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Coordinated Charging Optimization Strategy of Electric Vehicles

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The large-scale uncoordinated charging threatens the safety operation of power grid. In the paper, two coordinated charging modes were proposed: automatic on-off charging mode and the smoothly adjusting charging mode. The 2 coordinated charging modes were established based on existing power distribution networks in residential areas and the constraint conditions of the distribution transformer and circuit capacity in order to transmit maximum electric power to electric vehicles. The established mode formulas were solved with stochastic simulation and modified particle swarm algorithm. Taking the charging station in one residential area in Shenzhen as an example, we performed the simulation of vehicle charging according to the uncoordinated charging mode and the 2 coordinated charging modes. We compared the voltage distribution in the three modes respectively. Based on the computation of the profit amount and the load volatility, we proposed the concept of cost saving so as to compensate for the expense of involved users. The simulation results showed that the two coordinated modes could raise user satisfaction and promote the smooth operation of power grid. Charging management system can choose one operation mode as required.

1. Introduction

In China, electric vehicles include private cars, buses, taxis and official cars, most of the parked cars in the residential areas are private cars. In the coordinated charging optimization mode of electric vehicles, buses, taxies, or official cars were not considered. Private cars are often used in the day for work or entertainment and parked in residential areas for a short time in the day and a longer time in the night. Private cars allow a slow charging speed. Therefore, it is necessary to optimize the coordinated charging mode according to the night charging requirements (Rotering and Ilic, 2011).

2. Analysis of charging modes

2.1 Automatic on-off charging mode

In the automatic on-off charging mode, one or several electric cars automatically start or terminate the charging process at any time according to the procedure. When the load is approaching the rated capacity of the distribution transformer, the charging management system will automatically stop the charging process of one or several electric cars; when the common load continues to fall, the management system will automatically connect one or several electric cars into the grid network for charging (Cao et.al., 2012).

2.2 Smoothly adjusting charging mode

In the smoothly adjusting charging mode, at any time, the charging power of the off-board charger is adjusted continuously and automatically. The rated charging power of the battery charger is generally 4 kW, but the charging power will continuously vary between 0 and 4 kW to charge the electric vehicles in the smoothly adjusting charging mode (Tian et.al., 2013).

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3. Coordinated charging optimization mode

3.1 Coordinated charging model in the automatic on-off charging mode

According to the historical average load in the power distribution network in the residential area, the normal load curve of a certain day can be predicted with the 96-point daily load curve forecasting method with the interval of 15 min (Clement et.al., 2010). If the number of the alternating charging points in the residential area is N, according to the slow charging method, the battery charger charges the lithium battery under a constant power. The model aims to realize the maximum transmission energy to electric vehicles:

$$\max \sum_{t=1}^{T} \sum_{i=1}^{N} P_{EV} x_i(t) \Delta t \tag{1}$$

Where P_{EV} is the rated charging power of an electric vehicle; in the period t, when the ith charging point is disconnected with the electric car or the charging is completed, $x_i(t)=0$, when the ith charging point is connected with the electric car and the charging is not completed, $x_i(t)=1$; $\triangle t$ is the length of the charging period.

3.1.1 Constraint conditions

3.1.1.1 Constraints of the voltage range of the residential area

The load of connected electric cars will cause the voltage reduction of the distribution network node, which is determined by the access point of electric cars and the charging power. (Sortomme et.al., 2011). The rated voltage range of the charging point is:

$$V_{\min} \le V_i \le V_{\max} \tag{2}$$

Where V_i is the voltage of the ith charging point; V_{max} and V_{min} are the maximum and minimum voltage of the power distribution network, respectively.

3.1.1.2 Constraints of the transformer capacity

In the period t, the sum of the average load of the residential area and the charging rated load should not bigger than the rated output power of the transformer:

$$\sum_{i=1}^{N} P_{EV} x_i(t) + P(t) \le \mu S_N \cos\varphi_N \tag{3}$$

Where $P(t)$ is the average load of the residential area; S_N is the rated capacity of the transformer; $\cos\varphi_N$ is the rated power factor of the transformer and generally set as 0.95; μ is the load rate of the transformer and it is determined by the type and the model of the transformer and assumed to be between 30% and 65%.

