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Large Scale EVs' Charging Scheduling Ensuring Secure and Efficient Operation of Traffic and Distribution

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Abstract

Current research about the application of large scale electric vehicles (EVs) is carried out in two fields: (1) From the aspect of the traffic system, charging navigation technologies were proposed, to improve traffic efficiency and charging convenience of the EV driver. (2) From the aspect of the distribution system, the "smart" charging strategies were developed to optimize charging profile, where power loss of distribution system, voltage limits and load variance were taken into account. However, few studies focused on simultaneous improvement of EV owner's convenience, traffic system performance, charging station performance and distribution system performance after the application of large scale EVs. In this paper, a multi-objective function considering the performance indices of traffic system and distribution system including road travel speed, traffic flow, charging waiting time, power loss of distribution system and voltage of distribution node is developed to schedule large scale EVs' charging behaviour and obtain optimal performance of the whole system. Constraints including load capacity of charging stations, charging requirements and endurance mileage of EVs are overall considered, and a method for determining weights of the multi-objective function is discussed. A simulation system is built for verifying the effectiveness of proposed strategy. Simulation results shows that, compared with the usual charging scheduling strategy, average heavy congestion ratio of the district around the charging station in the evening rush hours is reduced from 0.52 to 0.48, the percentage of EVs waiting for charging is reduced from 7.5% to 0.5%, the maximal power loss rate of distribution system is decreased by 3.5%, and the maximal voltage deviation of distribution system is decreased by 3.4% due to the proposed strategy.

Keywords: electric vehicle, charging scheduling strategy, traffic system, distribution system, charging station

1 Introduction

With the increase of population and development of economy, the consumption of fossil energies increases, and environment worsens. In order to address these problems, the development of electric vehicles (EVs) may be a promising solution. Nowadays governments all over the world are building charging and battery exchanging infrastructures with great interest and announcing preferential policies to promote EVs. In the meantime, the worldwide leading automobile manufacturers and universities are also being vigorous to develop EV technologies [1-3].

However, key problems have to be discussed before EVs are able to replace the conventional vehicles. First, the limited driving range reduces the reliability and convenience of driving an EV. Second, due to the intermittency and randomness of the charging behaviour, during the application of large scale EVs, problems including traffic congestion, security and economy problems of distribution system, such as high node voltage drop and too much power loss of distribution system have to be considered. In order to solve these problems, some research has been performed to optimize the driving path of EVs and improve distribution system performance.

The influence on the distribution induced by the introduction of EVs was taken into account in [4-6]. Hu *et al*. discussed the influence on the operation of charging infrastructure, distribution system, and planning of distribution system induced by EVs' access to the distribution system [4]. Zhan *et al.* proposed a method to reduce the power loss of distribution system trigged by EVs charging [5]. Putrus *et al.* evaluated the influence on the energy supply/demand matching, power quality and power imbalances caused by EVs' charging [6]. The charging path planning and charging station recommendation technology considering the information of traffic or distribution are discussed in [7-9]. Artmeier *et al.* utilized the location of charging station and EV, to recommend the nearest charging station for the EV [7]. Besides, research on charging station recommendation and charging path planning was discussed in [8,9]. Guo developed a charging navigation system based on the intelligent transport system, in which the optimal charging path was calculated by the control center by means of converting geographical distance into electrical distance. Shu Su *et al.* recommended charging stations for EVs considering the real-time electric cost which was calculated by the node voltage and traffic congestion. However, the charging station recommending technologies above only served for a single EV, and didn't consider the influence on the traffic system.

