Optimization of joint energy micro-grid with cold storage

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Abstract. To accommodate distributed photovoltaic (PV) curtailment, to make full use of the joint energy micro-grid with cold storage, and to reduce the high operating costs, the economic dispatch of joint energy micro-grid load is particularly important. Considering the different prices during the peak and valley durations, an optimization model is established, which takes the minimum production costs and PV curtailment fluctuations as the objectives. Linear weighted sum method and genetic-taboo Particle Swarm Optimization (PSO) algorithm are used to solve the optimization model, to obtain optimal power supply output. Taking the garlic market in Henan as an example, the simulation results show that considering distributed PV and different prices in different time durations, the optimization strategies are able to reduce the operating costs and accommodate PV power efficiently.

1. Introduction

Energy micro-grid is an important and promising development direction in the future, and it is an inevitable choice for large commercial and industrial users to achieve efficient and economical energy consumption. It is necessary to reform energy systems and to build the energy internet by stablishing a universal energy supply system, realizing the long-term sustainable development of energy supply, accomplishing the energy technology revolution, and upgrading the energy industry. At present, the rapid development and high penetration of photovoltaic (PV) in northern China have brought many problems, such as solar power curtailment. Energy micro-grid system is considered as a good solution. The system contains a variety of joint energy micro-grids, composed by a number of distributed energy sources (DESs) and controllable loads. It is able to improve the energy consumption efficiency through complementary and alternative energy sources. This can fully develop the potential users and accommodate the PV power to the maximum [1]. Thus, such system can be regarded as a new energy supply system.

Continental climate in northern China has led to fast development of cold storage for fresh fruits and vegetables. The cold storage refrigeration energy consumption accounted for the most of the total energy consumption. At the same time, to ensure the cooling effect and to reduce the total energy consumption can effectively reduce the operating cost.

Current literatures mainly focus on the economic operation and optimal dispatch of joint energy micro-grids [2]. [3] proposes a linear searching method as an optimization model for combined cold, heat and power (CCHP), considering electricity tariff. [4] focuses on CO2 emission reduction and it is effectively applied to CCHP. [5] proposes a new energy management system based on multi-objective optimization according to the study the energy systems of the commercial buildings, reducing the cost in production and environmental impacts. [6] takes the minimum cost of energy management as the goal and sets up the random optimum mathematical model of demand-side and two-stage of prices in energy market. In summary, the existing literatures are lack of the integrated study of the energy micro-grid with DES and cold storage. Most of the cases are from hypothesis and thus be limited by practical application.

The optimization of joint energy micro-grid with cold storage is a non-linear, time-variable, and multi-objective problem. Multi-objective optimization is usually transferred as single objective optimization to be solved [7-9]. [10] proposed a two-stage optimization strategy for CCHP. The first stage considers the economic model and the second stage considers power fluctuations. [11] used the improved Particle Swarm Optimization (PSO) algorithm. [12] took the environmental and economic factors as objectives. The literature above lacks the comparison of the results between the single objective optimization and multi-objective optimization. In addition, there are always the locally optimal solutions.

This paper takes a real cold storage in Henan as an example, as shown in Figure 1. The example energy micro-grid includes combined heat and power (CHP), PV, thermal storage, cold storage, battery energy storage, and office buildings. This paper focuses on the optimal operation of such typical cold storages in China. Since all of the elements in this energy micro-grid, the parameters and operational characteristics are obtained from realistic attributes, measurement, and practice. Compared with numerous existing simulation-based analyses, this paper would provide practical and feasible operation strategies for the energy micro-grid operator to achieve the maximum financial benefits, as well as the most wind and solar provision.

