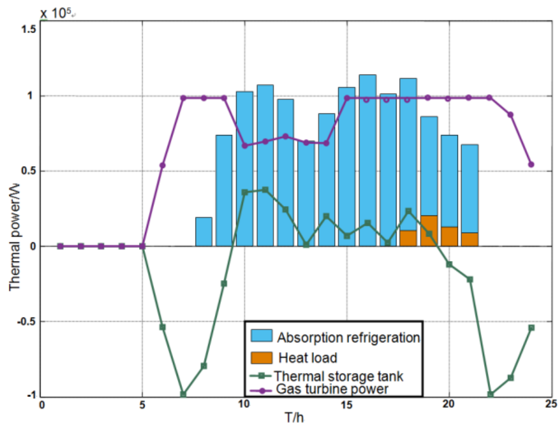


Figure 2. The structure of demonstration park bus type

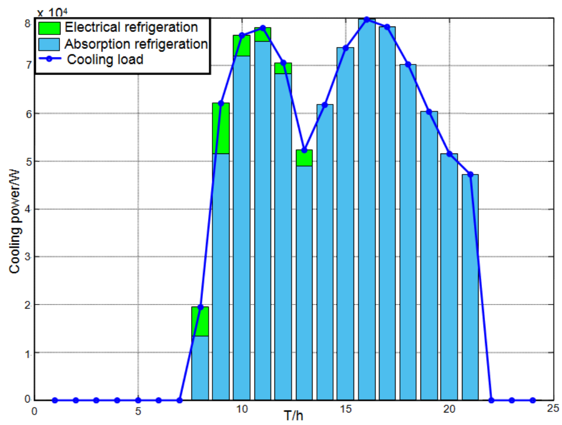
Stipulate that 10:00~15:00 and 19:00~20:00 are rush-hours. 15:00~19:00 and 19:00~23:00 are peak hours. Other times are valley duration. Figure3 (a)-(e), respectively, are the thermal equilibrium diagram, thermal equilibrium diagram and cold equilibrium diagram in summer and winter of CCHP under optimal typical day.

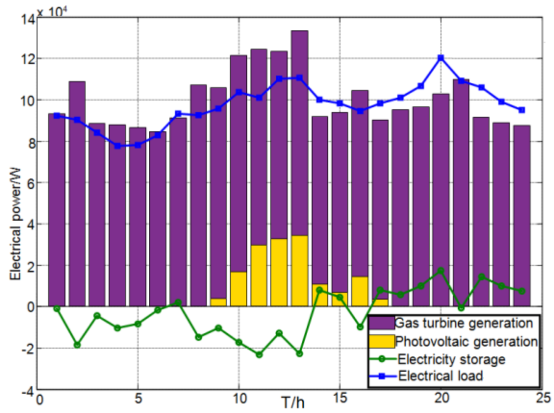


(a) The electric equilibrium diagram of optimal strategy of the typical day of the system for the transition of the system in the summer

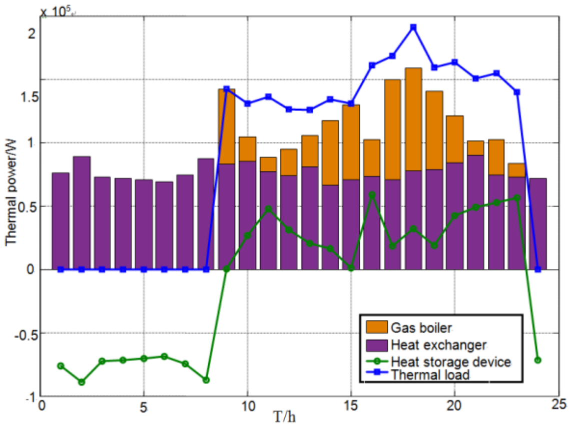


(b) The heat equilibrium diagram of optimal strategy of the typical day of the system for the transition of the system in the summer





(c) The cool equilibrium diagram of optimal strategy of the typical day of the system for the transition of the system in the summer



(d) The electric equilibrium diagram of optimal strategy of the typical day of the system for the transition of the system in the winner

(e) The heat equilibrium diagram of optimal strategy of the typical day of the system for the transition of the system in the winner

Figure 3. Equilibrium diagram under optimal typical day in winter and summer

It can be seen from figure 3 that with the effect of the load data prediction model and the optimal scheduling model, the CCHP system can provide an economical and suitable operation strategy that can well meet the load demand.

5. Conclusion

Distributed CCHP can carry on the cascade utilization of various energies. CCHP equipment is made as the core of the system, and renewable energy such as the photovoltaic is made as supplementary of the system. Time series characteristic of uncertainty is analysed from the perspective of the load and photovoltaic output. A one-dimensional time series is expanded to multidimensional by the chaos principle, and the rules implied in multidimensional space are studied by the dynamic fuzzy neural network to make the fitting network predict the change of the uncertainty in next day. The effectiveness of the model in this paper is verified by the experimental results.

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