3.1.1.3 Constraints of the charging power

To avoid the large load fluctuations caused by the sudden access or removal of electric cars, the variation of the charging power in the charging station should be restricted in sequential charging periods(Peter et al., 2012).

$$\left| \sum_{i=1}^{N} P_{EV} x_i(t) - \sum_{i=1}^{N} P_{EV} x_i(t-1) \right| \le \Delta P_0 \tag{4}$$

Where $\triangle P_0$ is the charging power range between the current charging period and the former charging period and defined as 20 kW in this paper.

3.1.1.4 Constraints of the charging capacity

$$\sum_{t=1}^{T} P_{EV} x_i(t) \Delta t = (1 - SOC_{i,0}) \omega_i \tag{5}$$

Where $SOC_{i,0}$ is the initial load state of the *i*th electric car; I ω_i is the battery capacity of the *i*th electric car.

3.1.1.5 Constraints of charge state continuity

$$SOC_{i,t} = SOC_{i,t-1} + \frac{P_{EV} x_i(t) \Delta t}{\omega_i} \tag{6}$$

where $SOC_{i,t}$ is the charge state of the *i*th electric car in the end of the charging period *t*; $SOC_{i,t-1}$ is the charge state of the ith electric car in the end of the charging period (t-1).

3.1.1.6 Constraints of charging protection

The management system will monitor the EMS of the electric car in the charging state in the period △t to avoid the overcharge phenomenon.

$$P_{EV}\Delta t > (1 - SOC_{i,t})\omega_i \tag{7}$$

3.1.1.7 Constraints of the circuit heat load

The heat load of the network element refers to the ratio of the apparent power of the element to its rated power. The heat load considered in this paper refers to the heat load of the connecting circuit between transformers:

$$L_{MC} \le L_{MC_{\max}} \tag{8}$$

L_{MC} means the heat load of the circuit; L_{MCmax} means the maximum heat load.

3.2 Coordinated charging model in the smoothly adjusting charging mode

In order to realize the more balanced distribution of the charging power of electric vehicles we improved the objective function mentioned above by introducing SOC factor(H et al., 2012; Su et al., 2013). In the smoothly adjusting charging mode, supposing that the charging power can be continuously adjusted, the maximum charging energy transmitted to electric vehicles is:

$$\max \sum_{t=1}^{T}\sum_{i=1}^{N}(1 - SOC_{i,t})P_{EV_i}(t)x_i(t)\Delta t \tag{9}$$

where $P_{MCi}(t)$ is the charging power of the electric vehicle in the *i*th charging point

3.2.1 Constraint conditions are respectively expressed below

The charging power of the electric vehicles should not surpass the rated output charging power

$$0 \le P_{EV_i}(t) \le P_{EV} \tag{10}$$

According to the current battery technology, in order to avoid the wide fluctuation of the charging power, the constraint of the charging power variation range is:

$$P_{EV_i}(t-1) - \Delta p_0 \le P_{EV_i}(t) \le P_{EV_i}(t-1) + \Delta p_0 \tag{11}$$

where $\triangle p_0$ is the maximum variation range of the charging power of the electric vehicles and the access/removal shifting of the charging load of electric vehicle. It is generally defined as 0.5 KW.

Constraints of the voltage range of the residential area are similar with Eq. (2).