As a conclusion, the aforementioned technologies focused on either EVs' drivers' convenience or distribution performance regarding the application of EVs [10, 11], which couldn't ensure optimal performance of the whole system. In fact, charging path planning technologies that merely considered EVs' drivers' convenience might result in local traffic congestion around the charging stations as well as severe power loss and voltage deviation of distribution system. In this paper, a distinguished charging scheduling strategy is proposed for large scale EVs, which can improve traffic efficiency, reduce the charging waiting time of the driver, and also reduce power loss and voltage deviation of distribution system. Indices such as road travel speed, traffic flow, charging waiting time, power loss of distribution system and voltage of distribution node are calculated for real-time estimation of performance of the traffic system and distribution system. On this basis, a multi-objective optimization function is developed to schedule large scale EVs' charging behaviour, constraints including load capacity of charging stations, charging requirements and endurance mileage of EVs are considered. The simulation results strongly prove the efficiency of the proposed charging scheduling strategy. Our work provides elementary conclusions that charging scheduling are necessary for both the traffic system and the distribution system with application of large scale EVs, and optimization of the two systems should be performed simultaneously for performance improvement of the whole system.

The contribution of the paper: (1) A charging scheduling strategy considering EV owners' convenience, running performance of traffic system, charging station and distribution system simultaneously is proposed with the application of large scale EVs. (2) To solve the multi-objective function, a method for determining weights of the multi-objective function is discussed considering the actual traffic condition and distribution load.

The remainder of the paper is organized as follows: In section 2, the EVs' charging scheduling strategy including the multi-objective function, constraints, determination of weight and implementation of real-time EVs' charging scheduling is developed. In Section 3 the simulation results are analysed. Finally, the conclusions are given in Section 4.

2 EVs' charging scheduling strategy

Application of large scale EVs may lead to traffic congestion, insecure operation of charging stations and high power loss of the distribution system. For this reason, a charging scheduling strategy becomes necessary for convenient and comfort travel of EV drivers, optimal operation of traffic system, charging stations and distribution system. The core of the strategy is to develop a multi-objective optimization function, build proper constraints of traffic system, charging stations and distribution system, and solve the optimal charging path based on mature path planning methods [12-15].

2.1 Objective function

In this paper, the proposed large scale EVs' charging scheduling strategy ensures secure and efficient operation of traffic system, distribution system and charging station, and it is a typical multi-objective optimization problem. The common method to transfer the multi-objective optimization problem into a single-objective problem is nondimensionalization and linear weighting of each objective [15]. A multi-objective function builds in this paper is shown as follows:

$$\min F = w_1\frac{f_1}{\min f_1} + w_2\frac{f_2}{\min f_2} + w_3\frac{f_3}{\min f_3} + w_4\frac{f_4}{\min f_4} + w_5\frac{f_5}{\min f_5} \quad (1)$$

where, f_1、f_2、f_3、f_4、f_5 denotes the reciprocal of road travel speed, quantity of EVs in charging station, charging power, power loss and voltage deviation of distribution system respectively. $minf_1$、$minf_2$、$minf_3$、$minf_4$、$minf_5$ denotes the minimal reciprocal of the road travel speed, optimal number of EVs of charging station, minimal charging power, minimal loss and minimal voltage deviation of distribution system respectively, which are calculated by optimizing the objective individually. w_1、w_2、w_3、w_4、w_5 are the weights of each objectives respectively.

2.1.1 Traffic system

To ensure the efficient operation of traffic system, road travel speed should be calculated at the beginning of each period. For any road $(p,q)\in A$ (A is the road set, and p, q is the node in the road network). The road travel speed $V_{road}\{p,q\}(j)$ at this period is calculated according to the traffic flow $q\{p,q\}(j\text{-}1)$ at last period and the classical velocity-flow model:

$$V_{road}\{p,q\}(j) = \frac{V_m\{p,q\}}{1+q\{p,q\}(j-1)/C\{p,q\}} \quad (2)$$

where, $V_m\{p,q\}$ is the limited value of velocity and $C\{p,q\}$ is the capacity of traffic flow, which are both constants. At the initial moment ($j=0$), traffic flow and road travel speed of all roads are the statistical results of the actual traffic system at corresponding moment. The traffic flow $q\{p,q\}(j\text{-}1)$ at each period could be calculated by EVs traveling through the roads.

