Dr. Norbert Cheung's Series in Electrical Engineering

Level 5 Topic no: 26

EV Infrastructure

Contents

Reference:

C.C. Chan and K.T. Chau, Modern Electric Vehicle Technology, London: Oxford, University Press, 2001

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1. Infrastructure Issues

In order to develop a successful EV infrastructure, we should pay attention on the following aspects:

- availability of charging stations
- convenience of payment for charging
- standardization of EV batteries and charging
- regulation of clean and safe charging
- support from training and promotion and
- impacts on power utilities.

The design of EV charging systems mainly depends on the level of charging currents to charge the EV batteries. There are three major current levels:

(1) Normal charging current—the EV batteries can be charged by a rather low charging current, about 15 A, and the charging period may last for over 6 h. The operation and installation costs of the corresponding charger are relatively low since the power and current ratings involved are not of critical values. This charging current usually benefits to increase the charge efficiency and to extend the battery life.

(2) Medium charging current—the EV batteries can be charged by a medium current of 30–60 A, and the charging period may last for a few hours. The operation and installation costs of the corresponding charger are relatively higher than that for normal charging current because of the necessity to upgrade the charging equipment.

(3) Fast charging current—the EV batteries can be charged up within a short time based on a high charging current of 150–400 A. In contrast to that using normal or medium charging current, the corresponding charger offers relatively low charge efficiency. Definitely, the corresponding operation and installation costs are high.

2. Domestic and Public Charging

Domestic Charging

The basic requirement of domestic charging is the availability of a garage or a parking lot that is fed with electricity. There are two different ways:

- For those houses with a private garage, an indoor socket outlet can be installed for recharging.
- For those apartments and multi-storey buildings with car parks attached, an outdoor socket outlet can be installed. The outdoor socket outlets should have individual protection circuits, and can be independently operated. Only residents with permission can access these socket outlets for EV charging.

Public Normal Charging Station

Normal charging stations are designed to recharge EVs based on their on-board chargers using the normal charging current. These charging stations are generally located nearby the residential areas or working areas in which the EVs will be parked for 5–8 h. These charging stations are usually designed in a large scale so that many EVs can be accommodated simultaneously for normal recharging. The corresponding charging poles are usually modular designed, consisting of control terminals and delivery terminals. In practice, EV drivers simply park their EVs on the allocated areas of the charging station, then connect the cable and initiate the recharging process.

Public Fast Charging Stations

The key of fast charging stations is obviously the off-board fast charging module, which can output 35 kW or even higher. The corresponding voltage and current ratings are 45–450 V and 20–200 A, respectively. As both power and current ratings are so high, it is preferable to install such recharging facilities in

supervised stations or service centres. To avoid overcharging the EV batteries and causing excessive heat generation, there should be a communication between the fast charging module of the station and the battery monitoring circuit of the EV for information exchange so that the EV battery condition can be on-line monitored and the charging current can be on-line modified. Unlike normal charging stations, the fast charging stations adopt the cables consisting of more wires. Typically, these cables are composed of seven wires, including positive, negative, ground, pilot wire and a three-wired communication channel.

Public Battery Swapping Stations

Instead of charging the batteries immediately, we have another way to refuel the energy source of EVs—mechanically swapping the discharged batteries with those fully charged batteries. Of course, all these batteries should be owned by the service station or battery company while the EV driver is only a battery borrower.

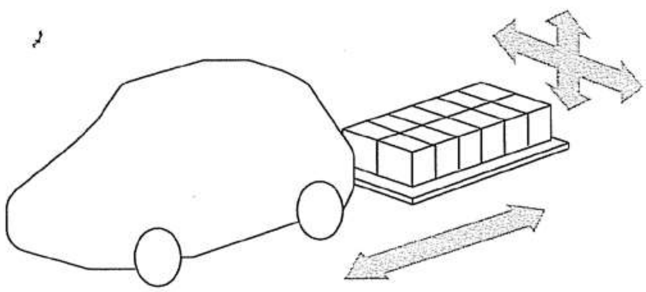


Fig. 9.1. Principle of battery swapping.

Move and Charge Zone

The most ideal situation for charging EV batteries is to charge the vehicle while it is cruising on the road, so-called the move-and-charge (MAC). Thus, there is no need for an EV driver to find a charging station, park the vehicle and then spend time to recharge the batteries. This MAC system is embedded on the surface of a section of roadway, the charging zone, and does not need any additional space.

