A Coordinated Charging Strategy for Electric Vehicles Based on Hierarchical Optimization

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Abstract. There are many electric vehicles charging stations in distribution network. Uncoordinated charging electric vehicles load is large and changes quickly; it brings risk to the operation of power grid. If taking each station as an independent unit, which will reduce the practicability of the proposed strategy because of the small consideration scope and incomplete information acquisition. Taking all electric vehicles in the distribution network as an object to study will lack the consideration about the differentiation of a single charging station. Also, controlling all electric vehicles directly through the control center has high demand on reliability. And it is difficult to implement. Given this, the paper used the hierarchical control method to control the electric vehicles in the charging stations and studied charging strategy based on hierarchical optimization. The upper layer used the distribution system load variance as an objective function to establish a model and peak load shifting. The lower level model took the actual charging power deviation and load variance of the charging station into account to reduce the load fluctuation of the charging station. The paper used function fmincon to solve the upper level model and used CPLEX to solve the lower layer model. Finally, using a modified IEEE 33-bus system with 3 EVAs to verify the feasibility of the model and method, which reduced frequency between the control center and electric vehicles. Also, it cuts peak load and reduces load fluctuations of charging stations.

Introduction

With the rapid development of the economy, the demand for energy in countries around the world is increasing. The negative effects brought about by traditional fossil fuels have gradually emerged and continuously restrict the sustainable development of the economy [1]. In order to solve the dilemma, it is necessary to find energy sources with higher energy efficiency, better energy-saving and emission-reducing effects to optimize the existing energy structure. Under this background, the development of electric vehicles not only can revitalize the automobile industry, inject fresh vitality into the automotive industry, but also greatly reduce energy consumption and promote energy conservation and emission reduction. Therefore, electric vehicles have become a hot spot for development in various countries in recent years [2]. However, uncoordinated charging of vehicles influences the grid, so it is very important to study a suitable charging strategy for electric vehicles. The electricity price guidance method means that the charging service provider formulates the time-of-use price according to the specific situation and then guides the users so that the users can respond autonomously to his own trip demand and electricity price, and ultimately achieve the purpose of coordinated charging. Reference [3] formulated the optimal valley price time period to guide the charging behavior of users, the difference between peak and valley load of the grid is greatly reduced. Reference [4] aimed at the slow charging mode of electric private cars; the corresponding model is established with the lowest charging cost of the user and the earliest start time of the charging period. The optimal time-of-use price period with the smallest peak-valley difference is obtained by solving the model. Reference [5] proposed strategy is mainly divided into two parts. Firstly, the most appropriate charging load curve is obtained by taking the minimum cost of electricity purchase at the charging station as the objective function, and then the objective function is modeled by minimizing the variance of the actual charging load curve and the tar-get load curve. Using PSO algorithm to obtain the optimal peak-to-valley time and optimal time-of-use price. Reference [6] based on the charging load of large-scale electric vehicles, they were modeled separately without considering the V2G responsivity and considering the V2G responsivity. Both introduced the valley price time period as a variable. The division of the peak-valley electricity price period obtained by solving the model can effectively improve the operation safety of the distribution network. Although the electricity price guidance method can shift the charging load of electric vehicles from the peak price period to the valley price period, it is easy to form a new load peak during the valley price period, which does not completely solve the problems caused by the uncoordinated charging of electric vehicles. Centralized control mainly refers to the centralized management of each electric vehicle through the controller [7]. Reference [8] combined the forecasting load of unconnected electric car charging with the traditional real-time charging control strategy to establish a new model, and used the rolling optimization algorithm to obtain the optimal charging power of the electric vehicle. Reference [9] Based on the peak-to-peak electricity price, the combination of on-line optimization and off-line optimization controls the charging power of the electric vehicle via the controller, so that the total electricity load is lower than the cell power limit. So the values are optimized at the end of each control period. Reference [10, 11] used centralized control strategies to optimize various objectives, including reducing power loss, minimizing load variance, and maximizing the load factor. This kind of control method requires an upper-level control organization to collect information on electric vehicles, including the initial SOC (State of charge), the SOC that the user needs when reaching the end of charging, and the time it takes to leave the charging system. The difficulty of this centralized optimization method increases with the increasing number of electric vehicles, coupled with the limitations of existing communication technologies. It is unrealistic to control and charge each electric car through the upper control center. So it is necessary to consider the hierarchical control mode and interact the charging station with the control center. This kind of control mode for issuing electric vehicles through layers of instructions avoids the heavy storage and computation burden of the control center, and at the same time greatly reduces the requirements on the reliability and bandwidth of the communication network. Reference [12] used hierarchical optimization model, but the impact of the load fluctuations of the charging station itself on the tie line is not taken into account in the lower level model.