To guarantee an unblocked traffic system, the objective function for traffic system could be expressed as:

$$f_1=V_{road}\{p,q\}(j) \quad (3)$$

2.1.2 Charging station

Charging waiting will inevitably happens during large scale EVs' application. So the number of each charging station is counted in this paper, which is expressed as:

$$f_2=Num(r,t0) \quad (4)$$

where: $Num(r,t0)$is the estimated number of EVs in charging station r at $t0$.

2.1.3 Distribution system

When large scale EVs are introduced into the distribution system, power loss of distribution system will increase, node voltage of distribution will change and charging load will increase as well. To guarantee secure and efficient operation of distribution system, the weight of distribution should be modified before planning the optimal charging path for each EV. For this reason, prediction on power loss of distribution system $P_{loss}(Pcs\_r,t0)$, voltage deviation $V_{shift}(Pcs\_r,t0)$ and charging load $Pcs(r,t0)$ is necessary.

1）Power loss of distribution system

The power loss of distribution system will increase as large scale EVs access to distribution system. Besides, the other parameters including load of the other node, the node accessed by the charging station and capacity of charging station, are concrete, and power loss of distribution system mainly relates to the load of the node the charging station access to. Therefore, power loss of distribution system can be expressed as:

$$f_3=(Pcs\_r,t0) \quad (5)$$

where: t0 is the estimated time for each EV arriving at the charging station r, Pcs_r denotes the estimated load of the charging station r at t0. $P_{loss}(Pcs\_r,t0)$ denotes the power loss of distribution system which can be calculated by MATPOWER utilizing the charging power at $t0$.

2) Voltage deviation of distribution system

Voltage profile of distribution system will change as the charging station access to distribution system, which will lead to insecure operation of distribution system. Voltage deviation of distribution system is calculated according to the shift between node voltage and the rated voltage, which can be expressed as:

$$f_4 = V_{shift}(P_{cs\_r}, t_0) = \sum_i^N \frac{|V_i - V_0|}{V_0 \bullet N} \qquad (6)$$

where: N is quantity of distribution nodes; V_0 is the rated voltage of distribution. V_i is node voltage, which is calculated by MATPOWER utilizing the charging power of charging station r at $t0$. $V_{shift}(Pcs\_r,t0)$ is voltage deviation of distribution at $t0$.

3）Charging power

The performance of distribution system can be improved by restraining charging power of charging station as it is related to the load of each node,

$$f_5 = P_{cs}(r, t_0) \qquad (7)$$

where：$P_{cs}(r,t0)$ is the estimated power of charging station r at $t0$, which is calculated by estimated charging power at $t0$.

The objective functions above shows that the proposed strategy in this paper will recommend the charging path and charging station with the high road travel speed, less charging power, less loss voltage deviation of distribution system, and less charging waiting time for the EVs.

2.2 Constraints

1) Charging station load constraint

The reasonable threshold of charging station load should be limited according to the charging requirement of EV users in the certain area.

$$P_{cs}(r, t0) < P_{lim}(r) \qquad (8)$$

Where, $P_{lim}(r)$ denotes the threshold load of charging station r.

2) EV charging constraint

Only EVs whose remaining driving range is less than thirty percent of the driving mileage will be charged:

$$D\_r(i) <= 0.3 * D\_m(i) \qquad (9)$$

where, $D\_r(i)$ denotes the remaining driving range of the EV i, and the $D\_m(i)$ denotes the driving range of the EV i.

3) EV driving range constraint

The recommended charging station should be in the EV's remaining range. If the charging path recommended by the optimal strategy exceeds the EV's remaining driving range, the nearest charging station will be adopted.

$$D\_r(i) <= d0(i) \qquad (10)$$

Where, $d0(i)$ denotes the length of path proposed by the strategy.