Both conductive and inductive types of MAC can be implemented. For the conductive MAC system, an on-board contact arch is mounted on the bottom of the EV body. By physically contacting the charging elements which have been embedded on the road surface, the arch picks up instantaneous high current. Since the EV is cruising through the MAC zone, the charging process is a kind of pulse charging. For the inductive MAC system, the on-board contact arch is replaced by inductive coils, and the embedded charging elements are replaced by high current coils which produce strong magnetic field. Obviously, the conductive MAC zone is relatively not attractive because it suffers from mechanical wears and positioning problems of the contact arch. In fact, recent investigations have only focused on

3. Payment System

(1) Charge for both parking and recharging separately—it seems to be most fair to all EV drivers because the parking time and recharging energy are separately counted or charged. None of the two components need to subsidize one another. However, both parking timer and revenue meter are necessary and the relevant management costs are relatively high.

(2) Charge for recharging only, with free parking—it can encourage EV drivers to charge the EV batteries whenever necessary. Because of free parking, those drivers park their EVs solely for recharging batteries need to subsidize the others. This scheme is particularly suitable to the public charging stations located in those rural areas where electricity is expensive. It takes the advantage that only the revenue meter is necessary.

(3) Charge for parking only, with free recharging—it can encourage EV drivers to fully charge up their EV batteries whenever possible. Because of free recharging, those EVs with high remaining capacity need to subsidize the others. This scheme is particularly suitable to the public charging stations located in those populated cities where space is very expensive. It takes the advantage that only the parking timer is necessary.

(4) One-line charge for both parking and recharging—EV drivers can pay for daily, weekly or monthly labels for parking and recharging. Thus, they can gain access to reserved parking areas and make use of those charging facilities.

In addition to the use of revenue meters for counting the power consumption, some electronic devices such as computers are necessary to record the power consumption and hence calculate the necessary payment. A mature method is to use slot machines which can provide the information of power consumption and payment so that EV drivers can make the payment by cash or credit cards. Another method is to employ smart cards which can be used to record the power consumption and also make payment automatically. The latest smart card is a proximity type which carries semiconductor chips to store the user identity and those related information.

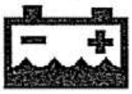
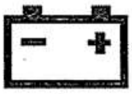
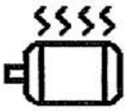
Symbol	Function	Symbol	Function
	State of charge of main batteries		Charge coupling
	Liquid level of main batteries		Electric brake
	State-of-charge of auxiliary batteries	READY	Operation ready
	Motor overheat		System malfunction
	Status of brake vacuum system		Reduced power

Fig. 9.2. JEVS symbols for control, indicators and tell-tales of EVs.

4. Impacts on Power System

EVs bring both good and bad influences on power system. Positively, the batteries of EVs can be charged at off-peak periods or at night so that the overall power demand can be levelled and the utilization of power system facilities can be improved. Negatively, the EV battery chargers are nonlinear devices which generate harmonic contamination to our power system, while the battery recharging of EVs at normal or peak periods creates additional current demand burdens on our power system.

Harmonic Impact

- Since conventional measuring devices, such as ammeters, voltmeters, watt-meters and energy meters, are calibrated at a fixed frequency (50 or 60 Hz), and generally have poor frequency response, the harmonic currents and voltages can deteriorate their accuracy to record the actual current, voltage, power and energy consumption, respectively.
- Since large capacitor banks are usually installed in our power system to improve the overall power factor, they may be damaged by excessive harmonic currents.
- As the triplen harmonic current flows through the neutral of a three-phase four-wire power system, the neutral conductor may be overloaded, causing excessive heat problems. Also, common mode noise (neutral to ground voltage) may occur at the neutral point and the live-to-neutral voltage may be affected.
- As the harmonic currents flow through the power transformer with delta connection, the triplen harmonic component can circulate within the delta loop, causing excessive heat problems.
- In the presence of harmonic currents and voltages, the over-current, over-voltage and under-voltage protection devices may suffer from false alarm or tripping.