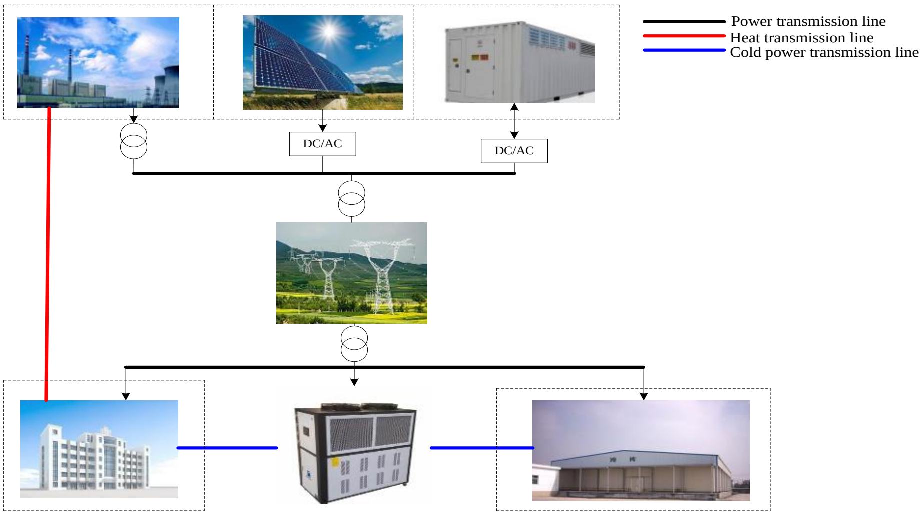

Figure 1. Joint energy micro-grid with cold storage.

This paper firstly establishes the mathematical models of the example energy micro-grid with the consideration of multi-energy of cold, heat and electricity. Two objectives, which are minimum total operating cost and minimum fluctuation of solar curtailment accommodation, are considered in the optimization model. The remains of this paper is organized as follows. Section 2 demonstrates the proposed optimization model. Next, Section 3 introduces the linear model of multi-objective optimization. Afterwards, Section 4 presents the proposed genetic-taboo PSO algorithm. Then, Section 5 provides the case studies. Finally, Section 6 concludes this paper.

2. Mathematical model of the joint energy micro-grid system with cold storage

2.1. Optimization model

There are two objectives in the optimization model.

Objective I is the minimization of the total cost f_1, which includes pollutant gas emissions costs $W_{gas}(t)$, running costs $W_{r,\cos t}(t)$, fuel costs $W_f(t)$ and costs of the coordination with upstream power $W_a(t)$, which means that the

$$\min f_1 = \sum_{t=1}^{T}[w_f(t)+w_{r,\cos t}(t)+w_a(t)+w_{gas}(t)] \tag{1}$$

Where,

$$w_f(t)=\sum_{t=1}^{24} v_n(t)\cdot w_n(t), n=1,2,3...n \tag{2}$$

$$\mathrm{W}_n(t)=v_n(t)*\frac{q}{1.399}*\eta_n(t), n=1,2,3...n \tag{3}$$

$$w_{r,\cos t}(t)=\sum_{i=1}^{u} p_i(t)\cdot l_i(t)+\sum_{i=1}^{n} p_b(t)\cdot\delta(p_b(t)) \tag{4}$$

$$w_a(t)=\begin{cases}\sum_{t=1}^{24} w_b(t)\cdot[p_g(t)-p_s(t)], p_g(t)\ge 0;\\ \sum_{t=1}^{24} w_s(t)\cdot[p_j(t)-p_s(t)], p_j(t)<0;\end{cases} \tag{5}$$

$$w_{gas}(t)=w_{pun}\left[\left(1+\frac{1}{\rho}\right)\cdot\sum_{j=1}^{N}E_{co_2}[p_j(t)]\right] \tag{6}$$

Where, $v_n(t)$ is the consumption of natural gas volume at the time t of the micro-turbine n; $w_n(t)$ is the price of the natural gas of the micro-turbine n; q represents heating value of natural gas; $\eta_n(t)$ is the micro-turbine efficiency; $W_n(t)$ is the power of the a micro-turbine. $p_i(t)$ is the power of the ith PV; $l_i(t)$ is the maintenance cost of the ith PV; $p_b(t,)$ is the exchange power at time t; $\delta(p_b(t))$ is the depreciation coefficient. $w_b(t)$, $p_g(t)$ is the electricity selling price and power at time t; $w_s(t)$, $p_j(t)$ is the electricity purchasing price and power at time t; $p_s(t)$ is grid loss. w_{pun} is the coefficient of environment penalties; ρ is the heat performance coefficient, which is 0.8; E_{co_2} is the coefficient of CO2 penalties, which is 0.65.