2.3 Weight of function

The core of solving a multi-objective function is to determine the weights of it. The power loss, voltage deviation of distribution system and charging power changes in the same trend, and shows a certain regularity. Therefore, in this paper the weights of the three objectives on distribution system are set to be the same value. As a result, only the weights of traffic, charging station and distribution has to be determined. Meanwhile, ensuring the rationality of (1), we determine the weights of traffic, charging station and distribution according to the traffic condition and load of distribution. From the aspect of traffic, according to the general traffic condition in Beijing, 7:00 to 9:00 and 17:30 to 19:30 are the rush hours, 9:00 to 17:30 and 19:30 to 23:00 are usual periods with light traffic congestion, 23:00 to 7:00 is night period with smooth traffic. From the aspect of distribution, according to the "Notice on Relevant Issues of North China Power Grid Implementing the Coal Price Linkage" published by national development and reform commission in 2006, 10:00 to 15:00 and 18:00 to 20:00 are peak load periods, 7:00 to 10:00 and 15:00 to 18:00 are usual load periods, 23:00 to 7:00 is valley load period. On the basis of condition of traffic congestion, load of distribution, and the tolerable waiting time of drivers of different periods in a day, we set the weights of objectives satisfying the following rules.

1) Either in the traffic rush hours or peak load time period of distribution.

The weights of traffic or distribution are correspondingly set to be large, and the other weights set to be small, which ensures the efficient operation of traffic system and distribution system.

2) Both in the traffic rush hour and peak load period of distribution.

a. To ensure the secure operation of distribution, node voltage of distribution is evaluated. According to GB/T 12325-2008 "Power quality - Deviation of supply voltage", voltage deviation of distribution should be less than 7%. Therefore,

when the voltage deviation is more than 7%, the weight of distribution is set to be large, and the other weights set to be small, which ensures the secure operation of distribution.
b. When the voltage deviation of distribution is less than 7%, the weight of traffic is set to be large, and the other weights set to be small, which ensures the efficient operation of traffic during the rush hours.

3) In the usual period of traffic and distribution.

The weights of traffic, distribution and charging station are set to be the average value.

4) In the period with smooth traffic and valley load of distribution.

With few EVs, the traffic runs smoothly and charging wait doesn't exit. In this case, we only considers the influence of distribution.
According to the above rules, we set the weight of traffic, distribution and charging station as shows in the table 1.

Table 1: Weights of traffic, charging station and distribution

Time		Traffic	Chargin g station	Distribution
23:00-7:00		0.1	0.1	0.8
7:00-9:00、17:30-18:00		0.7	0.1	0.2
9:00-10:00、5:00-17:30 21:00-23:00		1/3	1/3	1/3
10:00-15:00、9:30-21:00		0.2	0.1	0.7
18:00-19:30				
Distribution condition	Safe	0.7	0.1	0.2
	unsafe	0.2	0.1	0.7

2.4 EVs charging scheduling

In this paper, the Dijkstra's algorithm is chosen as the charging path planning algorithm. In this algorithm, position of each EV is set to be the start point and each charging station is set to be the end point. In the process of searching the optimal charging path, the directed weight between start point and end point is calculated, and the charging path and charging station with the minimal weight is chosen to be the "optimal" charging path and the "optimal" charging station. The directed weight is calculated by (1), which considers the influence of traffic, charging station and distribution. The core of the method is to calculate (1) utilizing the information of traffic, charging station and distribution before planning charging path and recommending charging station for the EV, which will lead the EV to the charging station with the minimal (1), and will ensure the secure and efficient operation of EVs, traffic, charging station and distribution.
The calculation of directed weights is shown in figure 1.