Harmonic Compensation

the device level, many new topologies of battery chargers are being proposed in such a way that the input harmonic current distortion is aimed to be minimal. These approaches rely on the invention of new battery chargers with minimum harmonic contamination and economically viable. In the system level, it can further be divided into two subgroups—passive and active filters. The passive filters can be simply phase-shifting transformers to suppress certain low-frequency harmonics or different combinations of inductor-capacitor sets to reduce those undesirable harmonics. On the other hand, the active filters are advanced power electronic systems which can on-line measure and diagnose the system harmonics so that they can instantaneously generate the same magnitude but anti-phase harmonics to neutralize the system harmonic content. As expected, these active filters need additional power source and sophisticated real-time control technology.

level). Rather than adding something to our power system, the basic idea is simply to coordinate the number of EV chargers per charging station. Since the phase angles of those harmonic currents generated by one EV charger are normally different from those by another EV charger, there is a natural effect that harmonic compensation or even cancellation may occur. The more the number of chargers are being used per station, the higher the possibility to compensate the overall harmonic currents flowing to that charging station can be resulted. However, there is a practical limitation on the number of EV chargers per station because of the availability of space.

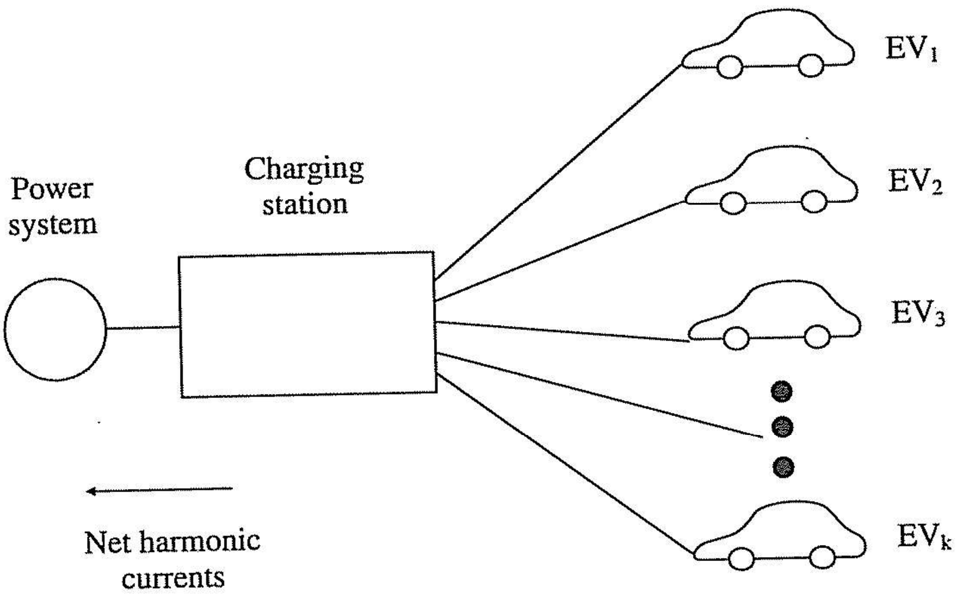


Fig. 9.3. Multiple EVs at a charging station.

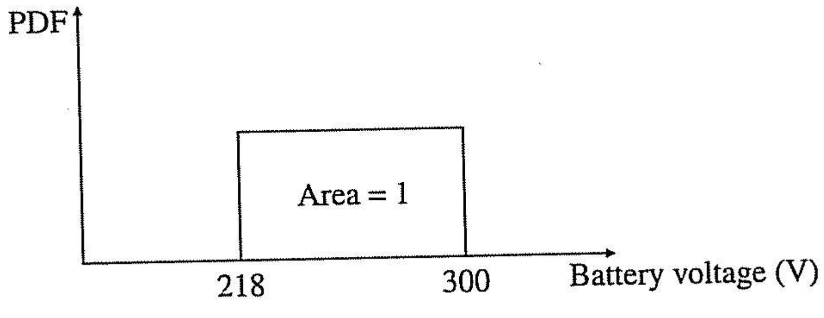


Fig. 9.4. PDF of EV battery voltages.

