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

Yuyao Wang, Yuan An, Fang Xi, Jiang Yao and Qian Wei

Institute of water Resources and hydro-electric Engineering, Xi'an University of Science and Technology, Xi'an, 710048, China

83008035@qq.com

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 Wꞏh. 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:

\[ P = \begin{cases} 1 + 0.6641(1-e)^{0.66}, & 0 < e < 1 \\ 1 - 0.9643(e-1)^{1.25}, & e \geq 1 \end{cases} \] (1)

The electricity price of non/normal industrial users is:

\[ P = 1.2532 - 0.4121 \eta \] (2)

In the formula, \( \eta \) is the per-unit value of real-time electricity price compared to the standard electricity price

\[ \eta(t) = \frac{P(t)}{\sum P_L(i)} \] (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.

\[ \Delta \eta(t) = \frac{\eta(t+1)}{\eta(t)} \] (4)

\[ e(t) = \mu(\eta(t) + \lambda)^2 + \varepsilon \] (5)

In which, \( \mu > 0 \), and \( \lambda > 0 \); \( \varepsilon \) 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:

\[ \min F_{\text{cost}} = C_G + k_1 C_{\text{grid}} + k_2 C_L + C_{\text{load}} \] (6)

\[ C_G = \sum_{i=1}^{N} \left[ C_{\text{fuel}}(P_L) + K_{\text{op}}^i P_L \right] \] (7)
\[ C_{\text{grid}} = e_{bt}Q_{bt} - e_{st}Q_{st} \]  
\[ C_{L} = \sum_{j=1}^{M} e_{L,j} Q_{L,j} \]  
\[ C_{\text{load}} = \sum_{j=1}^{M} e_{j} Q_{j} \]  
\[
\begin{cases}
\sum_{i=1}^{N} P_{it} + P'_{\text{grid}} = \sum_{j=1}^{M} P'_{L,j} \\
P'_{\text{min}} \leq P'_{L,t} \leq P'_{\text{max}}
\end{cases}
\]

In which

- \( C_{\text{grid}} \) is the dispatch cost, fuel cost of the power generation unit, and operation & management cost;
- \( C_{L} \) is the interactive cost with distribution network;
- \( C_{\text{load}} \) is the compensation cost of interruptible load outage;
- \( k_1 \) 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 \( 1 \sim N \);
- \( t \) is running time;
- \( P_{it} \) is the power output of the No. \( i \) generation unit at the time \( t \), kW;
- \( C_{\text{fuel}} \) 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 \( 1 \sim m \); 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;
- \( e_{bt} \) and \( e_{st} \) are the prices of purchasing and selling electricity from the distribution network at t-time respectively, Yuan/kW.h;
- \( Q_{bt} \) and \( Q_{st} \) are the amount of electricity purchased and sold by the system to the distribution network at t-time, kW;
- \( e_{L,t} \) is the compensation electricity price of type-j for interruptible load at the time \( t \), Yuan/kW.h;
- \( Q_{L,t} \) is the amount of interrupted load at the time \( t \), kW;
- \( P'_{\text{grid}} \) 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;
- \( P'_{L,t} \) is the electricity load of J-type power user at the time \( t \), kW;
- \( P'_{\text{max}} \) and \( P'_{\text{min}} \) 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](image)

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](image)

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:
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:

\[ C_f = \sum_{i=1}^{N} \sum_{t=1}^{M} \left[ C_f (P_t) + O_i (P_t) + C_{dep} (P_t) \right] + \sum_{t=1}^{N} \left[ C_{buy} (t) - C_{sal} (t) \right] P_{grid} (t) \]

\[ \text{min} \]

\( N \) is the total number of periods calculated, \( N=24 \); \( C_f \) is the fuel price; \( F_i (P_t) \) represents the fuel consumption of the machine set \( F_i (P_t) = C_u (P_t) + C_{op} (P_t) \), \( C_u (P_t) \) is the fuel used for generating units; \( C_{op} (P_t) \) is the fuel used in the start-up of the Unit; \( O_i (P_t) \) is the operation and maintenance cost of the unit set, \( O_i (P_t) = k_u (P_t) P_t \Delta t \), \( k_u (P_t) \) is the operation and maintenance parameters. \( P_t \) is the output power; \( C_{dep} (P_t) \) represents the unit's depreciation cost,

\[ C_{dep} (P_t) = \frac{C_i f_{cr}}{P_{cr} \tau}, \]  

\( C_i \) is the installation cost of the generator, \( f_{cr} \) is the capital recovery factor, \( P_{cr} \) is the generator's rated power, and \( \tau \) is the maximum use of hours;
C_{buy}(t)$ represents the electricity purchase price of the at $t$-time period, $C_{sell}(t)$ means the feed-in tariff at $t$-time period; 

$P_{grid}(t)$ is the power value in the power network exchange at $t$-time period.