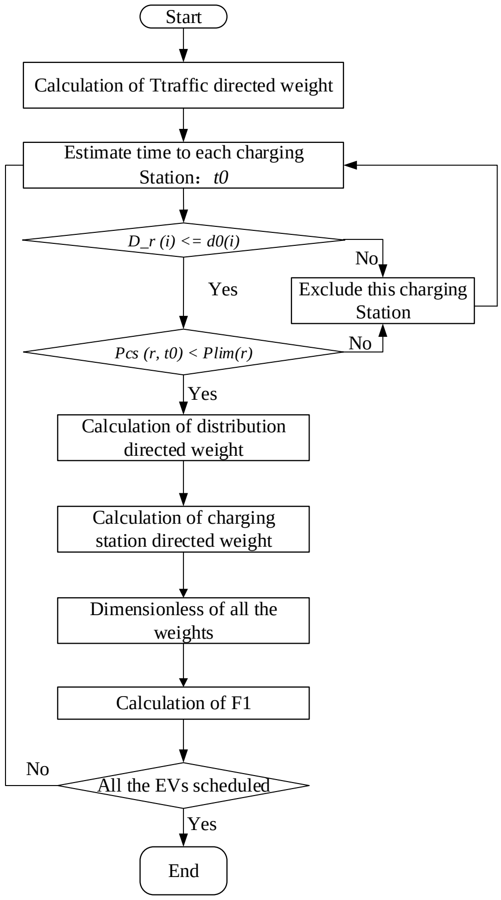


Figure 1: Flowchart of EVs' scheduling

3 Evaluation and analysis

3.1 Establishment of the simulation platform

In this study, the traffic system model is built based on the roads within third ring of Beijing, whose area is about 25km^2[17]. The distribution system is built on the basis of IEEE-33 radial distribution network, in which 9 distribution networks are built, and each distribution covers a charging station.
In this study, 200,000 EVs operating for 24 hours is simulated. Furthermore, rush hours (7:00-9:00 and 17:30-19:30), usual hours (9:00-17:30 and 19:30-23:00) and night period (23:00-7:00) are divided according to the general travel law of the citizens in Beijing. And different quantity of EVs are introduced to the system every 5 minutes according to different time periods, as shown in table 2.

In order to verify the effectiveness of the proposed EVs' scheduling strategy, i.e. “optimal strategy”, a "near strategy" is introduced for comparison, which relies on distance to schedules EVs' charging and leads the EVs to the nearest charging station.

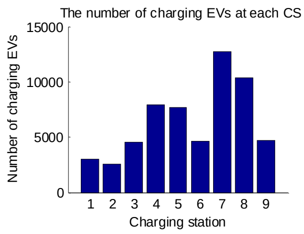
Table 2: Quantity of induced EVs of different periods

Time	Quantity of EVs
7:00-9:00	2080
9:00-17：30	700
17:30-23:00	2080
23:00-7:00	10

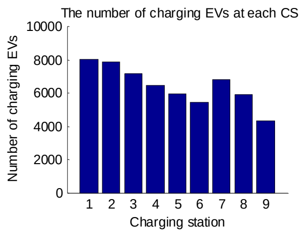
3.2 Evaluation result analysis

3.2.1 Traffic

On the basis of actual traffic condition in Beijing, the introduction of EVs will lead to traffic congestion around the charging station. Figure 2 shows the quantity of EVs in the each charging station under the two strategies. The quantity is more uniform under the “optimal strategy”, and traffic congestion around the charging station is relived.



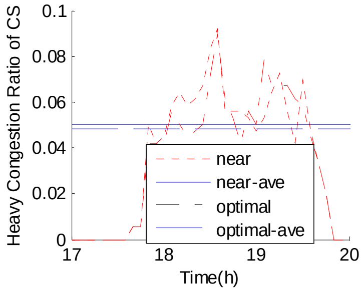
(a) “Near strategy”



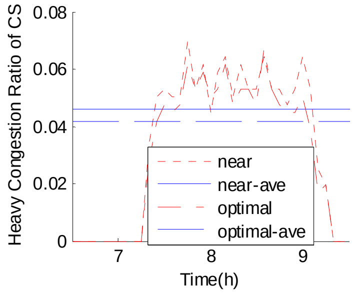
(b) “Optimal strategy”

Figure 2: Quantity of each charging station

Heavy congestion ratio of the districts around the charging station under the two strategies is shown in figure 5. The average heavy congestion ratio of the rush hours in the morning is reduced from 0.52 to 0.47, average heavy congestion-ratio in the evening is reduced from 0.52 to 0.48 under the “optimal strategy”.