Based on the above reasons, the upper layer model considers peak load filling. In the lower layer model, it is considered that the charging power should match the guidance power as much as possible. On the other hand, the load fluctuation of the charging station itself should be minimized. The fmincon function is used to solve the up-per model, CPLEX is used to solve the lower model, and the IEEE 33-node test system with three charging stations is used as an example to verify the proposed method.

Hierarchical Control Method for Electric Vehicles

For the hierarchical control proposed in this paper, the control model structure constructed as shown in Figure 1, the entire hierarchical control system is divided into control center, electric vehicle charging station, station charging equipment. The control center of the figure is connected with the external network and is the highest control layer of the system. Its main task is to coordinate the charging power of each electric vehicle charging station and reduce the impact of the charging load on the power grid.

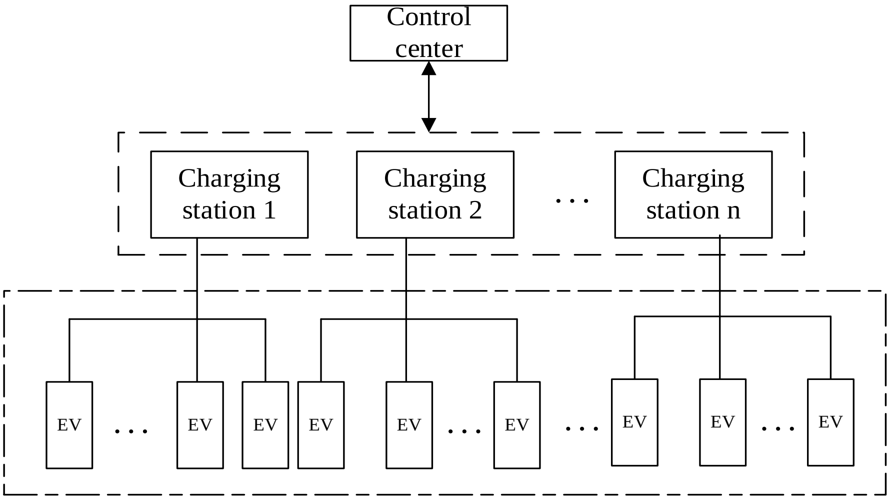

Fig. 1 Frame chart of electric vehicle stratified control

In order to facilitate the development of suitable strategies for upper-level control centers and electric vehicle charging stations, this paper uses the method described in reference [13] to analyze the results of the reference [14] and the Federal Highway Administration of the United States Department of Transportation in 2009 for families across the United States [15], It can roughly get the arrival time, the probability of leaving the station and the probability density function of the charging interval mileage of the vehicles in the charging station in the commercial area during the working day, as shown in formulas (1) to (3).

$$f_l(x)=\begin{cases}\frac{1}{\sqrt{2\pi}\sigma_l}\exp\left(-\frac{(x-\mu_l)^2}{2\sigma_l^2}\right) & 0<x\le\mu_l+12\\ \frac{1}{\sqrt{2\pi}\sigma_l}\exp\left(-\frac{(x-24-\mu_l)^2}{2\sigma_l^2}\right) & \mu_l+12\le 24\end{cases}. \tag{1}$$

Where, μ_l=8.7; σ_l=3.3.

$$f_a(x)=\begin{cases}\frac{1}{\sqrt{2\pi}\sigma_a}\exp\left(-\frac{(x+24-\mu_a)^2}{2\sigma_a^2}\right) & 0<x\le\mu_a+12\\ \frac{1}{\sqrt{2\pi}\sigma_a}\exp\left(-\frac{(x-\mu_a)^2}{2\sigma_a^2}\right) & \mu_a+12\le 24.\end{cases} \tag{2}$$

Where, μ_a=17.5; σ_a=3.34.

$$f_t(x)=\frac{1}{\sqrt{2\pi}\sigma_t x}\exp\left(-\frac{(\ln x-\mu_t)^2}{2\sigma_t^2}\right). \tag{3}$$

Where, μ_t=3.1; σ_t=1.1.

