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Research of hierarchical scheduling for macrogrid and microgrid[1]

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Abstract. A network model is established to solve the hierarchical scheduling problem for power system based on complex network theory. For the convenience of study, macrogrid and microgrid are set as first level network and second level network respectively. On the basis of the model, a hierarchical scheduling numerical example consisting of one macrogrid and one microgrid is calculated. Macrogrid and microgrid take different objectives. Two objectives are transferred into single objective using the weighted method. Then genetic algorithm is used to solve the hierarchical problem. Results show that proposed model can be used to solve the hierarchical scheduling problem of macrogrid and microgrid based on different objectives.

Key words. Hierarchical scheduling, complex network, network modeling, genetic algorithm.

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1. Introduction

Researches on microgrid scheduling have developed rapidly in recent years [1], and traditional power grid scheduling usually chose the minimum cost of electricity as the objective [2]. As a result of recent years' attention to the environment, environmental economic dispatching is gradually becoming the consideration of scheduling, which demands taking the environmental protection into account while considering the economic benefits [3]–[6]. Literature [3] proposed particle swarm optimization algorithm to solve power system optimization problem of environment and economy.

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In the actual operation, macrogrid and microgrid are often in grid connected mode, so macrogrid and microgrid should be studied as a whole. The problem has been studied in some papers recently [7]–[10]. Literature [7] investigated a hierarchical power scheduling approach to optimally manage the power trading, storage and distribution in a smart power grid with a macrogrid and cooperative MGs, and formulated the problem as a convex optimization problem and then decomposed it into a two-tier formulation. Literature [8] introduced the security and economic dispatch into optimization model based on the partition constraint and the hierarchical constraint.

The literature and research above mainly consider scheduling optimization from the perspective of macrogrid or micro network alone, but not consider macrogrid and microgrid as a whole. In this paper, a hierarchical scheduling network model of macrogrid and microgrid is established based on multi-node and mathematical scheduling information. The model considers both microgrid's and macrogrid's different scheduling objectives.

2. Grid hierarchical scheduling network model

2.1. Mathematical description of network model

This paper's hierarchical scheduling network model is based on the following assumption:

1. Power generation node is scheduled as a separate power plant, ignoring the optimal combination of power plant units, the main wiring and other issues.
2. This model mainly considers the active optimization in the scheduling.
3. As the calculation of the line loss and substation loss is complex, ratio of line transmission terminal power to substation bus power is proposed to represent the line and substation loss.
4. It is assumed that the voltage of each node satisfies its upper and lower limits.
5. There will be no such problems like voltage collapse and load rejection.
6. The energy storage device in the microgrid is restricted by the state of charge, which means it is in the limit of the state of charge, and is regarded as an interactive terminal using cluster theory.

The grid scheduling system can be represented by the following multivariate $U = (N, P, Ca, Iv, Ob)$. $N = (V, E, A, F : E, F : A)$ indicates the basic structure of the network, V contains five types of nodes: generation terminal G, substation terminal T, interface between macrogrid and microgrid C, utilization terminal D, interactive power end M. Quantity $P = (Pt, Pg, P_{T_{vwxyz}}, Pd)$ indicates energy system, which defines the transmission power as Pt, user demand information as Pd, energy information of substation as $P_{T_{vwxyz}}$, power supply information as Pg, initial value as Iv, objective as Ob.

2.1.1. Network basic connection rules. E indicates undirected path between the intermediate node to the interactive node or between the intermediate electrical node and the same level substation node.

A indicates directed path, and the direction is from power generation to the intermediate node, from high level to the low level of the intermediate node, from intermediate node to the power side.

First level network: $E = (E_1, E_2, E_3, \ldots, E_n)$, $A = (A_1, A_2, A_3, \ldots, A_n)$.

Second level network: $E = (E_1, E_2, E_3 \ldots\ldots E_n)$,$A = (A_1, A_2, A_3 \ldots\ldots A_n)$

The connection rules between nodes are as follows:

(1) There is at least one G, one T, one D or one M.

(2) $F : A \to \{(G,T),(T_1,T_2),(T,D)\}$ (T_1, T_2 not in the same class), $F : E \to \{(T_1,T_2)\}$ (T_1, T_2 in the same class).

G and T, T and T, T and D, T and M, T and C can be directly connected, other two points cannot be directly connected.