(a) Rush hour in the morning



(b) Rush hour in the evening

Figure 3: Heavy congestion-ratio curves near the charging stations

3.2.2 Charging station

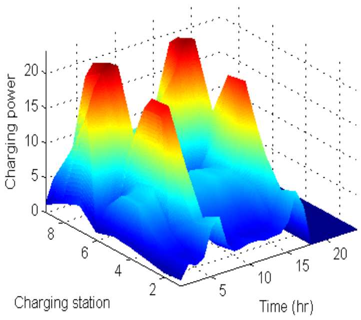
Charging waiting time of EVs under the two strategies is shown in table 2. With the “optimal strategy”, less than 0.5% EVs need to wait for charging. On the contrary, under the “near strategy”, almost 7.5% percent EVs have to wait for charging, and some EVs even queue more than one hour, which badly reduces the travel efficiency.

Table 3: Charging waiting time

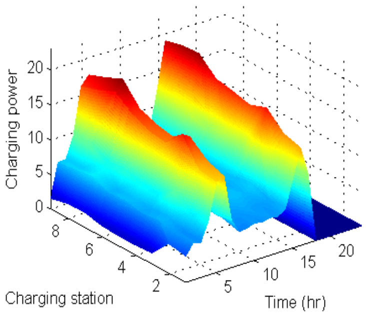
Time	“Near strategy”	“Optimal strategy”
0-5min	970	3893
5-10min	0	1886
10-15min	0	1520
15-20min	0	1514
25-30min	0	1373
30-70min	0	4686

3.2.3 Distribution

The temporal and spatial distribution of charging power under the two strategies is shown in figure 2. Under the “optimal strategy”, the charging power is more uniform during rush hours, and the charging profile of distribution is more reasonable, which means better performance of distribution system.



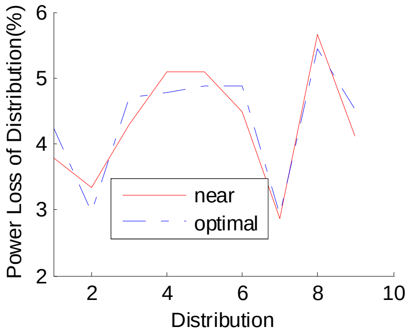
(a) “Near strategy”



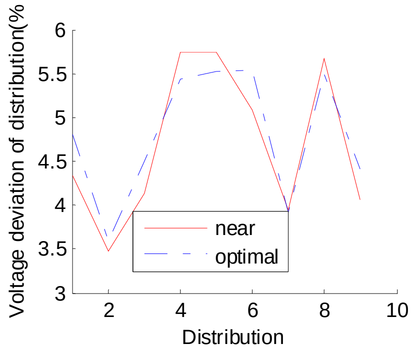
(b) “Optimal strategy”

Figure 4: Temporal and spatial distribution of the charging load

The loss and voltage deviation under the two strategies is shown in the figure 2. With the “near strategy”, loss and voltage deviation of distribution 4, 5 and 8 is higher than other distributions, which is reduced under the “optimal strategy”.



(a) Power loss of distribution system



(b) Voltage deviation of distribution system

Figure 5: Loss and voltage deviation of distribution system

4 Conclusion

In this paper, the EVs’ charging scheduling aims at secure and efficient operation of the traffic and distribution system, and is proved to be effective for the performance improvement of the whole system. The conclusions are summarized as follows:

1. Application of large scale EVs leads to local traffic congestion around the charging stations. The proposed charging scheduling strategy relives the congestion, which improves traffic efficiency.
2. Disordered charging behaviour of large scale EVs leads to long charging waiting time and high percentage of EVs waiting for charging. The proposed charging scheduling strategy significantly reduces both the charging waiting time and the quantity of waiting EVs, which improves driving convenience of EVs’ drivers.
3. The security and economy problems of distribution system, such as severe power loss and high deviation of voltage, are solved effectively by the proposed charging scheduling strategy. Moreover, it optimizes recommendation of charging stations for large scale EVs, which enhances secure and efficient operation of the distribution system.

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