Hierarchical Optimization Model for Electric Vehicles

Upper Optimization Model

The electric vehicle control center considers peak load shifting, and uses the minimum load variance of the distribution network system as an objective function to establish an optimization model to optimize the power steering curve delivered to the charging station. The mathematical expression is as follows:

$$F_1=\frac{1}{T}\sum_{t=1}^{T}(P_{b,t}+\sum_{n=1}^{N_0}P_{s,n,t}-\bar{P})^2. \tag{4}$$

$$\bar{P}=\frac{1}{T}\sum_{t=1}^{T}(P_{b,t}+\sum_{n=1}^{N_0}P_{s,n,t}). \quad (5)$$

Where, T is control period; $P_{b,t}$ is base load; $P_{s,n,t}$ is load guidance curve followed by electric vehicle charging stations,$P_{s,n,t}\geq 0$;N_0 is thenumber of charging stations

The constraints are as follows:

$$\sum P_{G,i,t}=\sum P_{D,i,t}+\sum P_{s,n,t}+\sum P_{loss}. \quad (6)$$

Where, $P_{G,i,t}$ is generator output; $P_{D,i,t}$ is load demand; P_{loss} is grid loss.

$$V_{min}\leq V_{i,t}\leq V_{max}. \quad (7)$$

Where, $V_{i,t}$ is node voltage at time t; V_{max},V_{min} are upper and lower limitation of node voltage.

$$|P_{l,t}|\leq P_{l,max}. \quad (8)$$

Where, $P_{l,max}$ is line l transmission power cap; $P_{l,t}$ is transmission power of line l at time t.

$$0\leq P_{s,n,t}\leq \sum_{i=1}^{N_1}AP_{n,i,t}. \quad (9)$$

Where, $P_{n,i,t}$ is the i-th electric car charging power in electric vehicle charging station n at time t;A is the i-th electric vehicle arrives at the charging station n;N_1 is the number of electric vehicles.

Lower Optimization Model

In order to formulate a coordinated charging strategy for an electric vehicle within a charging station, the total load peak-to-valley difference of the distribution system must be considered first. Moreover, the peak-to-valley difference of the charging station load is too large; it will bring a great impact to the connection line between the charging station and the power grid. Therefore, the peak-to-valley difference of the charging load of the charging station must also be considered. The mathematical expression is as follows:

$$F_2=\lambda_1\sum_{t=1}^{T}\left(P_{sc,n,t}-\frac{1}{T}\sum_{t=1}^{T}P_{sc,n,t}\right)^2+\lambda_2\sum_{t=1}^{T}(P_{s,n,t}-P_{sc,n,t})^2. \quad (10)$$

$$P_{sc,n,t}\leq \sum_{i=1}^{m}AP_{n,i,t}. \quad (11)$$

$$P_{n,i,t}=\begin{cases}P_{n,i,ch} & \alpha=1\\ 0 & \alpha=0.\end{cases} \quad (12)$$

Where,α=0 means electric vehicle does not charge；α=1 means electric vehicle is charging.

The constraints are as follows:

$$S_{i,t+1}=\begin{cases}S_{i,t}+\frac{P_{n,i,ch}\eta\Delta t}{Q_i} & \alpha=1\\ S_{i,t} & \alpha=0.\end{cases} \quad (13)$$

$$S_{min}\leq S_{i,t}\leq S_{max}.. \quad (14)$$

Where,$S_{i,t}$ is the SOC of the i-th electric vehicle in the charging station at the end of time period t; η is Charging efficiency of electric vehicle; Q_i is the battery capacity of the i-th electric car in the charging station;Δt is the length of a control period; S_{max} , S_{min} are upper and lower limitation of Power battery SOC; $P_{n,i,ch}$ is the i-th electric car charging power in electric vehicle charging station n.

$$\alpha=0 \quad t<t_a \text{ or } t>t_l. \quad (15)$$

Where,t_a is the moment of Electric car access charging system; t_l is the oment of Electric car leaves charging system.

$$S_{i,tl}\geq S_i\ . \quad (16)$$

Where, $S_{i,tl}$ is the SOC of electric vehicles when leaving the charging system; S_i is the SOC that the user needs to reach.

Solution

The upper model is a multivariable constrained quadratic programming problem. This paper can be solved by function fmincon. The lower model belongs to 0-1 planning and is a special kind of integer programming problem. The traditional intelligent algorithm solves the problem slowly. In this paper, the CPLEX solver is used to solve the problem quickly and the solution result is accurate. The specific solution flow is shown in Fig.2.

