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Multi-Objective Optimal Operation of Micro-Grid Based on Demand Side Management

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Abstract. In view of the demand response scheme referring the economic operation of the distributed generation system, a comprehensive mathematical model is established, which takes into account of fuel cost, operation management cost, grid interactive cost, the compensation cost of interruptible load outage, the cost of the demand side electricity charge, etc. In order to realize the effective interaction of energy, the demand response model is introduced to the optimization model. In this paper, the Bacterial foraging optimization algorithm (BFOA) optimized flower pollination algorithm is proposed to solve the optimization model. The model and algorithm presented in this paper are proved to be scientific and effective by case analysis.

1. Introduction

with the gradual depletion of fossil fuels, as well as the environmental pollution and climate change brought about by traditional energy exploitation and utilization, it has become the core content and inevitable choice of China's energy revolution to ensure energy supply and energy security by large-scale R&D of renewable energy, increasing energy-using efficiency and reducing pollution emission[1,2]. with the development and perfection of electric power market, the interest subject of power system will be diversified gradually, and the management of DSM resources is being recognized. At present, the optimization of distributed generation system has been studied in literatures from home and abroad. The literature [3] sets up a complete and detailed system steady-state mathematical model based on the distributed heating and cooling of co-generation system. In literature [4], based on the mathematical models of the various equipment of distributed generation system, the optimal model of the co-generation system running with the minimum cost of typical daily operating as the objective function is established. What's more, the linear programming method and the dynamic programming method are chosen as the optimization algorithm for the model solution. Literature [5] carries out modeling and simulation of distributed generation system. Based on the targets of system economy, eco-friendly feature, and primary energy saving rate, the residential and office buildings are optimized respectively; literature [6] establishes the optimal coordination model of cooling and heating power co-generation based on the complementary power generation of wind energy, solar energy, natural gas, and energy storage, which also considers different rate structures. And literature [7] constructs the distributed generation system and conventional system analysis model with the goal of operating cost, and analyzes the relevant policies and incentives that affect the economy of the distributed generation system.

Gathered from the above, there is hardly ever any study considers the demand-side adjustable resources, the large grid interactive, and distributed generation system at the same time. In order to promote the development of energy Internet in our country, this paper proceeds from the economic optimization research of distributed generation system. With the perspectives of the cost of electricity generation, the environmental cost and the standby cost these three aspects, this study has established the economic optimization model of distributed generation system which is comprehensively compatible with the demand side controllable resources and fully considers the electric load, thermal load and cooling load in the distributed generation system.

2. The optimization model of distributed generation system based on demand-side response

Distributed generation system generally refers to small energy systems [8], isolated or connected only to distribution networks, using clean fossil fuels such as renewable energy or natural gas. In which, the cooling and heating power co-generation system is one of the most commonly used technologies in distributed generation system [9]. In view of energy Internet, distributed generation is a subscriber terminal, through which a plurality of local distribution networks can be formed, thereby realizing the power transmission in the local area and exchanging energy with the centralized power grid, so as to provide support and supplement to the central energy supply system.[10]

Based on the demand response of excitation, interruptible load model is selected in this paper. During the peak time of the load, the system cannot meet the load demand independently and interact with the distribution network. Therefore load outage contract will be signed with large industrial users, and the compensation price is of 2 yuan K W·h. Based on the demand response of price, the real-time electricity price model is used in this paper. The electricity price and the electricity demand mathematics are in an inverse proportion:

The electricity price of large industrial users is:

$$P=\begin{cases}1+0.6641(1-e)^{3.08}, 0<e<1\\ 1-0.9643(e-1)^{3.25}, e\geq 1\end{cases} \tag{1}$$

The electricity price of non/normal industrial users is:

$$P=1.2532-0.4121e \tag{2}$$

In the formula, e is the per-unit value of real-time electricity price compared to the standard electricity price

$$\eta(t)=\frac{P_L(t)}{\sum_{i=1}^{H}P_L(i)} \tag{3}$$

Short period is 1h; the time period is divided by 1d, H is the number of time intervals divided in a daily basis, and $P_L(t)$ is the amount of load in t-period.

$$\Delta\eta(t)=\frac{\eta(t+1)}{\eta(t)} \tag{4}$$

$$e(t)=\mu(\eta(t)+\lambda)^2+\varepsilon \tag{5}$$

In which, $\mu>0$, and $\lambda>0$; ε is any tunable parameter.