2.1.2. Generation terminal information. $G_{\mathrm{I}} = (G_{\mathrm{I}_1}, G_{\mathrm{I}_2}, G_{\mathrm{I}_3}, \ldots, G_{\mathrm{I}_\mathrm{n}})$,$G_{\mathrm{II}} = (G_{\mathrm{II}_1}, G_{\mathrm{II}_2}, G_{\mathrm{II}_3}, \ldots, G_{\mathrm{II}_\mathrm{n}})$ indicate sets of power generation terminals in the first and second level networks. $Pg_{\mathrm{I}} = (Pg_{\mathrm{I}_1}, Pg_{\mathrm{I}_2}, Pg_{\mathrm{I}_3}, \ldots, Pg_{\mathrm{I}_\mathrm{n}})$, $Pg_{\mathrm{II}} = (Pg_{\mathrm{II}_1}, Pg_{\mathrm{II}_2}, Pg_{\mathrm{II}_3}, \ldots, Pg_{\mathrm{II}_\mathrm{n}})$ indicate the information set of power generation terminals in the first and second level networks, Pg_i indicates the information set of the power supply, such as unit rated power Pg_{iN}, the power adjustment range $Pg_{i\,\min} \le Pg_i(t) \le Pg_{i\,\max}$, the upper and lower limits of the unit climbing rate U_{R_i}, D_{R_i} and the power plant rotation reserve S.

2.1.3. Utilization terminal information. $D_{\mathrm{I}} = (D_{\mathrm{I}_1}, D_{\mathrm{I}_2}, D_{\mathrm{I}_3}, \ldots, D_{\mathrm{I}_\mathrm{n}})$,$D_{\mathrm{II}} = (D_{\mathrm{II}_1}, D_{\mathrm{II}_2}, D_{\mathrm{II}_3}, \ldots, D_{\mathrm{II}_\mathrm{n}})$ indicate the sets of utilization terminals in the first and second level network. $Pd_{\mathrm{I}} = (Pd_{\mathrm{I}_1}, Pd_{\mathrm{I}_2}, Pd_{\mathrm{I}_3}, \ldots, Pd_{\mathrm{I}_\mathrm{n}})$, $Pd_{\mathrm{II}} = (Pd_{\mathrm{II}_1}, Pd_{\mathrm{II}_2}, Pd_{\mathrm{II}_3}, \ldots, Pd_{\mathrm{II}_\mathrm{n}})$ represent the information sets of utilization terminals in first and second level network, where Pd indicates the information set of the electricity demand, or load curve. This model considers the distribution of demand information only, ignoring specific electricity allocation for substation terminal nodes.

2.1.4. Interactive terminal information. $M_{\mathrm{II}} = (M_{\mathrm{II}_1}, M_{\mathrm{II}_2}, M_{\mathrm{II}_3}, \ldots, M_{\mathrm{II}_\mathrm{n}})$ indicates the set of interactive terminals, including electric vehicle charging pile and energy storage devices like large batteries, capacitors, etc. As individual characteristics of the distributed charging pile is difficult to research, this paper studies large scale cluster characteristics of the charging pile by abstraction as a whole.

$Pm_{\mathrm{II}} = (Pm_{\mathrm{II}_1}, Pm_{\mathrm{II}_2}, Pm_{\mathrm{II}_3}, \ldots, Pm_{\mathrm{II}_\mathrm{n}})$ represents information set of interactive terminals, represents electricity information set of interactive terminals, such as energy storage device upper and lower energy storage limit, maximum charge and discharge constraints.

2.1.5. Interface. Under the condition of grid-connected operation, distribution network interface must meet the requirements of the upper and lower limits of power transmission to ensure interactive energy within a reasonable range so that big impact on macrogrid and large fluctuations can be avoided.

2.1.6. Substation terminal information. $Tw.x.y.z = \{Ct, \beta, \alpha\}$ represents substation terminal information, including rated capacity C_t, loss rate β, load rate α, where w, x, y, z represent substation class, with $w > x > y > z$ ranking successively. For example, $T_{1.2.3}$ represents the connection point belongs to the third substation of the dispatching mechanism 1's slave mechanism 2. $P_{T_{w.x.y.z}k}$, $k = 1, 2, 3 \ldots, u$ represents the transmission power of the line connected to the substation terminal, where u indicates the number of connected lines. The input power value is positive and the output power value is negative.

2.1.7. Transmission line. Ca represents the information set of transmission line, including power type (DC or AC), voltage level $U_{(V_a,V_b)}$, line impedance $R_{(Va,Vb)}$, transmission line limit $Pm_{(V_a,V_b)}$, length $L_{(Va,Vb)}$, power flow through the transmission line $P_{(Va,Vb)}$, V_a, V_b indicating two connected nodes.

2.1.8. Initial value. Before operation of the system, it is necessary to set the initial input information Iv.

2.1.9. Scheduling objective. The main scheduling objective of the hierarchical scheduling system is made up of each level network's sub-objective. Each level network's scheduling objective has different emphasis, so the main target is set of sub targets. And sub target may contain more than a single goal, so comprehensive consideration must be involved. This paper used multi-objective method to solve the scheduling objectives. The multiple objectives are transferred into a single objective model using the weighted method. The following is formula summary of the description above.

