A charging pricing method for electric vehicles on freeways considering charging demands and strategy

Lixing Chen1*, Zhenya Ji2, Xiaoxin Han1 and Qi Wang1

1School of Electrical & Information Engineering, Jiangsu University of Technology, Changzhou 213001, China
2School of Electrical and Automation Engineering, Nanjing Normal University, Nanjing 210023, China

*Corresponding author e-mail: chenlixing@jsut.edu.cn

Abstract. The effective electric vehicles (EVs) charging price is one of economic incentive approaches for implementation of charging strategy for EVs on freeways. An EVs charging pricing method is proposed by considering the EV charging demands and strategy. The busy and idle charging capacities model, and busy and idle charging prices model are established to test the proposed method effectiveness. The charging of EVs on freeways, under different charging strategies, is simulated by queuing model and queuing algorithm according to related data, and the paper verifies the proposed method.

1. Introduction

Most electric vehicles (EVs) drive in urban and highway areas where EVs driving, charging station (CS) selection and charging facilities operation status have different characteristics. In urban area, EVs drive flexibly, and have multiple CS choices due to the relatively intensive CSs construction (e.g., the average service radius is about 3~5km)[1]. When the EV users arrive at the target CS for a short time after booking, it can be considered that the operation status of charging facilities in the CS may have changed hardly. However, in highway area, EVs usually follow the shortest path, and have few CS choices due to the large distance between CSs on freeways (e.g., the average distance is about 50km[2]). When the EV users arrive at the target CS for a long time after booking, it can be considered that the operation status of charging facilities in the CS may have changed greatly. Therefore, a study on charging strategy of EVs on freeways has a greater challenge.

Charging strategy for EVs on freeways can be divided into static charging strategy and dynamic charging strategy depending on whether or not the operation status of charging facilities is taken into consideration. The former does not consider operation status of charging facilities[3], while the latter considers the operation status of charging facilities. Both of them optimize the CS choice or charging capacity, in order to reduce the total travel time or charging cost of users. Therefore, static charging strategy will make users face greater risk of charging waiting, which is not conducive to promotion.

A win-win situation for EVs, CSs, power grid and road network can be achieved by considering EV flexible demand response characteristics and introducing charging price to guide EV charging. Chen et al. [2] proposed an orderly charging strategy which can encourage EVs to charge beforehand, which can reduce EVs charging cost and waiting time, and raise CSs utilization ratio of charging facilities. Chen et al. [4] proposed an orderly charging strategy which can encourage EVs to adjust charging time beforehand, which can reduce EVs waiting time and raise CSs utilization ratio of
charging facilities. These studies have their own characteristics in EV charging guidance, but only the charging price is introduced as an economic or technical means to ensure the strategy implementation, which has not been effectively formulated. Therefore, a charging pricing method for EVs on freeways is proposed by considering charging demands and dynamic charging strategy. The busy and idle charging capacities model, and busy and idle charging prices model are established, and the effectiveness of the method is verified by the simulation.

2. Models

2.1. Busy and idle charging capacities model

The total busy and idle charging capacities can be expressed as

\[
Q_{BC} = \sum_{k=1}^{m} \sum_{i=1}^{n} \Delta Q_{BC}^{k,i} \\
Q_{IC} = \sum_{k=1}^{m} \sum_{i=1}^{n} \Delta Q_{IC}^{k,i}
\]

where \(m\) is EVs number; \(n\) is CSs number; \(\Delta Q_{BC}^{k,i}\) (\(\Delta Q_{IC}^{k,i}\)) is busy/idle charging capacity of EV \(k\) at CS \(i\) (kWh), which can be expressed as

\[
\begin{align*}
\Delta Q_{BC}^{k,i} &= (\text{SOC}_{E}^{k,i,\text{max}} - \text{SOC}_{E}^{k,i,\text{min}})Q_{max}^{k}, \quad L\left(t_{A}^{k,i}\right) \leq N_{C} \\
\Delta Q_{IC}^{k,i} &= (\text{SOC}_{E}^{k,i,\text{max}} - \text{SOC}_{E}^{k,i,\text{min}})Q_{max}^{k}, \quad L\left(t_{A}^{k,i}\right) > N_{C}
\end{align*}
\]

where \(Q_{max}^{k}\) is the battery capacity of EV \(k\) (kWh); \(t_{A}^{k,i}\) is the time of arrival of EV \(k\) at CS \(i\); \(L\left(t_{A}^{k,i}\right)\) is CS \(i\) queue length at the time of arrival \(t_{A}^{k,i}\); \(\text{SOC}_{E}^{k,i,\text{min}}\) is expected state-of-charge (SOC) of EV \(k\) at CS \(i\); \(\text{SOC}_{E}^{k,i,\text{max}}\) is initial SOC of EV \(k\) at CS \(i\). Both of them are related to the charging demands (related to the mileage, maximum mile, SOC and battery capacity) which can be expressed as

\[
Q_{E}^{k} = \left(\frac{L_{OD}^{k}}{L_{\text{max}}^{k}} - \text{SOC}_{O}^{k} + \text{SOC}_{D}^{k}\right)Q_{max}^{k}
\]

where \(L_{OD}^{k}\) (\(L_{\text{max}}^{k}\)) is the mileage/maximum mile of EV \(k\) (km); \(\text{SOC}_{O}^{k}\) (\(\text{SOC}_{D}^{k}\)) is the SOC at the origin/destination of EV \(k\) (km); \(Q_{max}^{k}\) is the same as the Equations (2), and the EV \(k\) shall be charged at least once, if \(Q_{E}^{k} > 0\).