This section takes the daily running cost of distributed generation system as the target, considering the fuel cost, operation and management cost, grid interactive cost, load outage compensation cost and demand side electric charge expense, the following models are established with power balance and output limit of power generation unit as the constraint conditions:

$$\min F_{\cos t}=C_G+k_1C_{grid}+k_2C_L+C_{load} \tag{6}$$

$$C_G=\sum_{i=1}^{N}\left[C_{fuel}^{i}(P_{it})+K_{op}^{i}P_{it}\right] \tag{7}$$

$$C_{grid} = e_b Q_{bt} - e_{st} Q_{st} \tag{8}$$

$$C_L = \sum_{j=1}^{M} e_{Lt}^j Q_{L,t}^j \tag{9}$$

$$C_{load} = \sum_{j=1}^{M} e_{jt} Q_{jt} \tag{10}$$

$$\begin{cases} \sum_{i=1}^{N} P_{it} + P_{grid}^t = \sum_{j=1}^{M} P_{L,t}^j \\ P_i^{\min} \le P_{it} \le P_i^{\max} \end{cases} \tag{11}$$

In which

C_G is the dispatch cost, fuel cost of the power generation unit, and operation & management cost;

C_{grid} is the interactive cost with distribution network;

C_L is the compensation cost of interruptible load outage;

C_{load} is the electricity expenditure on demand side;

k_1 and k_2 are cost consideration factors; 1 will be set if the item is taken into consideration, otherwise it shall be 0;

i is the number of the distributed generation Unit, which is set as 1~N ;

t is running time;

P_{it} is the power output of the No. i generation unit at the time t, KW;

C_{fuel}^i is the cost of fuel consumption for the operation of No. i generation unit, Yuan/h

K_{op}^i is the operating management cost factor for the No.i generation unit;

j is the number of power users' types, which is set as 1~m; in this article, M is set as 4;

e_{jt} is the electricity price of the J-type power user at the time t, yuan/kW.h;

Q_{jt} is the electricity consumption of the J-type power user at the time t, kW;

$e_{b,t}$ and $e_{s,t}$ are the` prices of purchasing and selling electricity from the distribution network at t-time respectively, Yuan/ kW.h;

$Q_{b,t}$ and $Q_{s,t}$ are the amount of electricity purchased and sold by the system to the distribution network at t-time, kW;

$e_{L,t}^j$ is the compensation electricity price of type-j for interruptible load at the time t, Yuan/kW.h;

$Q_{L,t}^j$ is the amount of interrupted load at the time t, kW;

P_t^{grid} is the capacity of the interactive between the system and distribution network at the time t. This paper defines the power supply from the distribution network to the system is positive, conversely is negative, kW;

$P_{L,t}^j$ is the electricity load of j-type power user at the time t, kW;

$P_i^{\max}$ and $P_i^{\min}$ are the upper and lower limits of the active power of the No.i generation unit, kW.

3. Example analysis and simulation

This paper takes the summer typical daily as an example to verify the validity of the algorithm and the theory; the load and cooling load of various industries before the optimization are as shown in Fig. 1.