Main scheduling objective of hierarchical scheduling system:

$$Ob = Ob_{\mathrm{I}} + Ob_{\mathrm{II}} + \ldots . \tag{1}$$

2.2. Graphical description of network model

A macrogrid and microgrid hierarchical scheduling models are shown in Fig. 1.

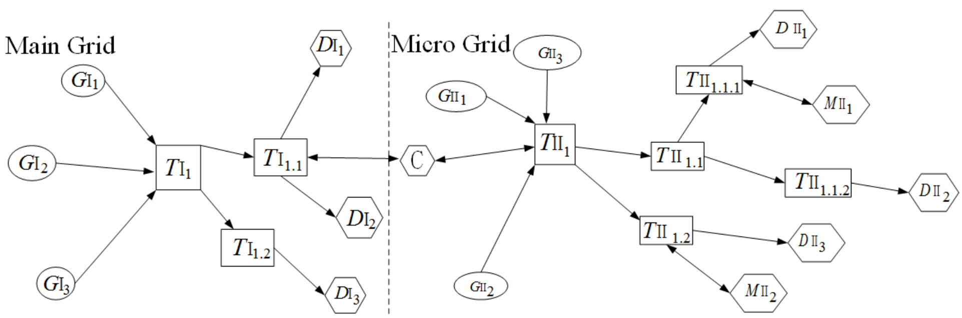

Fig. 1. Graphical description of grid hierarchical scheduling network model

3. Numerical example of hierarchical scheduling

3.1. Conditions and assumptions

According to the above model assumptions, following conditions and assumptions are given.

(1) The first level grid system included a wind farm with 150 MW, two thermal power plants with 600 MW, 450 MW. Second level grid system included a wind farm with 50 MW, a photoelectric plant with 45 MW, and a thermal power plant with 50 MW.

(2) The coal consumption of the thermal power plant uses the quadratic function model, which is expressed by the cost of coal consumption:

$$f(Pg_i) = a_i Pg_i^2 + b_i Pg_i + c_i \,. \tag{2}$$

(3) The minimum cost of purchasing electricity is expressed as

$$f(Pi) = K_i \, Pi \,. \tag{3}$$

(4) Minimum operating cost of microgrid:

$$\min W_{\mathrm{Cost}} = W_{\mathrm{Initial}} + W_{\mathrm{Fuel}} + W_{\mathrm{OM}} + W_{\mathrm{EXC}} \,. \tag{4}$$

Assume that a simplified power grid structure is shown in Fig. 1. The system consists of six generators ($G_{\mathrm{I}_1}, G_{\mathrm{I}_2}$, G_{I_3}, G_{II_1}, G_{II_2}, G_{II_3}), eight transformer terminals ($T_{\mathrm{I}_1}, T_{\mathrm{I}_{1.1}}$, $T_{\mathrm{I}_{1.2}}$, T_{II_1}, $T_{\mathrm{II}_{1.1}}$, $T_{\mathrm{II}_{1.2}}$, $T_{\mathrm{II}_{1.1.1}}$, $T_{\mathrm{II}_{1.1.2}}$) six substations ($D_{\mathrm{I}_1}, D_{\mathrm{I}_2}$, D_{I_3}, D_{II_1}, D_{II_2}, D_{II_3}), two energy storage systems(M_{II_1}, M_{II_2}), and twenty-two transmission lines ($L_1 - L_{22}$).

3.2. Equality constraints and inequality constraints

(1) The total load of transformer bus is

$$P_{\mathrm{Lbdj}}(t) = P_{\mathrm{dj}}(t), \; b = 7, 8, 9, \; j = 1, 2, 3 \,, \tag{5}$$

$$P_{\mathrm{LaX}}(t) = P_{\mathrm{LbY}}(t) \times (1 + L_k \times \eta_k), \; a = b = k = 5, 6, 7, 8, 9 \,, \tag{6}$$

$$\sum_b P_{\mathrm{LbY}}(t) = (1 + \beta_{T\ldots}) \times \sum_a P_{\mathrm{LaX}}(t), \; X = Y = T\ldots \tag{7}$$

In the three above equations, $P_{\mathrm{LaX}}(t)$ indicates transmission power at starting end and $P_{\mathrm{LbY}}(t)$ indicates transmission power at destination end, where $a, b = 1, 2, \cdots, 14$, X and Y are the starting point and destination, respectively.