Objective II is the minimum fluctuation of solar curtailment accommodation.

$$\min f_2=\left(\frac{10*\delta*p_i(t)-\sum_{i=1}^{24}p_{load}(t)}{24}\right)^2 \tag{7}$$

Where, δ is the power fluctuation coefficient, which is 0.9; $p_{load}(t)$ is load power at time t.

To sum up, objective function of the joint energy micro-grid is as follows:

$$\min f=(f_1, f_2) \tag{8}$$

2.2. Constraints

1) the constraints of the conservation of the power:

$$\sum_{i=1}^{n}[p_i(t)+p_{grid}(t)+p_{cchp}(t)+p_{dis}(t)]=\sum_{i=1}^{n}[p_{load}(t)+p_{ch}(t)+p_s(t)] \tag{9}$$

Where, $p_{dis}(t)$, $p_{ch}(t)$ are the discharging and charging power of battery at time t.

2)constraints of heat (cold) energy:

$$H_{cchp}(t) = H_{load}(t) + H_{hs}(t)$$
$$L_{ref}(t) = L_{load}(t) + L_s(t) \tag{10}$$

Where, $H_{cchp}(t), H_{load}(t), H_{hs}(t)$ are heat supply power, heat load and heat loss at time t;and $L_{ref}(t)$, $L_{load}(t), L_s(t)$ are cold supply power, cold load and cold loss at time t

3) constraints of the generation of the distributed power :

$$p_{gv.i}^{\min}(t) \le p_{gv.i}(t) \le p_{gv.i}^{\max}(t), i = 1,2,3...n \tag{11}$$

4) constraints of the power of the refrigeration

$$p_{ref,i}^{\min}(t) \le p_{ref,i}(t) \le p_{ref,i}^{\max}(t), i = 1,2,3...n \tag{12}$$

5) constraints of the storage of heat and the storage of cold load

$$\begin{cases} H_{hsd.i}^{\min}(t) \le H_{hsd.i}(t) \le H_{hsd.i}^{\max}(t) \\ L_{sd.i}^{\min}(t) \le L_{sd.i}(t) \le L_{sd.i}^{\max}(t) \end{cases}, i = 1,2,3...n \tag{13}$$

6) constraints of the battery

a. constraints of the State of Charge (SOC)

$$SOC_{xd,i}^{\min}(t) \le SOC_{xd,i}(t) \le SOC_{xd,i}^{\max}(t), i = 1,2,3...n \tag{14}$$

b. constraints of charging power

$$p_{ch,i}^{\min}(t) \le p_{ch,i}(t) \le p_{ch,i}^{\max}(t), i = 1,2,3...n \tag{15}$$

c. constraints of discharge power

$$p_{dis,i}^{\min}(t) \le p_{dis,i}(t) \le p_{dis,i}^{\max}(t), i = 1,2,3...n \tag{16}$$

7) constraints of the exchange power

$$p_{\text{exchange}}^{\min}(t) \le p_{exchange}(t) \le p_{exchange}^{\max}(t) \tag{17}$$

The subscript max and min refer to the upper and lower limits of the parameters in (11)-(17).

3. Model of multi-objective linear weighted sum method

Linear weighted sum method, also known as "utility model", is applied in this paper.

$$F(x) = \sum_{i=1}^{m} w_i \cdot f_i(x), i = 1,2,3...m \tag{18}$$

Where, $F(x)-$ is the comprehensive function; w_i is the weight; $(\sum_{i=1}^{m} w_i = 1, 0 \le w_i \le 1)$, $w_i = \dfrac{x_i}{f_i(x)^2}$.

4. Optimization algorithm

The model is solved by genetic-taboo PSO algorithm. The algorithm firstly introduces the taboo PSO to avoid local optimum and finally introduces the genetic algorithm (GA) to improve the global searching.