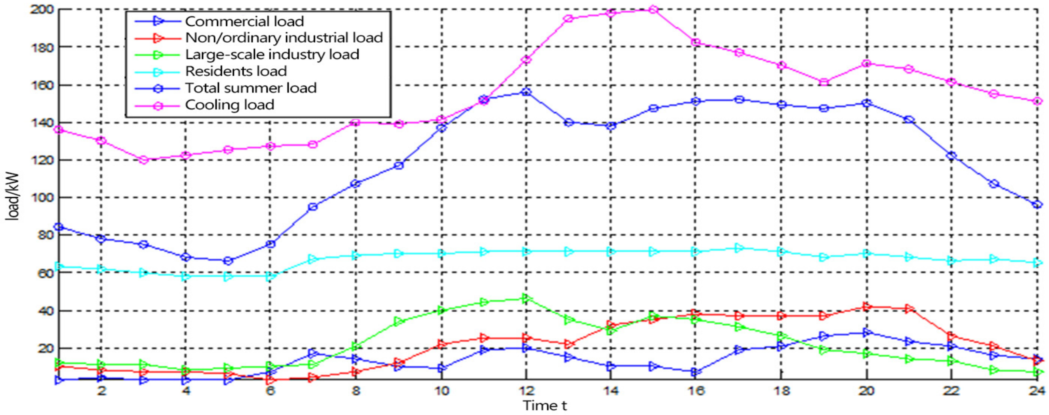

Fig. 1 Summer typical daily cooling load and various industry load curves

The real-time electricity price is executed with the unit of 1h, and its standard price is shown in Figure 2.

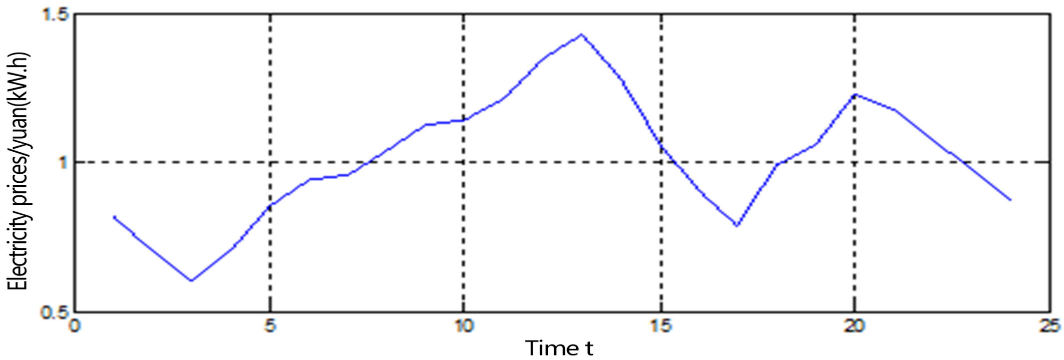

Fig. 2 Real-time electricity price and standard electricity price

The parameters of the bacterial foraging algorithm optimized pollination algorithm are as follows:

The bacterial foraging algorithm parameters: the population quantity sizepop equals 20, the chemotaxis times Nc=50, the swarm frequency Ns=4, the replication times Nre=6, scatters (migrations) times Ned=4, replication (divides) times Sr=10, migration probability Ped=0.25, the smallest step length of bacterial individual overturn Cmin =-2, and the maximum step Cmax=2; in the flower pollination algorithm, the approximate probability p=0.6, and $\lambda = 1.5$;

In this discussion k1=1, k2=0; k1=0, k2=1; k1=1, k2=1; the synchronized drawing is as follows:

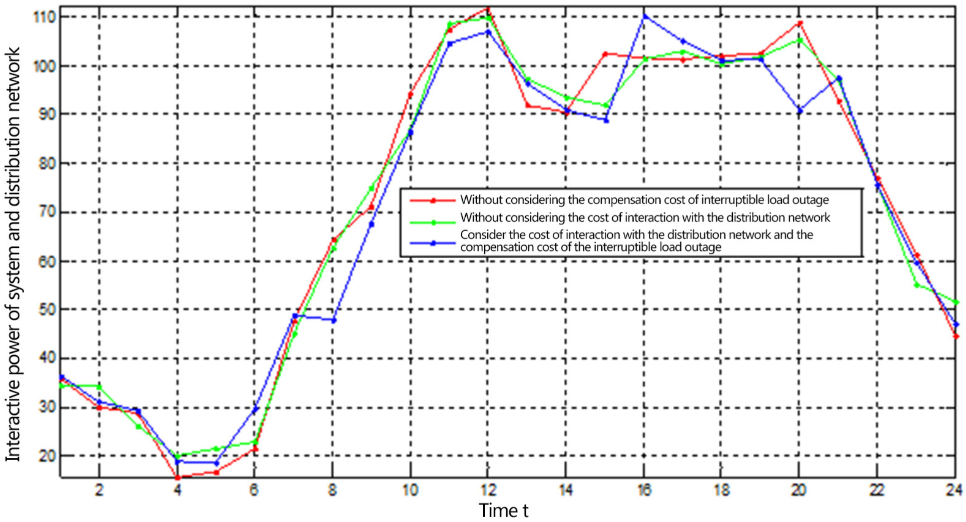

Figure 3 Comparison display

From Fig. 3, it can be seen that the implementation of real-time electricity price increases the load rate of the power grid during the valley period, and the load of the peak period is also relieved, which has a certain stimulating effect on the users, and has good ability of regulating the peak and valley. The Green line in the image is available and the interruptible load is considered to be able to alleviate the peak-valley difference.

4. Demand response model considering generation cost and environmental cost

The economic optimization model of distributed generation system in this paper is based on the condition that the system satisfies the normal operation and load cancellation of each distributed generation. Through reasonable planning and arrangement of each unit's output plan and timely load adjustment, the total operating cost of distributed generation system can be minimized. The model is a complex and nonlinear multi-objective optimization subject, with economic operation mainly takes into account economic cost, environmental cost and the standby cost of distributed generation, and the consideration of the demand side adjustable resource is mainly embodied in demand side load constraint.

Power Cost:

$$\min C_F=\sum_{t=1}^{N}\sum_{i=1}^{M}\left[c_f F_i(P_i)+O_i(P_i)+C_{dep}(P_i)\right]+\sum_{t=1}^{N}\left[C_{buy}(t)-C_{sell}(t)\right]P_{grid}(t) \tag{12}$$

N is the total number of periods calculated, N=24; c_f is the fuel price;

$F_i(P_i)$ represents the fuel consumption of the machine set $F_i(P_i)=C_{st}(P_i)+C_{op}(P_i)$,

$C_{st}(P_i)$ is the fuel used for generating units;

$C_{op}(P_i)$ is the fuel used in the start-up of the Unit;

$O_i(P_i)$ is the operation and maintenance cost of the unit set, $O_i(P_i)=k_o(P_i)P_i\Delta t$, $k_o(P_i)$ is the operation and maintenance parameters.

P_i is the output power;

$C_{dep}(P_i)$ represents the unit's depreciation cost, $C_{dep}(P_i)=\dfrac{C_I f_{cr}}{P_{cr}\tau}$, C_I is the installation cost of the generator, f_{cr} is the capital recovery factor, P_{cr} is the generator's rated power, and τ is the maximum use of hours;

$C_{buy}\left(t\right)$ represents the electricity purchase price of the at t-time period, $C_{sell}\left(t\right)$ means the feed-in tariff at t-time period;

$P_{grid}\left(t\right)$ is the power value in the power network exchange at t-time period;

Environmental costs:

$$\min \quad C_H = \sum_{t=0}^{N}\sum_{k=1}^{M} 10^3 \beta_k \sum_{i=1}^{M} \alpha_{ik} P_i\left(t\right) + \alpha_{grid,k} P_{grid}\left(t\right) \tag{13}$$

In the formula: C_H is the harness cost of pollution disposal, k is the pollutant type number, and α_{ik} is the pollutant emission coefficient of different types of unit sets;

$\alpha_{grid,k}$ is the pollutant emission coefficient of system generation; β_k is the cost needed for pollution control

The constraint equation is as follows:

1) System energy balance constraint:

$$\begin{cases} \sum_{i=1}^{M} P_i\left(t\right) + P_s\left(t\right) + P_w\left(t\right) + P_{batt}\left(t\right) + P_{grid}\left(t\right) = \tilde{P}\left(t\right) \\ \sum_{k=1}^{n_1} W_{MT,k} + \sum_{l=1}^{n_2} W_{RT,l} = W_D \\ \sum_{m1=1}^{N_1} P_{m1}^{E_c}\left(t\right) + \sum_{m2=1}^{N_2} P_{m2}^{Ab}\left(t\right) = P_D\left(t\right) \end{cases} \tag{14}$$

In the formula: $P_i\left(t\right)$ is the power of the No.i unit at the t-time, $P_s\left(t\right)$ is the output power from PV, $P_w\left(t\right)$ is the output power from wind power, $P_{grid}\left(t\right)$ is the capacity in the exchange with power network, and $\tilde{P}\left(t\right)$ is the dispatchable output

2) Distributed power output constraint

$$\begin{cases} P_{\min} \le P_i \le P_{\max} \\ 0 \le R_i^{up} \le R_{i,\max}^{up} \\ R_{i,\max}^{down} \le R_i^{down} \le 0 \\ \sum_{i=1}^{N} \left[u_i\left(t\right) - u_i\left(t-1\right) \right] \le N_{i,\max} \\ T_{off,i} \ge T_{off,i,\min} \\ T_{on,i} \ge T_{on,i,\min} \end{cases} \tag{15}$$

In the formula, $P_{\min}$ = 20, and $P_{\max}$ =60 are the minimum/maximum output of the unit; $R_{i,\max}^{up}$ = 10, and $R_{i,\max}^{down}$ =-5 are the maximum climbing rate and the maximum downhill rate of the unit, $u_i\left(t\right)$ is the startup & shutdown state of machine set; $N_{i,\max}$ is the maximum starting times of the unit during the dispatch period =1 (one start-up in a day); $T_{on,i}$ and $T_{off,i}$ are the time of the unit set startup &

shutdown; $T_{off,i,\min}$ =0、and $T_{on,i,\min}$ =0 are the minimum startup & shutdown time of the unit set.

3 Storage battery restraint

$$\begin{cases} 0 \le P_{discharge}(t) \le P_{discharge,\max} \\ 0 \le P_{charge}(t) \le P_{charge,\max} \\ E_{batt,\min} \le E_{batt}(t) \le E_{batt,\max} \\ E_{batt}(0) = E_{batt}(N_t) \\ \sum_{i=1}^{N_t}\left[u_{discharge,i}(t) - u_{discharge,i}(t-1)\right] \le \eta_{1i,\max} \\ \sum_{i=1}^{N_t}\left[u_{charge,i}(t) - u_{charge,i}(t-1)\right] \le \eta_{2i,\max} \end{cases} \quad (16)$$

In the formula, $P_{discharge,\max}$ = 35, and $P_{charge,\max}$ =35 are battery discharge/charging power respectively; $E_{batt,\min}$ and $E_{batt,\max}$ are the minimum and maximum value of the battery storage respectively, $E_{batt}(0)$ and $E_{batt}(N_t)$ are the battery energy storage value of the initial time and the end of the dispatch respectively; $u_{charge,i}(t)$ and $u_{discharge,i}(t)$ are the charge/discharge state of the battery i at time t respectively, and $\eta_{1i,\max}$ and $\eta_{2i,\max}$ are the maximum discharge/charge times of the battery during the dispatch period.