(2) System active power balance:

$$\sum_{i=1}^{4}(Pg_i(t)/(1+L_k\times\eta_k))=\sum_{b=1}^{4}P_{\mathrm{LbT1.1}}(t),\ b=i=k=1,2,3,4\,. \tag{8}$$

(3) Power regulation constraint:

$$Pg_{i.\min}\le Pg_i(t)\le Pg_{i.\max}\,, \tag{9}$$

$$\Delta Pg_{i.U}(t)=Pg_i(t)-Pg_i(t-1)\le\Delta Pg_{i.U.\max}\,, \tag{10}$$

$$\Delta Pg_{i.D}(t)=Pg_i(t-1)-Pg_i(t)\le\Delta Pg_{i.D.\max}\,. \tag{11}$$

(4) Network loss is the sum of substation loss and line loss:

$$\sum P_{\mathrm{loss}}=\sum P_{\mathrm{loss.l}}+\sum P_{\mathrm{loss.t}}\,, \tag{12}$$

$$P_{\mathrm{loss.l}}=P^2_{(V_a,V_b)}\times(R_{(V_a,V_b)}/U^2_{(V_a,V_b)})\,, \tag{13}$$

$$P_{\mathrm{loss.t}}=\eta\times\sum P_{T_{vwxyz}m}/2)\,. \tag{14}$$

Here, $P_{\mathrm{loss.l}}$, $P_{\mathrm{loss.t}}$ indicate the line loss and substation loss, $P_{T_{vwxyz}m}$ indicates the substation power.

(5) Network power balance constraint:

$$\sum Pg_i(t)=\sum Pd_j(t)+\sum P_{\mathrm{loss}}+\sum P_{\mathrm{esd}}\,. \tag{15}$$

Here, P_{esd} represents the energy storage device, including battery, capacitor, charging pile. When P_{esd} is positive, battery is charging, when P_{esd} is negative, battery is discharging.

3.3. Decision variable

For first level network, G_{I_1}, G_{I_2}, G_{I_3}. For second level network, G_{II_1}, G_{II_2}, G_{II_3}.

3.4. Scheduling objective

Sub-objective of first level network is described as

$$Ob_{\mathrm{I}}=\min\sum_{i=1}^{3}\sum_{t=1}^{24}\{0.5\times[a_i(Pg_i(t))^2+b_iPg_i(t)+c_i]+0.5\times[\alpha_iPg_i(t)]\}\,. \tag{16}$$

Sub-objective of second level network is described as

$$Ob_{\mathrm{II}} = \min \sum_{i=1}^{3} \sum_{t=1}^{24} (W_{\mathrm{Initial}} + W_{\mathrm{Fuel}} + W_{\mathrm{OM}} + W_{\mathrm{EXC}}) \tag{17}$$

In the above equations, W_{Initial} indicates the initial installation cost, W_{Fuel} indicates the fuel cost, W_{OM} indicates the operation and maintenance cost and W_{EXC} indicates the electric energy interactive cost.

For the main objective function, weighted method is used again to associate the two sub-nets:

$$Ob = \omega_1 \cdot Ob_{\mathrm{I}} + (1 - \omega_1) \cdot Ob_{\mathrm{II}} \,. \tag{18}$$

3.5. Parameters

3.5.1. System load demand. The distribution terminal load at each period is shown in Figs. 2 and 3. The distribution terminal and its post-users are regarded as a node to simplify the calculation, among which Pd_{I_1}, Pd_{I_2}, Pd_{I_3}, Pd_{II_1}, Pd_{II_2}, Pd_{II_3} indicate five distribution terminal load demand.

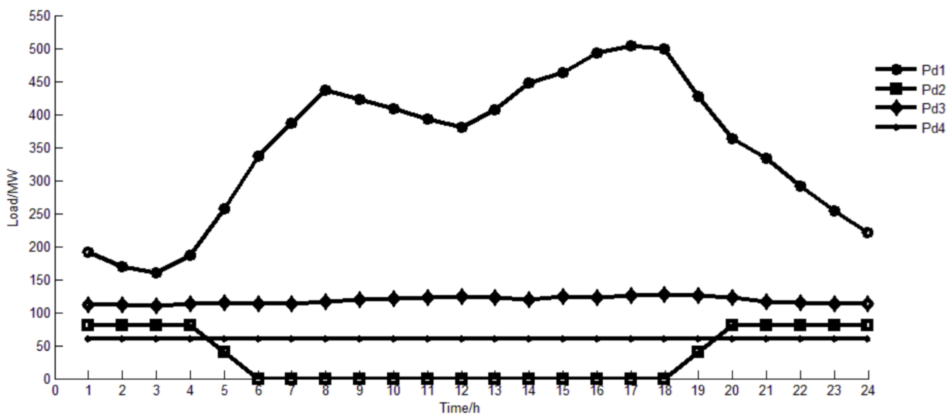

Fig. 2. Load demand of first level network

3.5.2. Interactive terminal. Maximum storage powers of energy storage devices M_{II_1} and M_{II_2} are 6 MW and 5 MW, respectively, charge state constraint is $0.2\,P_m$ and maximum transmission power is $0.2\,P_m$.