First, the random group of particles is generated. Through the fitness of the function calculate the value of fitness of each particle. Secondly, the threshold is set to judge the "premature" phenomenon. During the Iterative process, when the difference between the two iterations is less than $\xi(0.05 \ge \xi \ge 0)$, it can be considered as "premature", which leads to get the locally optimums. Finally, the global optimum is obtained by the selection, crossover, and mutant of the particle.

The flow chart of genetic-taboo PSO is shown in Figure 2.

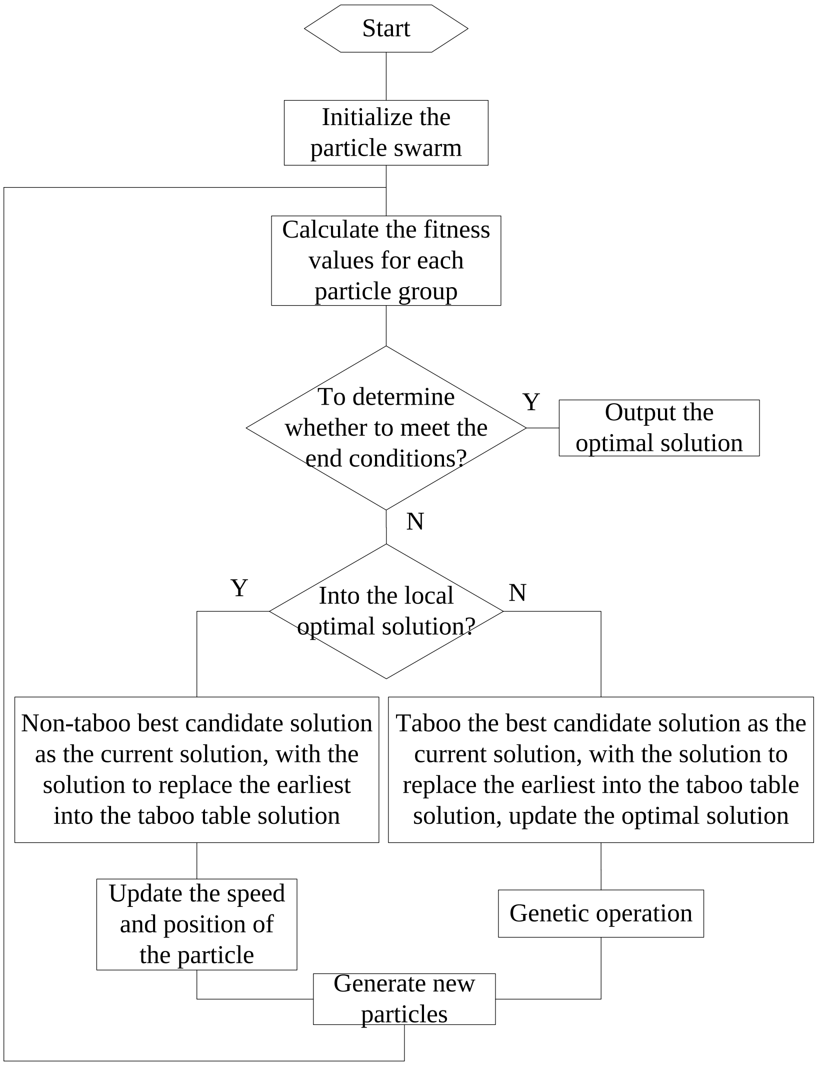

Figure 2. Flow chart of genetic-taboo PSO.

5. Case studies

5.1. Parameters

The joint energy micro-grid with cold storage is based on a garlic trade market in Henan. The capacity of the micro-turbine is 50kW. The gas heating value is 38.97MJ/kg. The general efficiency is η=0.27. Total PV capacity is 200kW. $l_i(t)$=0.6 yuan/kW, w_{pun}=0.98 yuan/kW. The battery capacity is 180kW-h, and the depreciation coefficient is 0.3 Yuan/kW. The rated charging/discharging power is 18kW, and the initial SOC is 50%. The thermal storage capacity is 3200kW. The cold storage capacity is 8000kW. Electricity tariff is agreed with local electricity supply companies and PV selling prices contains government subsidy. The gas price is 2.7yuan/m3. The number of particles is 50, and the iteration is 400. The micro-turbine works in "heat" mode. The solar radiation intensity is based on local meteorological departments.