Therefore, at this point, there are three object functions:

Daily running cost of distributed generation system: $\min F_{cost} = C_G + k_1 C_{grid} + k_2 C_L + C_{load}$

Cost of electricity geneneration:min $C_F = \sum_{t=1}^{N}\sum_{i=1}^{M}\left[c_f F_i(P_i) + O_i(P_i) + C_{dep}(P_i)\right] + \sum_{t=1}^{N}\left[C_{buy}(t) - C_{sell}(t)\right]P_{grid}(t)$

Environmental cost：min $C_H = \sum_{t=0}^{N}\sum_{k=1}^{M}10^3\beta_k\sum_{i=1}^{M}\alpha_{ik}P_i(t) + \alpha_{grid,k}P_{grid}(t)$

Pareto solution of the bacterial foraging algorithm optimized flower pollination algorithm:

Parameter initialization settings: target number is 3, the population number is sizepop=300, the population number of non-dominated solution, repository=150, the solution domain size of each target function expands nGrid=7, the solution set extension factors of non-dominated solution alpha=0.1, the selection factors of the non-dominant solution beta= 2; the bacterial foraging algorithm parameters include: the number of chemotaxis Nc=6, the swarm times Ns=4, replication times Nre=6, disperse (migration) times Ned=4, replication (division) times Sr=150, migration probability Ped=0.25, minimum step length of bacterial individual turnover Cmin=-10, and the maximum step length Cmax= 10. In the flower pollination algorithm, the approximate probability p=0.6，and λ =1.5；Pareto solution set is shown in Figure 4.

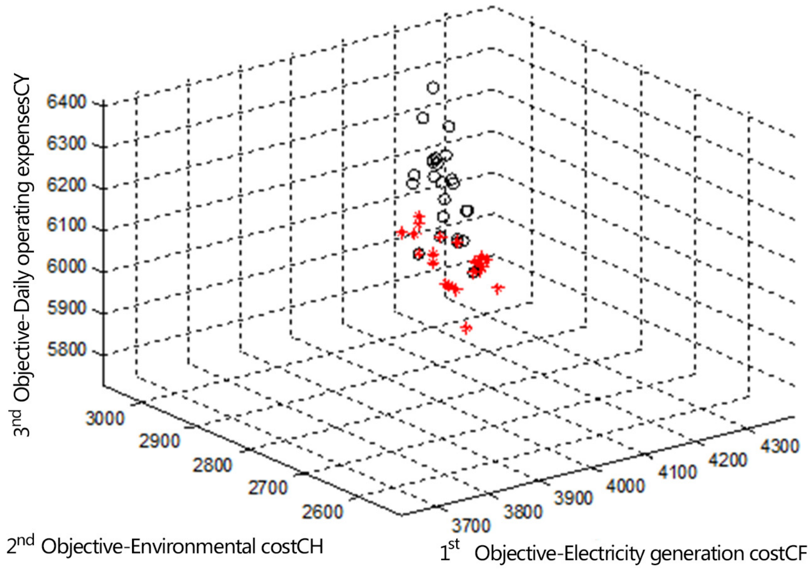

Fig. 4 Pareto solution

As shown in Fig. 5, the red dots represent the non-dominated solution, i.e. the Pareto solution set; the black circles are the solution set of optimal population. In this paper, the load balancing algorithm under the optimal solution of the three-target is considered, the optimal population in Pareto solution set is chosen as the final solution set. Here we set the weight factors as ξ_1=0.35 、 ξ_2=0.25 , and ξ_3=0.4， that is $\min = \left(\xi_1 \cdot F_{cost} + \xi_2 \cdot C_F + \xi_3 \cdot C_H\right)_{min}$ 。

Using the weights sum of the total coast of Pareto solution set $\left(\xi_1 \cdot F_{cost} + \xi_2 \cdot C_F + \xi_3 \cdot C_H\right)$, the schematic diagram shown in Fig. 5 can be obtained.