3.5.3. Line parameters. Assume that line loss is proportional to the transmission power, line loss from power plant to substation is $10^{-3}P$ MW/km, line loss between two substations is $10^{-4}P$ MW/km, and line loss between substation and distribution section is $4{\times}10^{-3}P$ MW/km. The most important parameters are listed in Table 1.

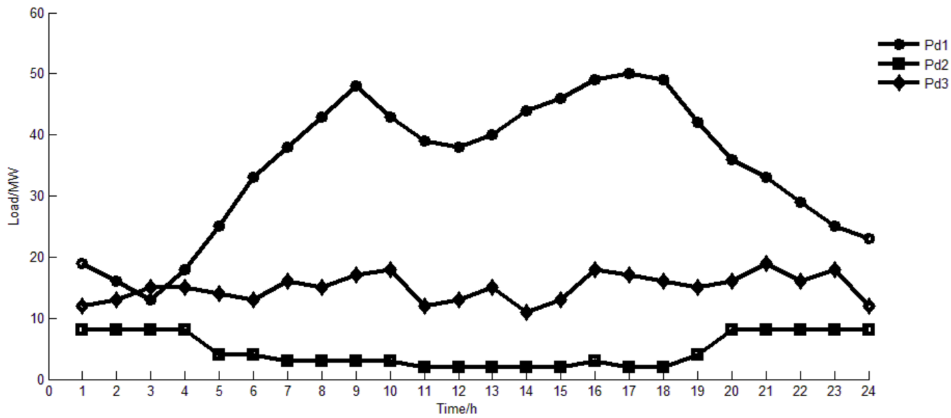

Fig. 3. Load demand of second level network

Table 1. Transmission line parameters

Line	Start	End	Line length L_k (km)	Loss coefficient η_k
1	GI_1	TI_1	42	10^{-3}
2	TI_1	$\mathrm{TI}_{1.1}$	192	10^{-4}
3	TI_1	$\mathrm{TI}_{1.2}$	180	10^{-4}
4	GI_2	TI_1	35	10^{-3}
5	GI_3	TI_1	50	10^{-3}
6	$\mathrm{TI}_{1.1}$	DI_1	67	10^{-3}
7	$\mathrm{TI}_{1.1}$	DI_2	49	10^{-3}
8	$\mathrm{TI}_{1.2}$	DI_3	26	4×10^{-3}
9	$\mathrm{TI}_{1.1}$	C	15	4×10^{-3}
10	C	TII_1	25	4×10^{-3}
11	GII_1	TII_1	17	4×10^{-3}
12	GII_2	TII_1	15	4×10^{-3}
13	GII_3	TII_1	13	4×10^{-3}
14	TII_1	$\mathrm{TII}_{1.1}$	33	10^{-3}
15	TII_1	$\mathrm{TII}_{1.2}$	35	10^{-3}
16	$\mathrm{TII}_{1.1}$	$\mathrm{TII}_{1.1.1}$	25	4×10^{-3}
17	$\mathrm{TII}_{1.1.1}$	DII_1	16	4×10^{-3}
18	$\mathrm{TII}_{1.1.1}$	MII_1	17	4×10^{-3}
19	$\mathrm{TII}_{1.1}$	$\mathrm{TII}_{1.1.2}$	26	4×10^{-3}
20	$\mathrm{TII}_{1.1.2}$	DII_2	16	4×10^{-3}
21	$\mathrm{TII}_{1.2}$	DII_3	19	4×10^{-3}
22	$\mathrm{TII}_{1.2}$	MII_2	18	4×10^{-3}

3.5.4. Substation parameters. Use β_T to represent the loss coefficient, and set primary substation loss coefficient 0.1 %, secondary substation loss coefficient 0.15 %, and third substation loss coefficient 0.2 %. Then the parameters are set as follows: $P_{\text{lossT1.1}}(t) = 0.1\,\% \times P_{\text{T1.1}}(t)$, $P_{\text{lossT11.x}}(t) = 0.15\,\% \times P_{\text{T11.x}}(t)$, $\beta_{\text{T1.1}} = 0.1\,\%$, $P_{\text{lossT1.1.1.x}}(t) = 0.2\,\% \times P_{\text{T1.1.1.x}}(t)$, $\beta_{\text{T11.1}} = \beta_{\text{T11.2}} = 0.15\,\%$, and $\beta_{\text{T1.1.1.1}} = \beta_{\text{T1.1.2.1}} = \beta_{\text{T1.1.2.2}} = 0.2\,\%$.