In the period t, the sum of the average load of the residential area and the charging load should not surpass the rated output power of the transformer:

$$\sum_{i=1}^{N} P_{EV_i}(t)x_i(t) + P(t) \le \mu S_N \cos\varphi_N \tag{12}$$

Constraints of charging capacity:

$$\sum_{t=1}^{T} P_{EV_i}(t)x_i(t)\Delta t = (1 - SOC_{i,0})\omega_i \tag{13}$$

Constraints of charge state continuity

$$SOC_{i,t} = SOC_{i,t-1} + \frac{P_{EV_i}(t)x_i(t)\Delta t}{\omega_i} \tag{14}$$

Because the objective function has introduced the SOC factor, the overcharge phenomenon will not come out when charging the high SOC battery with a low charging power. Thus, the overcharge condition should be neglected. The computing method of the constraints of the circuit heat load is the same to Eq. (8)

3.3 Coordinated charging control algorithm

Combined with the stochastic simulation, the modified particle swarm optimization (PSO) method was adopted to solve maximum electric energy transmitted to electric cars in the paper(Zhan. et al., 2012). Taking the advantage of randomness and periodicity to generate the initial particle, the search diversity of the algorithm can be strengthened. Through the introduction of the algorithm stagnation mutation mechanism, the probability to realize global optimization instead of local optimization will be increased, thus avoiding the premature convergence of the algorithm(Yang et al., 2013). In addition, the dynamic inertia factor W is introduced to balance global search ability and local search ability of the algorithm in the iteration process:

$$w = w_{max} - t' \frac{w_{max} - w_{min}}{T_{max}} \tag{15}$$

where w_{max} and w_{min} are the maximum and minimum dynamic inertia factors, respectively. Generally, w_{max}=0.9, w_{min} =0.9; w_{min} =0.4; t' and T_{max} are respectively the present iterations and the maximum iterations.
In this paper, only the charging period of 14 h from 16: 00 to 6: 00 in the next day was considered.

4. Simulation

4.1 Power distribution network in residential areas

Taking a residential area in Shenzhen as an example, the model parameters are provided as follows: 2 distribution transformers with the capacity of 630 kVA, the no-load voltage ratio of 10/0.4 kV, 2.8-km long three-phase line, 1.2km long single cable, and 500 domestic households. The voltage fluctuation range of the low-voltage distribution network is -10%~+10% (220 V/380 V).
It is assumed that there are 60 charging points and 100 electric cars in the residential area. According to the normal load distribution, we distributed the charging points into Districts A and B in an unequal way. When all the charging points are connected to the electric cars, other electric cars wait for charging. The battery capacity of an electric car is 20 kWh. In addition, the car should be fully charged before 6: 00 in the next morning.

4.2 Comparison of the 3 modes

4.2.1 Uncoordinated charging mode of electric vehicles

In the uncoordinated charging mode, the stochastic simulation of the arrival time and SOC of each car was performed through the Monte-Carlo method to start the charging process. In the uncoordinated charging process, when a car is connected to the charging point, it will be charged at the rated power until the full charging process is completed. In the calculating calculation of the average load, the load curve is prone to be gathered in the peak time, as shown in Figure 1. In the evening, electric car users will start to charge cars as soon as they arrive at the residential area. If the number of charging points is not enough, partial electric cars will wait for charging. If one transformer is in an overhaul, the other transformer works alone. In the period (21: 45-22: 30), the transformer will be seriously overcharged and the circuit will be overheated. The overheat phenomenon is not permitted.

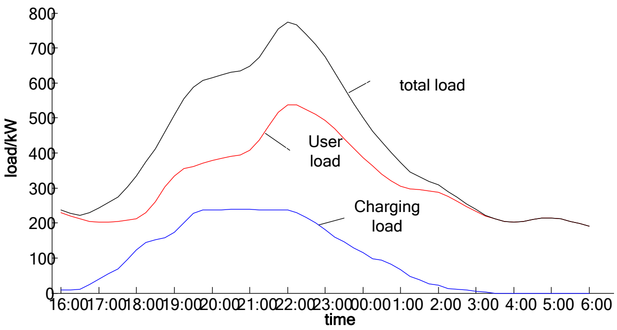

Figure 1: Load curves of the uncoordinated charging mode.

4.2.2 Automatic on-off charging mode

Considering the travel habits of users in the residential area, in this paper we only studied the charging time in the night from 16: 00 to 6: 00 in the next day. In the automatic on-off charging mode, the management system will automatically control the switches of the battery charger to realize the safety operation of the grid power according to the charging requirements.