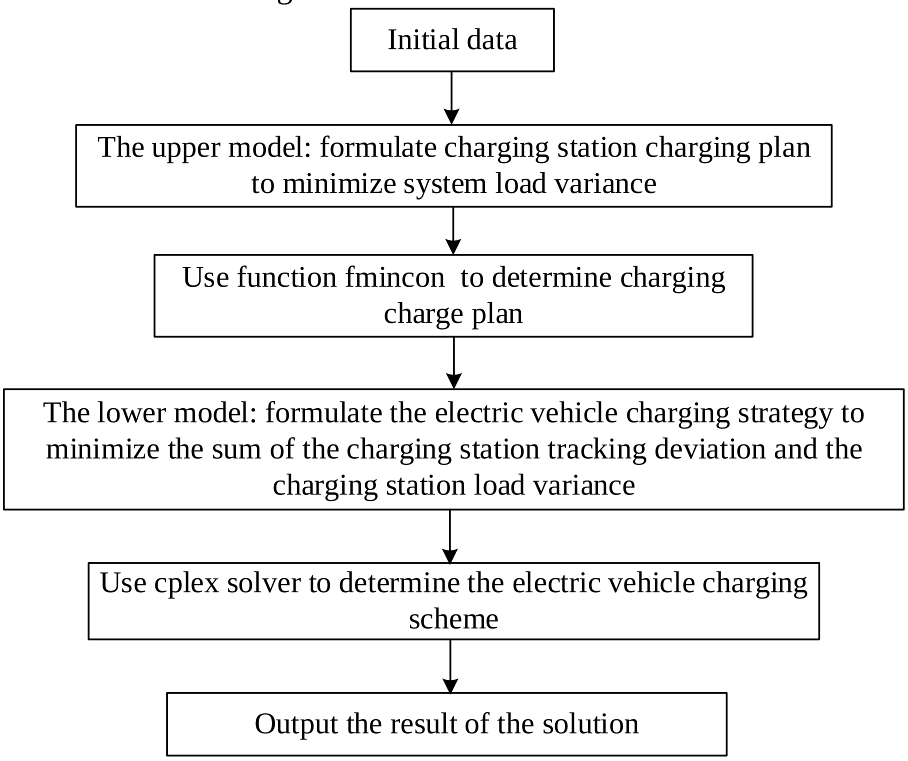

Fig. 2 Flow chart for solving hierarchical optimal model for electric vehicles charging

Case Studies

The modified IEEE33 node system is used as the test system, shown in Figure 3. The IEEE33 node distribution network contains 33 nodes, 32 branches, and 5 contact switch branches. The detailed data of the branch is shown in Table A1. Distribution system load data and changes are shown in Table A2 and Figure A1. Node 0 is set as a balanced node. The generator is accessed at node 15 and node 19. Data is shown in Table 1. The three electric vehicle charging stations are connected to node 11, node 20 and node 28. The total number of electric vehicles accepted every day is shown in Table 2, and the charging power of each electric vehicle is 3 kW.

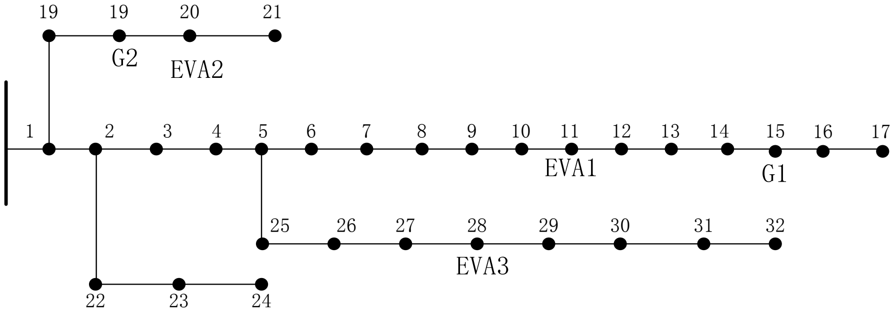

Fig. 3 Topology structure of the IEEE33 node distribution network

Table 1 Data of generators

generator	Active power upper limit [MW]	Active power lower limit [MW]
G1	46	13
G2	40	10

Table 2 Numbers of electric vehicles in charging stations in business area

Charging station	Number
EVA1	800
EVA2	760
EVA3	840

Using the charging strategy proposed in this article to charge electric vehicles,distribution system load increases on the original basis.Comparing it with the uncoordinated load curve of the distribution network system, as shown in Figure 4. More detailed data of distribution system load peaks and valleys is shown in Table 3.The charging curve of charging station 1 of coordinated and uncoordinated charging comparison is shown in Fig. 4.