3.5.5. Unit parameters. In order to simplify the calculation, the capacity of each power plant is considered as a single unit, which means that the system has six units: thermal power plant G_{I_1}, G_{I_3}, wind power plant G_{I_2},G_{II_2}, small gas turbine unit G_{II_1}, and photovoltaic plantG_{II_3}. The related parameters are shown in Table 2 and Table 3.

Table 1. Unit parameters

Unit	G_{II_1}	G_{II_2}	G_{II_3}
Unit output parameter (MW)			
Minimum output $Pg_{i\,\min}$	30	0	100
Minimum output $Pg_{i\,\max}$	90	200	400
Rising rate $\Delta Pg_{i\,\min}$	20	200	100
Descent rate $\Delta Pg_{i\,\max}$	20	200	100
Installation cost			
α	6.65	2.375	4.275
Maintenance cost			
γ	0.00962	0.0287	0.0283
Fuel cost			
λ	396	0	0

Table 3. Unit parameters - continuation

Unit	G_{I_1}	G_{I_2}	G_{I_3}
Unit output parameter (MW)			
Minimum output $Pg_{i\,\min}$	120	0	100
Minimum output $Pg_{i\,\max}$	320	200	400
Rising rate $\Delta Pg_{i\,\min}$	90	200	100
Descent rate $\Delta Pg_{i\,\max}$	90	200	100
Coal cost coefficient			
a_i	0.156	0	0.482
b_i	79.2	0	79.7
c_i	1561	0	487
Purchasing electricity cost			
K	410	540	350

4. Genetic algorithm

4.1. Genetic algorithm coding design

In this paper, the initial population M is generated by traditional random number method, and population size is 50. This example uses integer encoding, the output value of each unit at each time corresponds to one gene in the individual. For an N-unit, T-time system, the length of its individual encoding L is equal to $N \times T$, and each gene value in the individual is expressed as

$$Pg_i t) = Pg_{i.\,\min} + m_i(t)(Pg_{i.\,\max} - Pg_{i.\,\min})\,. \tag{19}$$

Here, Pg_i indicates output of an individual in the initial population of a certain period of time and m_i is a random number belonging to [0,1].

4.2. Design of fitness function

A function that measures individual fitness in a genetic algorithm is called fitness function. The fitness function of this example is as follows:

$$Y = \omega_1 Y_1 + (1 - \omega_1)Y_2\,, \tag{20}$$

$$Y_1 = \min \sum_{i=1}^{3} \sum_{t=1}^{24} \{0.5 \times [a_i(Pg_i(t))^2 + b_i Pg_i(t) + c_i] + 0.5 \times [\alpha_i Pg_i(t)]\} + \\ + C_1R_1 + C_2R_2\,. \tag{21}$$

$$Y_2 = \min \sum_{i=1}^{3} \sum_{t=1}^{24} (W_{\text{Initial}} + W_{\text{Fuel}} + W_{\text{OM}} + W_{\text{EXC}}) + C_1R_1 + C_2R_2\,. \tag{22}$$

In equations (20), (21) and (22), Y_1 is the fitness function of macrogrid,Y_2 is the fitness function of microgrid, C_1R_1 and C_2R_2 indicate two penalty terms, and R_1, R_2 are the penalty conditions which represent the power generation's change at adjacent time ΔPg and the change of power generation's change at adjacent time $\Delta(\Delta Pg)$. Parameters C_1 and C_2 are the penalty coefficients. Because R_1 is the constraint of unit operation, it is necessary to set a larger C_1. SinceR_2 condition is to reduce the regulation of the mutation, C_2 should be smaller so as not to affect the objective function and the decisive role of penalty R_1.

5. Results and analysis

After the above design, take the C_1 as 500 (similar to the average cost). When C_2 is 10 and iteration number is 1500, the results are shown in Figs. 4–9.

The results show that different scheduling objectives can be solved by setting different values for ω_1, and different emphasis on optimization can be solved. When