In order to calculate the EV expected/initial SOC, we can define unordered charging (UC) and orderly charging (OC) strategy\[2]\,\,\text{[2]}\. When the current SOC reaches to the alarm value, most EVs in the UC (about 90%) will be charged owing to user's refuelling habits. When these EVs arrive at CSs, they have to be charged whether the CSs are busy or not, or else they would stay on the road owing to low SOC of battery. So, they are unable to take into account their waiting time. It is assumed that 90% of EVs in the OC case have SOC level above the alarm value, and can maintain to the next CS or several CSs. These users can choose to charge their EVs according to the state of the CSs. If the current CS is busy, they can choose to leave for the next CS. Thus, they are able to take into account the waiting time.

If the EV \(k\) is charged once to meet its charging demand under UC, the expected SOC can be expressed as

\[
\text{SOC}_{E,1}^{k} = \frac{Q_{E}^{k}}{Q_{max}^{k}} + \text{SOC}_{E,1}^{k} \leq \text{SOC}_{E,\text{max}}^{k}
\]
where $SOC_{A,i}^{k_f}$ is the initial SOC; $SOC_{A,i}^{k_f}$ is the maximum expected SOC; $SOC_{C,\min}^{k_f}$ is the warning value; $L_{OA,i}^{k_f}$ is the distance from CS $i$ to origin of the route (km); Equations (6) is the forced charging condition; If the expected SOC exceeds the maximum expected SOC, the EV $k_i$ is charged more than once, and the corresponding first expected SOC is equal to $SOC_{E,max}^{k_f}$; If the charging position (expected SOC) is regarded as a new origin position (initial SOC), the corresponding expected SOCs will be calculated for charging twice or many times according to Equations (3)-(6). Thus, each expected SOC can be estimated in advance.

If the EV $k_i$ is charged once to meet its charging demand under OC, the expected SOC can be calculated according to Equations (4)-(5). If the current CS is idle, the EV $k_i$ can be charged, and its SOC meets Equation (7); Otherwise, it can be charged at the next CS and its SOC meets Equation (6).

$$SOC_{C,\min}^{k_f} < SOC_{A,i}^{k_f} \leq SOC_{C,\min}^{k_f}$$

where $SOC_{k_i,\min}^{k_f}$ is SOC upper limit of EV $k_i$; $SOC_{C,\min}^{k_f}$ is the same as the Equation (6). In the same way, the corresponding expected/initial SOCs can be calculated for charging twice or many times.

### 2.2. Busy and idle charging prices model

Each CS adopts the single charging price before the busy and idle charging prices are implemented, which can be expressed as

$$e_{p0,m} = e_{p0} \quad (8)$$

where $e_{p0,m}$ is busy/idle charging price (yuan/kWh); $e_{p0}$ is single charging price (yuan/kWh). After the implementation of busy and idle charging prices, they can be expressed as

$$\begin{align*}
    e_{p0,m} &= (1 + \alpha) e_{p0} \\
    e_{p0,x} &= (1 + \beta) e_{p0}
\end{align*}$$

where $\alpha$ and $\beta$ are floating scale factors.

Before and after implementation of busy and idle charging prices, their changes can be expressed as

$$\begin{align*}
    \Delta e_{p0,m} &= \alpha e_{p0} \\
    \Delta e_{p0,x} &= \beta e_{p0}
\end{align*}$$

The elasticity coefficient of charging capacity and price can be expressed as

$$\varepsilon = \frac{\Delta q}{q} \left( \frac{\Delta e_e}{e_e} \right)^{-1}$$

where $q$ is total charging capacity, and $\Delta q$ is the change (kWh); $e_e$ is the charging price, and $\Delta e_e$ is the change (yuan/kWh).

Self-elastic and cross-elastic coefficients can be calculated as
The charging capacity can be divided into two parts in the busy and idle charging prices model. We can define an elasticity coefficient of charging capacity and price based on the busy and idle charging prices, which can be expressed as

\[
\begin{cases}
\varepsilon_{\alpha} = \frac{\Delta q_i - \Delta e_{p_i}}{q_i - e_{p_i}} \\
\varepsilon_{\beta} = \frac{\Delta q_i - \Delta e_{w_i}}{q_i - e_{w_i}}
\end{cases}
\]

(12)

The adjustment range of charging service charging price (excluding electricity charge) needs to meet the national macro policy. So, the range of single charging price here is set to 0~0.58 yuan/kWh[6]. In addition, the user-side proportion is set to 5%~10%. Therefore, the calculation results

| Charging capacity | UC  | OC  |
|-------------------|-----|-----|
| Busy (MWh)        | 122.1 | 82.7 |
| Idle (MWh)        | 169.5 | 213.2 |

Table 1. The busy and idle charging capacities under two charging strategies.
of EV charging prices based on the two charging strategies are shown in Figure 1 and Figure 2. When the single charging price (user-side proportion) is 0.433 yuan/kWh (0.1), the busy charging price is 0.5792 yuan/kWh, and the idle charging price is 0.3162 yuan/kWh. Both of them can be introduced as an economic or technical means to ensure the implementation of OC.

![Figure 1. Busy charging price](image)

![Figure 2. Idle charging price](image)

5. Conclusion
The percentage of EVs total idle charging capacities in the case of OC can be increased by 25.8%, compared to UC. When the single charging price (user-side proportion) is 0.433 yuan/kWh (0.1), the busy charging price is 0.5792 yuan/kWh, and the idle charging price is 0.3162 yuan/kWh. Both of them can be introduced as an economic or technical means to ensure the implementation of OC.

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