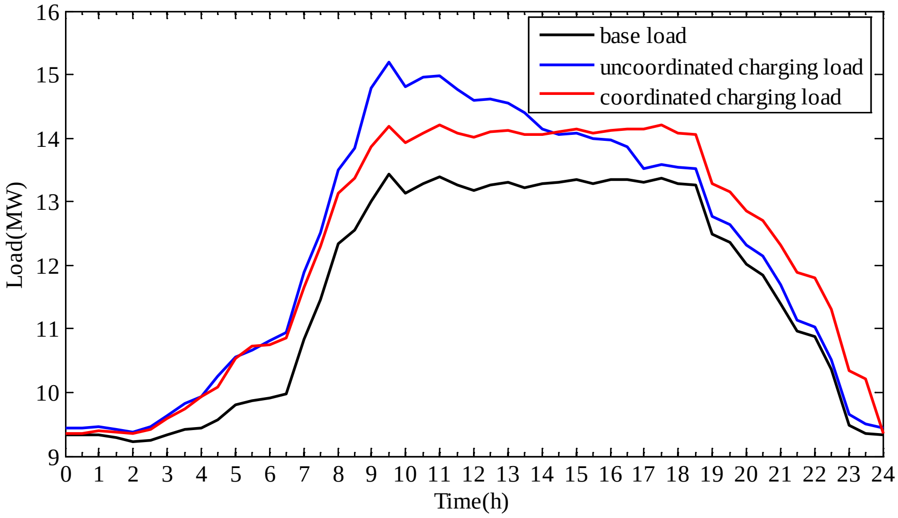

Fig. 4 Comparison of free charging mode and optimal charging mode

Table 3 Comparison of distribution network system load

Mode	Peak[MW]	Valley[MW]
Base load	13.50	9.22
Uncoordinated charging	15.20	9.38
Coordinated charging	14.21	9.36

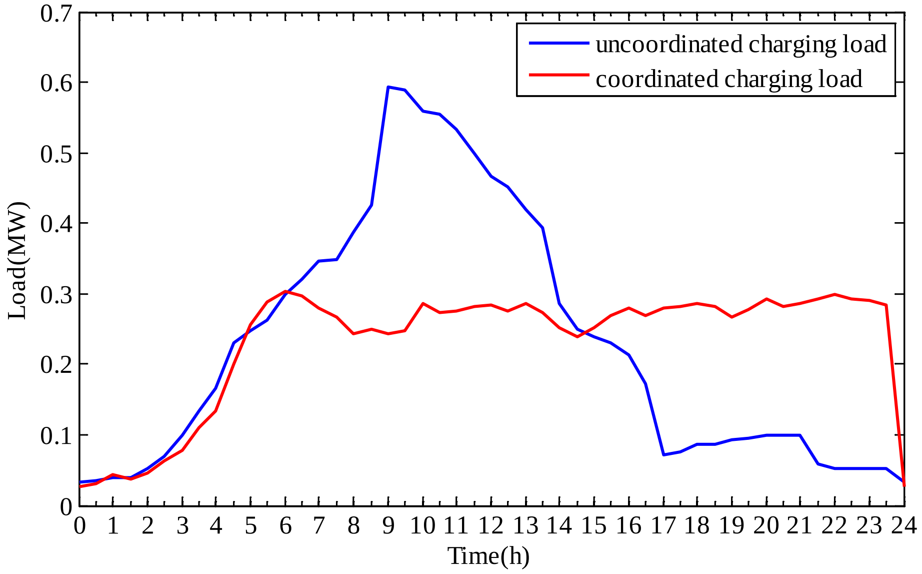

Fig. 5 Comparison of Charging station 1 load

The data in the figure and table can be clearly seen that the coordinated charging strategy studied in this paper can greatly reduce the peak load under the premise of guaranteeing the user's charging demand. Although the valley of the load has not changed much, the load curve of the entire distribution network system tends to slow down, reducing the impact on the grid. At the same time, the load peak load of the charging station is also reduced and becomes more stable.

Conclusions

In this paper, the electric vehicle charging strategy based on hierarchical optimization is established. The upper model uses the load variance of the distribution system as the objective function, while the lower model focuses on the actual charging power deviation of the charging station and the charging station load variance. For the two models, fmincon and CPLEX were used to solve the problem. Finally, an IEEE33 node test system including three charging stations was used as an example to verify the proposed method, which greatly reduced the number of communication between the system control center and electric vehicles. At the same time, it has played a good role in cutting peaks and reducing load fluctuations of charging stations.