As illustrated in Fig. 9.3, the net harmonic current injected to the power system from a charging station with k EVs is investigated. We assign k random numbers to represent the state-of-charge (SOC) of these EVs, and represent the corresponding battery voltages by $\xi_1, \xi_2, \ldots, \xi_k$. At any instant, an EV in the station may be fully discharged, partially discharged or even fully charged (after a period of recharging). Thus, its SOC can be described by a random number with a uniform probability density function (PDF) ranging from fully discharged to fully charged. Assuming that the battery voltage is linearly related to the SOC, all EV battery voltages are represented by a uniform PDF (for example, between 218 and 300 V) as shown in Fig. 9.4. The charging current I required by each EV can be described by a Fourier series:

$$I = \sum \left\{ \frac{1}{n\pi} [\sin(n\beta_2) - \sin(n\beta_1) - \sin(n\beta_4) + \sin(n\beta_3)] \cos(n\omega t) \right\} + \sum \left\{ \frac{1}{n\pi} [-\cos(n\beta_2) + \cos(n\beta_1) + \cos(n\beta_4) - \cos(n\beta_3)] \sin(n\omega t) \right\},$$

where β_1, β_2, β_3 and β_4 are the conduction angles of the EV charger, and n is the order of harmonics. It can be rewritten as:

$$I = \sum c_n \cos(n\omega t + \varphi_n),$$

where $c_n = \sqrt{a_n^2 + b_n^2}$ and $\varphi_n = \tan^{-1}(b_n/a_n)$ are the magnitude and phase angle of the nth harmonic components, respectively. For various battery voltage levels, β_1, β_2, β_3 and β_4 are different. Hence, both c_n and φ_n are different for those k EVs in the same station. By summing up all generated harmonics in the complex domain, harmonic compensation at certain orders can be resulted.

Based on the Monte Carlo method (Hammersley and Handscomb, 1979; Sobol, 1994), the expected value of the total harmonic distortion (THD) of the input current flowing to the whole charging station can then be expressed as:

$$E[\mathrm{THD}] = \frac{1}{N} \sum_{j=1}^{N} \left\{ \frac{1}{k} \sum_{i=1}^{k} f(\xi_{i,j}) g(\xi_{i,j}) \right\},$$

where N is the total number of calculation for the Monte Carlo process, $\xi_{i,j}$ is the battery voltage of the ith EV at the jth calculation, $f(\xi_{i,j})$ and $g(\xi_{i,j})$ are the corresponding PDF and THD. Hence, the expected THD with respect to the number of EVs being charged in the same station is calculated as shown in Fig. 9.5. It is obvious that the higher the value of N (equivalent to the more the sample of calculation), the less the ripples (equivalent to the higher the degree of accuracy) can be resulted. Since the computational time significantly increases with the value of N, $N = 100$ is sufficient enough to provide the accuracy. It can be easily found that the expected THD decreases as the number of EVs increases.

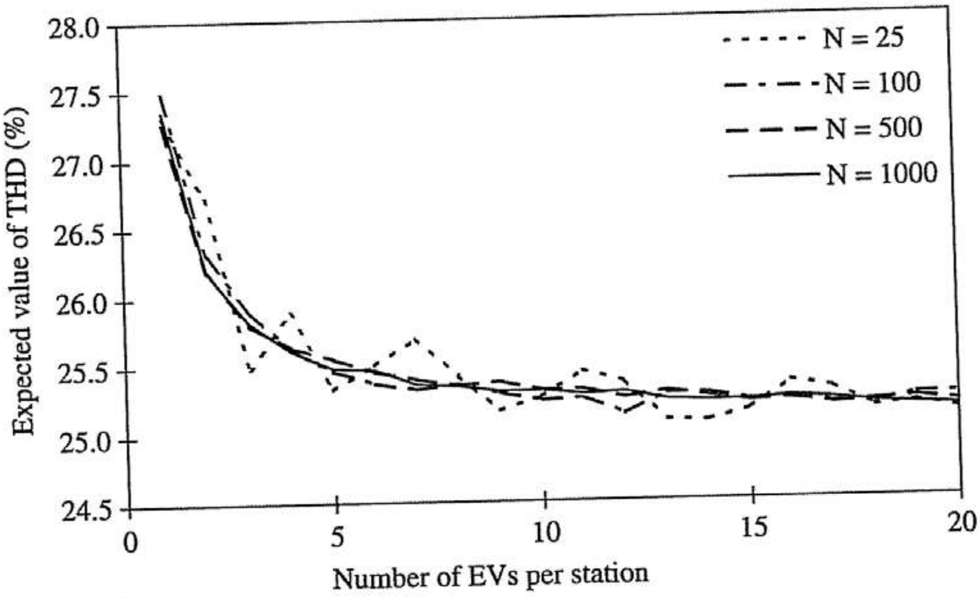


Fig. 9.5. Expected THD vs. number of EVs at a charging station.