Figure 3 shows an typical example of characteristics of electricity, heat and cold load. Figure 4 shows the characteristics of multi-objective optimization algorithm for power consumption of load. The power of each unit of joint Energy micro-grid system in distribution is shown in Table 1 and the electricity tariff is shown in Table 2.

Table 1. Parameters of power of each unit in distribution.

Device name	Lower power limit/kW	Upper power limit/kW
PV	0	300
Battery	10	70
CHP	0	70
Electric refrigerator	0	200

Table 2. Electricity tariff in Henan.

Electricity time	Period of time	Electricity price (yuan / degree)
Peak hours	7:00-11:00、18:00-22:00	1.2165
Peace hours	11:00-18:00、22:00-24:00	0.7912
Valley hours	0:00-7:00	0.4182

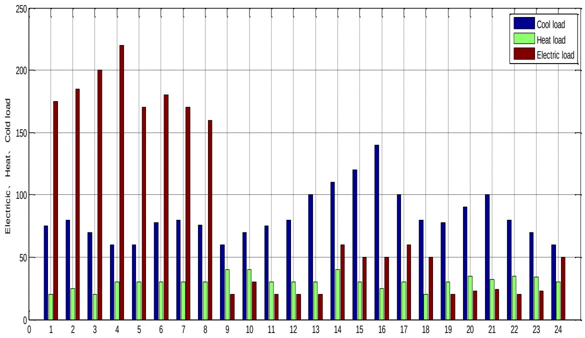

Figure 3. Typical electrical, thermal and cold load characteristics.

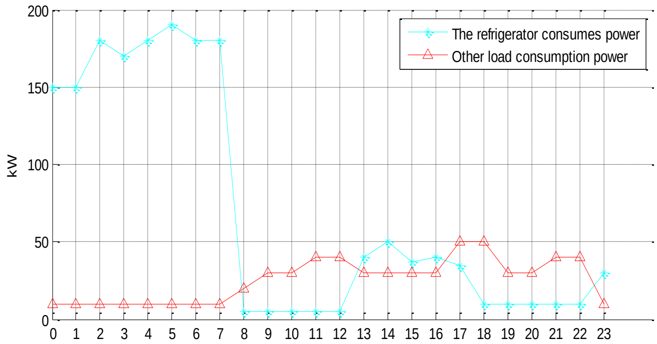

Figure 4. The characteristic of the Multi-objective optimization algorithm of the power of the load consumption.

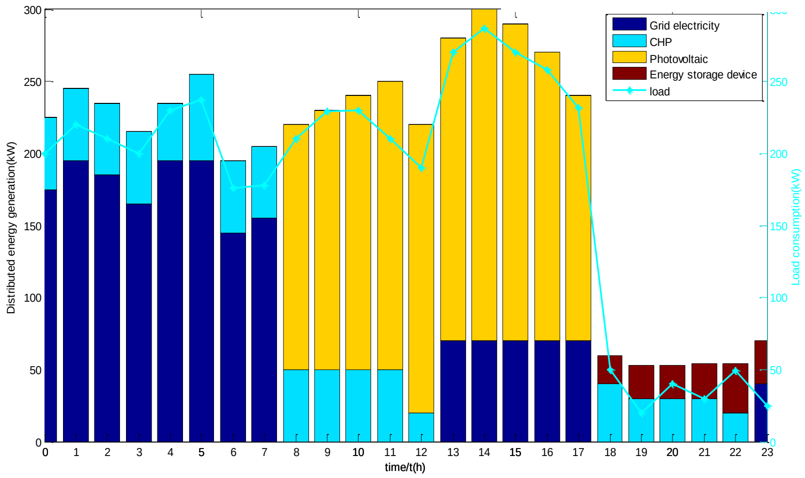

Figure 5. Sources of the optimization power under multi-objective.