As shown in Figure 2, the switches of the car will be shut down at the peak time and reconnected at the low-load time, thus realizing the purpose of minimizing the charging cost and the gap between peak and valley time by peak load shifting.

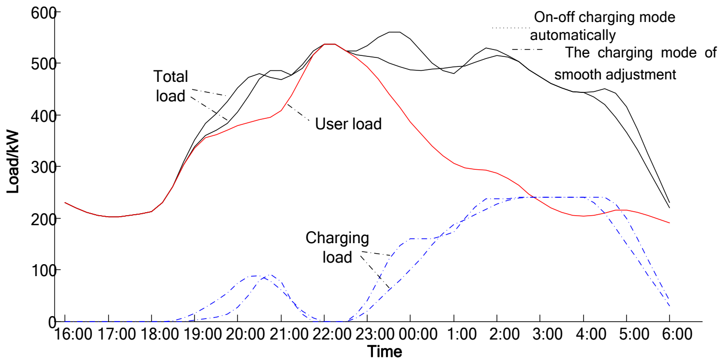

Figure 2: Load curves of the coordinated charging mode.

4.2.3 Smoothly adjusting charging mode

In this mode, the charging power of electric cars can be adjusted continuously. We have collected the data every 15 min. The 12th car starts to charge at 19: 30 and its charging power is rising. However, at the peak time, the power decreases to 0. Then, the car is reconnected at 23: 00 and the power rises to the highest power (3.5 kw) until 00: 30. The full charging process is completed at 2: 30.

5. Results and analysis

Table 1: Parameter settings of energy prices

Charging periods	TOU price (Yuan/kWh)	uniform power pricing (Yuan/kWh)
16: 00-17: 00	0.687	
17: 00-21: 00	0.869	1.2
21: 00-00: 00	0.687	
00: 00-06: 00	0.365	

Table 2: Simulation results of coordinated and uncoordinated charging modes

Charging modes	Profit amount	Load volatility	Total maximum load	The end time of charging	The end charged state
Uncoordinated charging mode	334.7870	9.0413	780	3: 00	100%
Automatic on-off charging mode	523.1480	4.3014	550	6: 00	100%
Smoothly adjusting charging mode	576.6970	4.2176	550	6: 00	100%
50% automatic on-off charging mode	421.6492	4.9947	650	6: 00	100%
50% smoothly adjusting charging mode	465.1440	6.0316	650	6: 00	100%

Power grid sells the electricity in the form of TOU electric price, and the battery charger management sectors develop the uniform power pricing system. The parameter settings of energy prices are provided in Table 1. According to the simulating calculation with Monte-Carlo method, total charging electric energy of all the electric cars is 1442 kWh. The simulating results of the coordinated charging mode and un-coordinated charging mode are provided in Table 2.

According to the results in Table 2, the coordinated charging mode can increase the profit amount of the charging stations in the residential area. However, the charging stations in the residential area are not aimed at making profit. After deducting the capital cost of the stations, the rest are assumed as the saving cost, which will be paid to the users so as to raise the customer response coefficient. The cost in the two modes mentioned in this paper is lower. Therefore, they will attract more users of electric vehicles to participate in the coordinated charging mode.

For the electric power sector, the coordinated charging mode is helpful to reduce the volatility of load curve; for the electric car users, the coordinated charging mode is helpful to obtain additional compensation and reduce the charging cost. After the electric vehicles are widely used, the charging station with the coordinated charging mode will be a mutually beneficial strategy.

6. Results and analysis

Taking a residential area in Shenzhen as an example, we compared the two coordinated charging modes with the uncoordinated charging mode and found that coordinated charging modes could be directly adopted in the original power distribution network without the upgrade or transformation of the power grid infrastructures, thus reducing the project cost.

The smoothly adjusting charging mode has a higher profit potential and the smoother load curve. The automatic on-off charging mode is simple and reliable. The two modes can both realize the minimum charging cost and the smallest gap between peak and valley time by peak load shifting. If the mode is promoted in a large scale, its economic profit will be considerable.

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