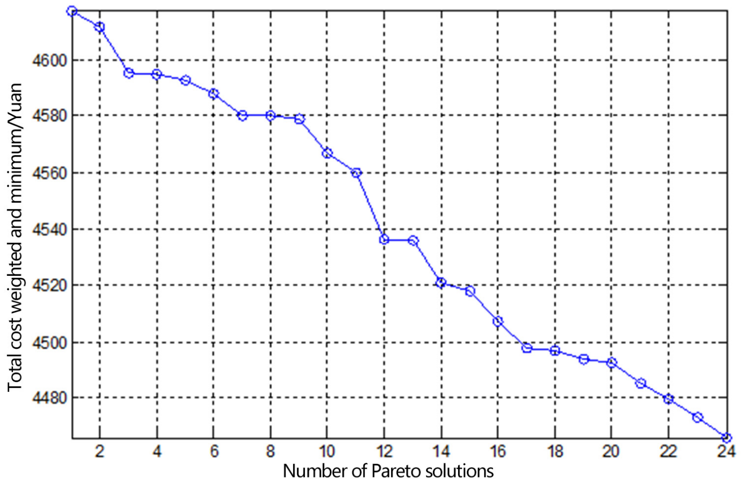

Fig. 5 The weights sum of the total coast of Pareto solution set and schematic

The load curve under the minimum cost weight sum is obtained, as shown in Figure 6.

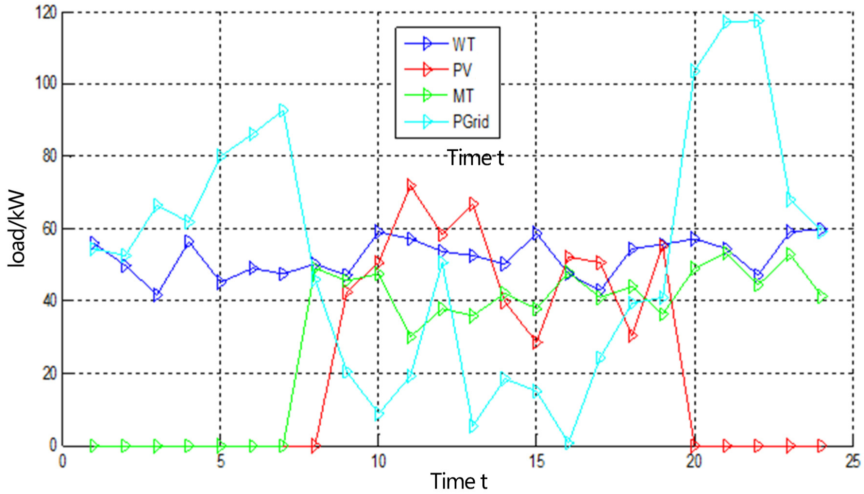

Figure 6 Load curve

As shown in Figure 7, the gas-fired generator is set up at 8:00; and the stable power output is carried on from 12:00 to 23:00, which is because that the power generation cost of gas-fired generator in the peak period is lower than electricity price, while in the valley period, the power generation cost of gas-fired generator is higher than the electricity price; so, during 0:00-7:00, gas-fired power does not provide any power output, and the power output of the period is mainly provided by the power grid. The power generation cost of fuel cell is lower than electricity price during the peak period, and it is higher than electricity price in the valley period, so the power output is not provided during the period of 0:00-7:00, and from 8:00 to 23:00, the output power is continuously steady. The power output time of PV power generation starts from 7:00 and does not provide any power output at night; Wind power provides output at a steady manner almost all day. The storage battery discharge in peak period, and be charged during the valley time, which fully uses the peak-and-valley-difference electricity price to reduce costs. In other stages, it almost has no output, which can reduce the battery loss by charge and discharge.

5. Conclusion

1)This paper studies the economic optimization of distributed generation system, comprehensively considers the cost of electricity generation, environmental cost and daily running cost these three perspectives, and establishes the distributed generation system economic optimization model of compatible demand side controllable resources, with fully consideration of the electrical load, thermal load and cooling load in distributed generation system.

2) Compared with bacterial foraging algorithm and flower pollination algorithm, the proposed algorithm in this paper has better global searching ability and can traverse the search space in a shorter time, so as to find the optimal result effectively, thereby avoiding the situation that the algorithm tends to be trapped in local optimal situation.

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