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Appendix A

Table A1 Branch data

Line number	Starting node	End node	Resistance [Ω]	Reactance [Ω]	Line number	Starting node	End node	Resistance [Ω]	Reactance [Ω]
1	0	1	0.182	0.147	17	16	17	0.824	0.674
2	1	2	0.591	0.352	18	1	18	0.236	0.265
3	2	3	0.457	0.286	19	18	19	1.602	1.454
4	3	4	0.472	0.214	20	19	20	0.515	0.575
5	4	5	0.92	0.813	21	20	21	0.819	1.373
6	5	6	0.283	0.729	22	2	22	0.512	0.483
7	6	7	0.824	0.728	23	22	23	0.913	0.812
8	7	8	1.120	0.245	24	23	24	0.996	0.801
9	8	9	1.144	0.831	25	5	25	0.312	0.204
10	9	10	0.265	0.165	26	25	26	0.384	0.247

Line number	Starting node	End node	Resistance [Ω]	Reactance [Ω]	Line number	Starting node	End node	Resistance [Ω]	Reactance [Ω]
11	10	11	0..474	0.238	27	26	27	1.159	1.037
12	11	12	1.568	1.255	28	27	28	0.904	0.806
13	12	13	0.843	0.645	29	28	29	1.074	1.063
14	13	14	0.691	0.626	30	29	30	1.074	1.036
15	14	15	0.843	0.645	31	30	31	0.415	0.462
16	15	16	1.389	1.821	32	31	32	0.441	0.632

Table A2 Load data

Node	Load[MW]	Node	Load[MW]	Node	Load[MW]	Node	Load[MW]	Node	Load[MW]
0	0	7	0.745	14	0.155	21	0.24	28	0.510
1	0.355	8	0.155	15	0.13	22	0.245	29	0.705
2	0.315	9	0.155	16	0.195	23	1.775	30	0.560
3	0.51	10	0.125	17	0.210	24	1.790	31	0.785
4	0.185	11	0.155	18	0.280	25	0.155	32	0.580
5	0.155	12	0.155	19	0.280	26	0.165		
6	0.745	13	0.510	20	0.250	27	0.155		

Note: The data in the table is 9:00 load and the total node load is 13.5 MW.

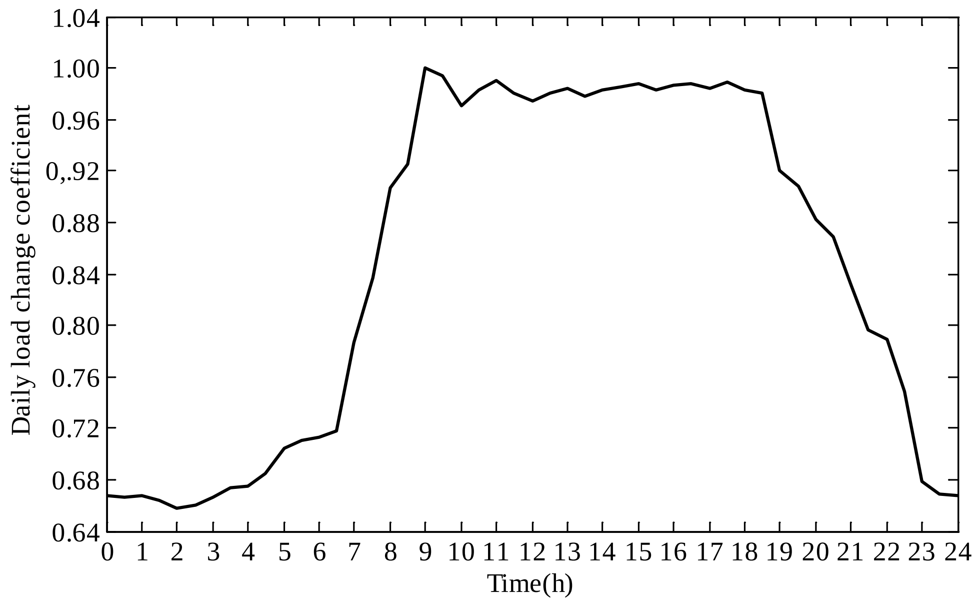

Fig. A1 Variation curve of daily load ratio