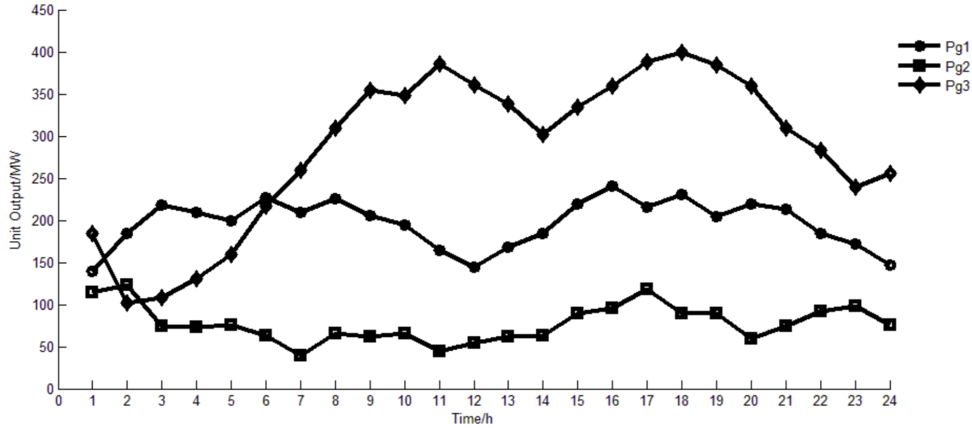

Fig. 4. Unit output of macrogrid when ω_1 is 0.5

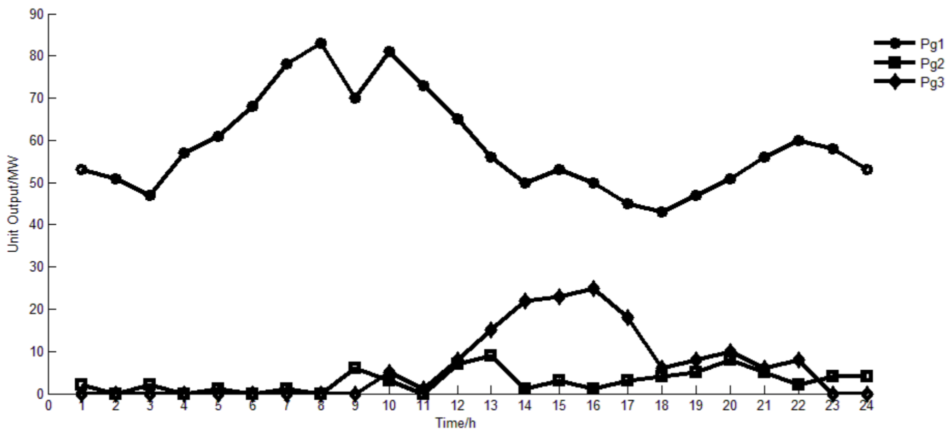

Fig. 5. Unit output of microgrid when ω_1 is 0.5

ω_1 is greater than 0.5, the scheduling objective focuses more on the macrogrid strategy; when ω_1 is less than 0.5, the scheduling objective focuses more on the microgrid strategy. Thus, hierarchical scheduling based on different targets and different weight coefficients can be realized.

6. Summary

The hierarchical scheduling network model of macrogrid and microgrid is established based on complex network modeling theory, then two-level network numerical example is solved by genetic algorithm programming. The results of power allocation are calculated based on different scheduling objectives. Numerical examples show