5.2. Results

When $p_g(t) > p_s(t)$, the system total cost reduces from 1461.34Yuan to 942.83Yuan with the proposed method. When $p_g(t) < p_s(t)$, the total cost can be saved for about 90Yuan. With the proposed method, the system fluctuation is significantly decreased to 153kW, which is 24.48% of that without optimization. The Henan garlic market could reduce the cost 518.51yuan per day after using the optimization method. The annual cost savings are about 189,000 yuan. That could help the users to reduce production costs and increase profits.

The multi-energy outputs are as shown in Figure 5.

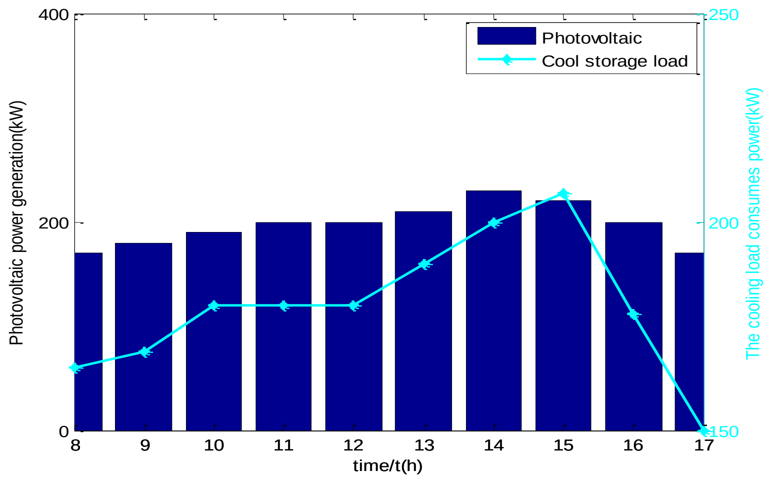

Figure 6. Storage capacity to absorb photovoltaic power.

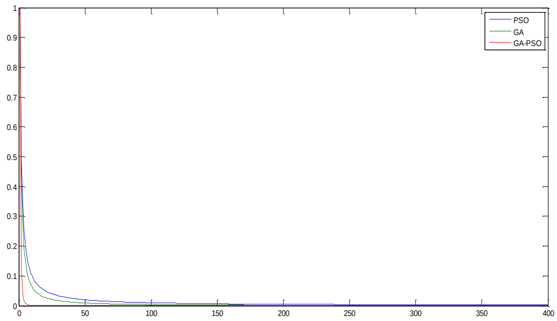

Figure 7. Comparison of convergence speed of intelligent algorithm.

From Figure 5 it can be seen that at time 0-7, grid purchasing is the main power source of the energy micro-grid. There is also a little CHP output. At 8-12, both PV and CHP output power. At 13-17, CHP stops and PV continues, while purchasing power from grids. At 18-22, CHP and battery energy storage output power. The difference between the power supply and the load curve is the grid loss.

From Figure 6, it can be seen that at 8-17, PV power is the main power source of the joint energy micro-grid. The characteristics of thermal storage load and PV power are in the same manner.

From Figure. 7 it can be seen that the convergence speed and the stability of taboo PSO and GA are similar. However, the convergence speed and stability of genetic-taboo PSO is better.

6. Conclusions

This paper studies the optimal operation of joint energy micro-grid system, which includes PV, CHP, gas turbines, battery, thermal storage and cold storage. The mathematical model is firstly expressed and the genetic-taboo PSO algorithm is applied to solve the optimization model to achieve economic operation of the system. The simulation results show that The Henan garlic market could reduce the cost 518.51yuan per day after using the optimization method and the annual cost savings are about 189,000 yuan. The proposed method could effectively reduce the system total cost while minimize the power fluctuation. Meanwhile, the proposed solving algorithm is with fast convergence and well stability.

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