Current Demand Impact

During the recharging of EVs at non-off-peak periods, the additional current demand inevitably creates burdens on the existing power system. These burdens are summarized below:

(1) In case the existing power system has been fully utilized, the additional current demand due to EV recharging at non-off-peak periods inevitably overloads the system. Otherwise, additional power plants and transmission networks are necessary to account for such additional current demand.

(2) Based on the reserve margin approach (Berrie, 1983), the product of the capacity of a reliable power plant and the number of power plants must be greater than or equal to the peak demand plus the reserve margin, typically 20%. The higher the peak current demand, the higher the generation and transmission capacities are necessary. Thus, the peak current demand governs the sizing of power plants and transmission networks, hence affecting the capital cost of the power system.

(3) In case of excessive current demand, the generators with short run-in time should be started to share the extra load or the spinning reserve should be increased to meet the maximum requirement. However, since the generators take time to run into the steady state, they should be started in advance to the occurrence of peak demand but remain running even though the peak load has passed away, hence wasting the generated energy. Similarly, the high spinning reserve also causes the power plants operating in a low-efficiency mode. Thus, the peak current demand significantly increases the running cost of the power system.

Current Demand Coordination

Basically, there are two types of coordination approaches:

- distributive coordination and
- centralized coordination.

In case of the distributive coordination, each EV needs to install a distributive coordination controller which functions to maximize its individual charging current provided that the total current demand of the whole charging station is within the specified limit. Whenever there is any remaining current due to the charge-up or the leave of a particular EV, this unused current will be picked up by another EV based on the first-come-first-serve (FCFS) arbitration. Since each EV simply knows the total current demand and aims to grasp the unused current to shorten its individual charging time, this approach takes the advantages of simplicity and low-cost implementation. However, the FCFS arbitration cannot re-distribute the remaining current to other EVs in a balance way, thus the charging times of those EVs spread around. Also, since each EV charger knows only the total current demand of the charging station and nothing about the conditions of other EV chargers, some complicated control algorithms are not applicable to such approach.

In case of the centralized coordination, the charging station needs to install a central computer which gathers the necessary information, such as the battery capacity, SOC, current and voltage ratings as well as expected charging times, from all EV chargers. Hence, intelligent arbitration made by the central computer is adopted so that the total current demand can be minimized while the EV charging times can be equalized as far as possible. This central coordination approach takes the advantages over the distributive counterpart that the current demand fluctuation can be reduced, the spread of charging times can be optimized, and those sophisticated control algorithms can be implemented. The drawback is the increase in implementation complexity and cost, which can be well outweighed by the associated advantages.

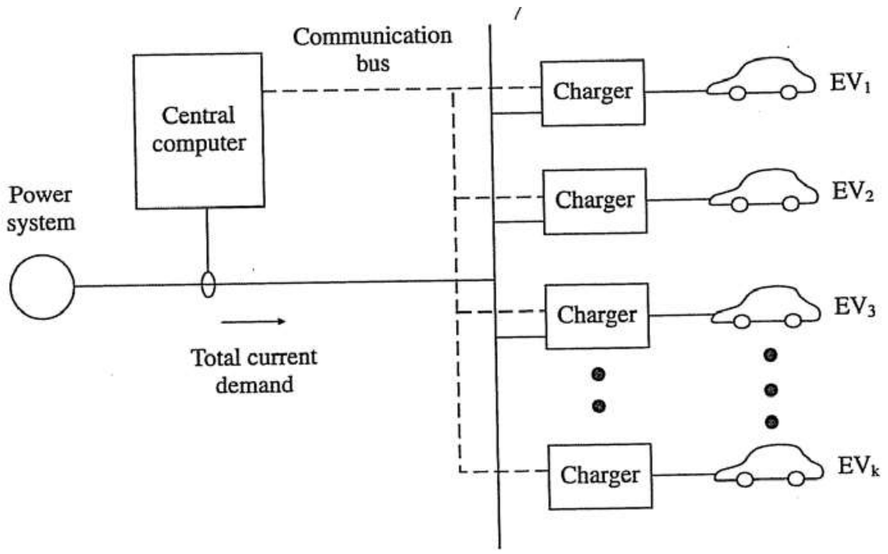


Fig. 9.6. EV charging station adopting centralized coordination.