Environmental costs:

$$C_H = \sum_{i=0}^{N} \sum_{k=1}^{M} 10^3 \alpha_k \sum_{i=1}^{M} \alpha_{grid,k} P_i(t)$$

\begin{equation}
\min C_H = \sum_{i=0}^{N} \sum_{k=1}^{M} 10^3 \beta_k \sum_{i=1}^{M} \alpha_{grid,k} P_i(t) + \alpha_{grid,k} P_{grid}(t)
\end{equation}

In the formula: $C_H$ is the harness cost of pollution disposal, $k$ is the pollutant type number, and $\alpha_k$ is the pollutant emission coefficient of different types of unit sets; 

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

The constraint equation is as follows:

1) System energy balance constraint:

$$\sum_{i=1}^{M} P_i(t) + P_i(t) + P_{w}(t) + P_{wind}(t) + P_{grid}(t) = \tilde{P}(t)$$

$$\sum_{k=1}^{N} W_{MT,k} + \sum_{l=1}^{N} W_{RT,l} = \tilde{P}_D$$

$$\sum_{m=1}^{M} P_{w,m}(t) + \sum_{m=1}^{M} P_{w,2}(t) = \tilde{P}_D(t)$$

\begin{equation}
(14)
\end{equation}

In the formula: $P_i(t)$ is the power of the No.$i$ unit at the $t$-time, $P_{i}(t)$ is the output power from PV; 

$P_{w}(t)$ is the output power from wind power, $P_{grid}(t)$ is the capacity in the exchange with power network, and $\tilde{P}(t)$ is the dispatchable output.

2) Distributed power output constraint

$$P_{min} \leq P_i \leq P_{max}$$

$$0 \leq R_{i,up} \leq R_{i,up,max}$$

$$R_{i,down,max} \leq R_{i,down} \leq 0$$

$$\sum_{i=1}^{N} [u_i(t) - u_i(t-1)] \leq N_{i, max}$$

$$T_{off,i} \geq T_{off,i,min}$$

$$T_{on,i} \geq T_{on,i,min}$$

\begin{equation}
(15)
\end{equation}

In the formula, $P_{min} = 20$, and $P_{max} = 60$ are the minimum/maximum output of the unit; $R_{i,up} = 10$, and $R_{i,down} = 5$ are the maximum climbing rate and the maximum downhill rate of the unit, $u_i(t)$ 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; $T_{\text{off},i,min}=0$, and $T_{\text{on},i,min}=0$ are the minimum startup & shutdown time of the unit set.

3 Storage battery restraint

\[
\begin{align*}
0 & \leq P_{\text{discharge}}(t) \leq P_{\text{discharge,max}} \\
0 & \leq P_{\text{charge}}(t) \leq P_{\text{charge,max}} \\
E_{\text{batt, min}} & \leq E_{\text{batt}}(t) \leq E_{\text{batt, max}} \\
E_{\text{batt}}(0) & = E_{\text{batt}}(N_t) \\
\sum_{i=1}^{N_t}[u_{\text{discharge},i}(t)-u_{\text{discharge},i}(t-1)] & \leq \eta_{i,\text{max}} \\
\sum_{i=1}^{N_t}[u_{\text{charge},i}(t)-u_{\text{charge},i}(t-1)] & \leq \eta_{2i,\text{max}}
\end{align*}
\]

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

\[
\min F_{\text{cost}} = C_G + k_1 C_{\text{grid}} + k_2 C_L + C_{\text{load}}
\]

Cost of electricity generation:

\[
\min C_{hi} = \sum_{t=0}^{N_t} \sum_{k=1}^{M} 10^3 \beta_k \sum_{i=1}^{M} \alpha_{ik} P_i(t) + \alpha_{grid,k} P_{grid}(t)
\]

Environmental cost:

\[
\min
\]

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 Ne = 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 $\lambda = 1.5$; Pareto solution set is shown in Figure 4.
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 $\xi_1 = 0.35$, $\xi_2 = 0.25$, and $\xi_3 = 0.4$, that is

$$\min = (\xi_1 \cdot C_{\text{cost}} + \xi_2 \cdot C_F + \xi_3 \cdot C_H)_{\text{min}}.$$ 

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

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

Reference
[1] Zeng ming. Energy Revolution and Energy Internet [N]. China Energy News, 2015-06-15 (4).
[2] Zeng ming. New Energy Power System and Energy Internet [N]. State Grid News , 2015-06-01
(6).
[3] Jiang Xushuo, A Mathematical Modeling and Optimization Research of Distributed Heat and
Cooling Co-Generation System Based on Multi-Energy Complementarity [D]. Guangzhou:
South China University of Technology, 2014.
[4] Bai Haishang, A Study on the Optimization of Small Distributed Generation System [D]. Taiyuan:
Taiyuan University of Technology, 2014.
[5] Li L X, Mu H L, Gao W J, et al . Optimization and analysis of CCHP system based on energy
loads coupling of residential and office building[J]. Applied Energy, 2014(136): 206-216.

[6] Xiong Yan, Wu Jiekang, Wang Qiang, et al. An optimization coordination model and solution for combined cooling, heating and electric power systems with complimentary generation of wind, PV, gas and energy storage[J]. Proceedings of the CSEE, 2015, 35(14): 3616-3625 (in Chinese).

[7] Wang Hui, Zhao Jun, An Qingsong, et al. Study on optimization and policy incentives of distributed energy system under different building loads[J]. Proceedings of the CSEE, 2015, 35(14): 3734-3740 (in Chinese).

[8] Yang Yongping. Distributed Energy System [M]. Beijing: Chemical Industry Press, 2011: 274.

[9] Sun Zhongwu. CCHP system effectiveness analysis [J]. Value Engineering, 2012, 31(21): 53-54 (in Chinese).

[10] Wu QH, Zheng JH, Jing ZX. Coordinated scheduling of energy resources for distributed DHCs in an integrated energy grid [J]. CSEE Journal of Power and Energy Systems, 2015, 1(1): 95-103.