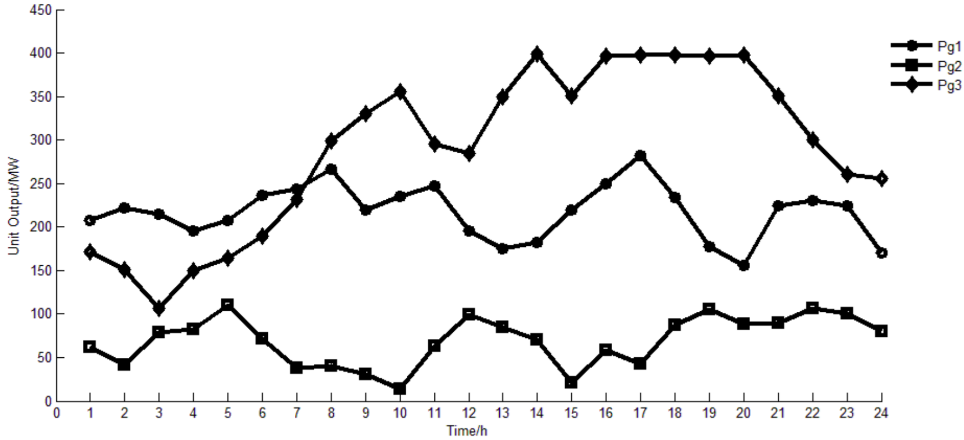

Fig. 6. Unit output of macrogrid when ω_1 is 0.3

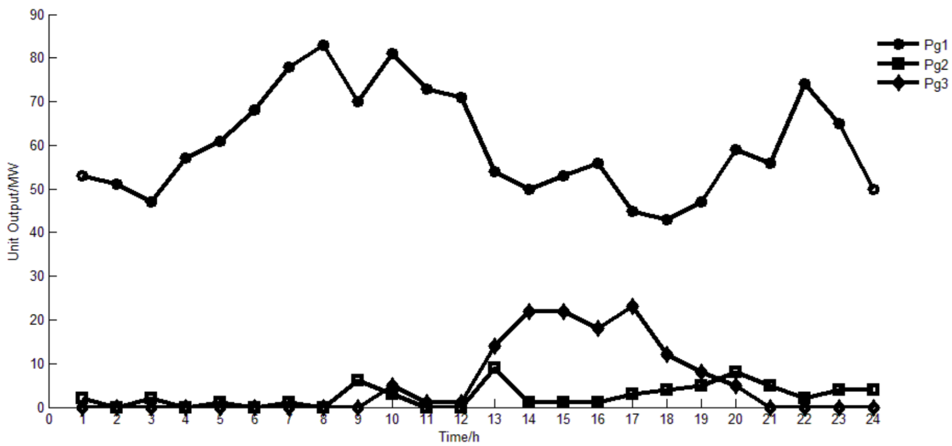

Fig. 7. Unit output of macrogrid when ω_1 is 0.3

that the proposed scheduling model and method can be used to unify macrogrid and microgrid with different objectives to achieve the joint scheduling in the hierarchical environment. Through the hierarchical scheduling strategy, the hierarchical coordination optimization of the main microgrid can be realized.

This paper's numerical example can be extended, for example, macrogrid (or microgrid)'s scheduling objective could be transformed into multi-objective scheduling combining economic benefits environmental effects. The hierarchical network can be changed into more complex problems like multi-level network consisting of more than two levels. The method presented in this paper can be extended to solve this kind of multi-level network problem.

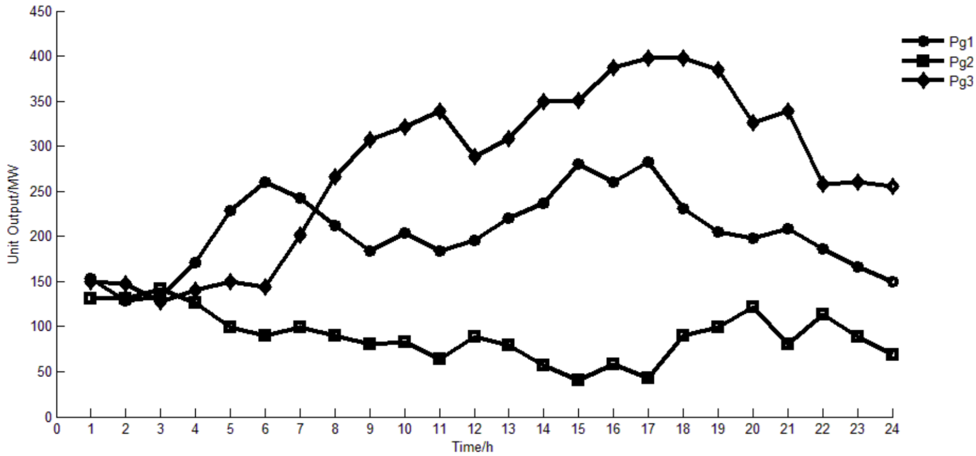

Fig. 8. Unit output of macrogrid when ω_1 is 0.7

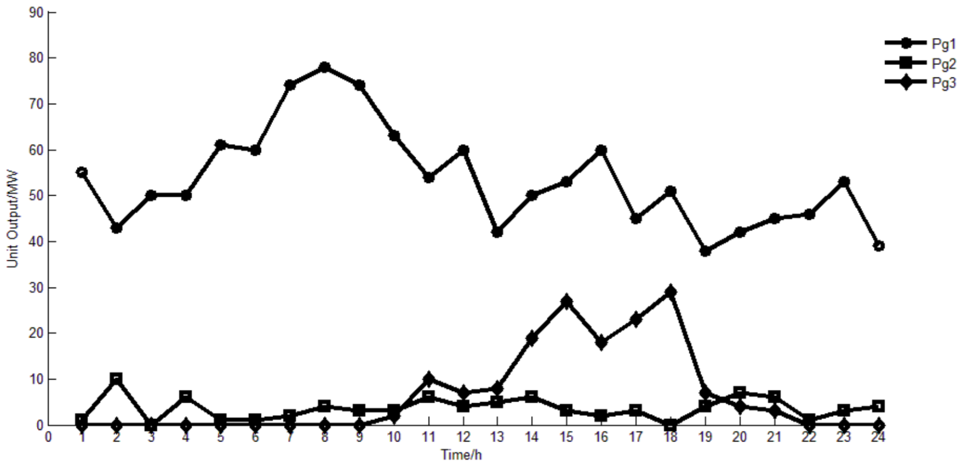

Fig. 9. Unit output of macrogrid when ω_1 is 0.7

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