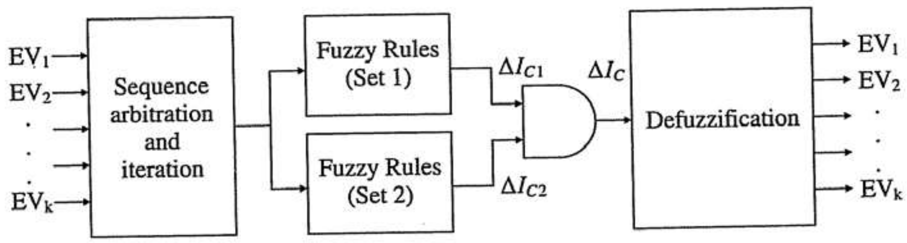


Fig. 9.7. Fuzzy controller for centralized coordination.

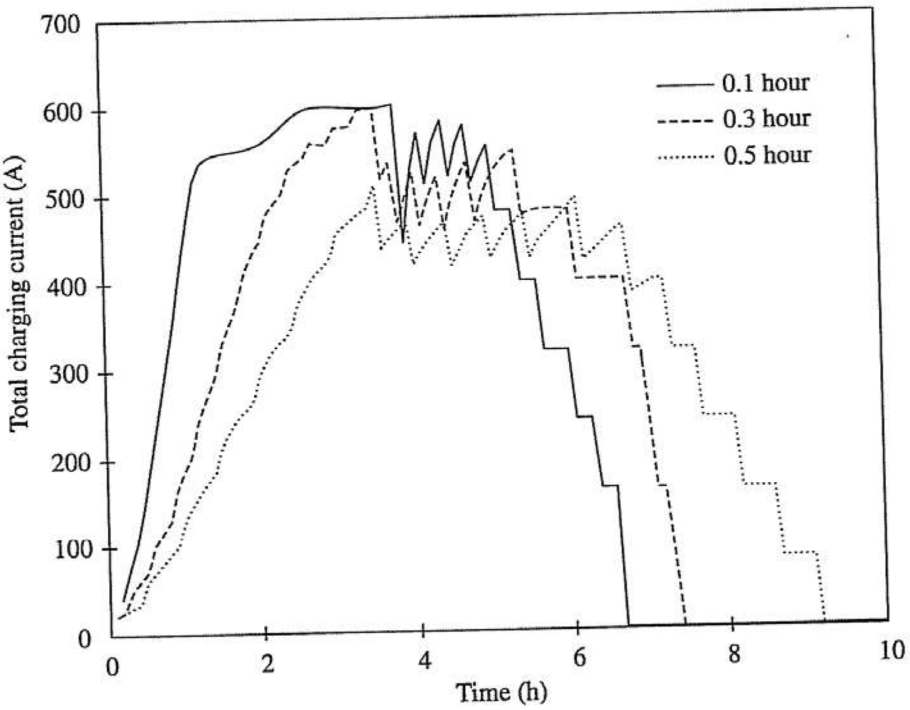


Fig. 9.8. Total charging current profiles under various arrival time intervals.

Table 9.2 Charging times and peak current demands under various arrival time intervals

	Arrival time intervals				
	0.1 h	0.2 h	0.3 h	0.4 h	0.5 h
Charging time of EV_1 (h)	3.8	3.6	3.6	3.6	3.6
Charging time of EV_2 (h)	3.8	3.6	3.6	3.6	3.6
Charging time of EV_3 (h)	4.0	3.6	3.6	3.6	3.6
Charging time of EV_4 (h)	4.2	3.7	3.6	3.6	3.6
Charging time of EV_5 (h)	4.4	4.0	3.7	3.7	3.6
Charging time of EV_6 (h)	4.6	4.3	4.0	3.9	3.8
Charging time of EV_7 (h)	4.8	4.6	4.4	4.2	3.9
Charging time of EV_8 (h)	5.0	5.0	4.8	4.3	3.9
Charging time of EV_9 (h)	5.3	5.1	4.7	4.2	3.8
Charging time of EV_{10} (h)	5.5	5.0	4.5	4.1	3.8
Charging time of EV_{11} (h)	5.7	4.9	4.4	4.1	3.8
Charging time of EV_{12} (h)	5.6	4.8	4.2	4.0	3.8
Average charging time (h)	4.725	4.350	4.092	3.908	3.733
Peak current demand (A)	602	599	597	548	510

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