Applied Energy 225 (2018) 857–868

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

A charging pricing strategy of electric vehicle fast charging stations for the voltage control of electricity distribution networks

Xiaohong Dong[a], Yunfei Mu[a,*], Xiandong Xu[b], Hongjie Jia[a,*], Jianzhong Wu[b], Xiaodan Yu[a], Yan Qi[c]

[a] Key Laboratory of Smart Grid of Ministry of Education, Tianjin University, Tianjin 30072, China
[b] Institute of Energy, School of Engineering, Cardiff University, Cardiff CF24 3AA, UK
[c] Electric Power Research Institute, State Grid Tianjin Electric Power Company, Tianjin 300384, China

HIGHLIGHTS

- A charging pricing strategy of electric vehicle fast charging stations was proposed.
- Improvement of the voltage profiles of distribution networks in the strategy.
- Consideration of the stations' income and the users' response to the pricing scheme.
- Fully exploitation of the fast charging loads' flexibility by the pricing scheme.
- Consideration of the users' travel characteristics in the simulation model.

ARTICLE INFO

Keywords:
Electric vehicle (EV)
Electric vehicle mobility
Charging pricing strategy
Voltage control of electricity distribution networks

ABSTRACT

With the increasing number of electric vehicles (EVs), the EV fast charging load will significantly affect the voltage quality of electricity distribution networks. On the other hand, EVs have potentials to change the choices of charging locations due to the incentives from the variations of charging prices, which can be considered as a flexible response resource for electricity distribution networks. In this paper, a charging pricing strategy of EV fast charging stations (FCSs) was developed to determine the pricing scheme for the voltage control of electricity distribution networks, which consisted of a simulation model of EV mobility and a double-layer optimization model. Considering the travel characteristics of users, the simulation model of EV mobility was developed to accurately determine the fast charging demand. Taking the total income of FCSs and the users' response to the pricing scheme into account, the double-layer optimization model was developed to optimize the charging pricing scheme and minimize the total voltage magnitude deviation of distribution networks. A test case was used to verify the proposed strategy. The results show that the spatial distribution of EV fast charging loads was reallocated by the proposed charging pricing scheme. It can also be seen that the proposed strategy can make full use of the response capacity from EVs to improve the voltage profiles without decreasing the income of the FCSs.

1. Introduction

With the growing concerns on the energy depletion and environmental issues around the world, the large-scale adoption of electric vehicles (EVs) is considered as an effective way in decarbonizing the transport sector. In recent years, the EV industry has made considerable progress with the great promotion from governments and automobile enterprises [1]. As the EV supply equipment, the charging infrastructure plays a crucial role in the EVs promotion [2]. With respect to the emergency charging of EVs, the fast charging station (FCS) is becoming the mainstream solution [3]. However, from the view point of electricity distribution networks, the fast charging load will cause the deterioration of voltage quality due to the short charging period and high power demand [4]. Thus, it is necessary to regulate the charging behaviors of EVs so as to improve the voltage quality of electricity distribution networks.

One way to support the operation of distribution networks is the direct control of EV charging load, due to the EVs' flexibility in the charging time and the vehicle-to-grid (V2G) capability [5,6]. In [7], a hierarchical coordinated charging framework was proposed to generate

* Corresponding authors at: Room E/627, The Building 26, Tianjin University, Weijin Road No.92, Tianjin 300072, China.
E-mail addresses: dongxiaohong@tju.edu.cn (X. Dong), yunfeimu@tju.edu.cn (Y. Mu), xux27@cardiff.ac.uk (X. Xu), hjjia@tju.edu.cn (H. Jia), WuJ5@cardiff.ac.uk (J. Wu), yuxd@tju.edu.cn (X. Yu), qiyan_fly@163.com (Y. Qi).

https://doi.org/10.1016/j.apenergy.2018.05.042
Received 13 January 2018; Received in revised form 6 May 2018; Accepted 7 May 2018

the charging curve for each aggregator of EVs in order to reduce the peak load of EV charging. In [8], the capacitor, the on-load tap changer and the EV chargers were coordinated to control the voltage of electricity distribution networks. In [9], the on-load tap changers and EVs were collaborated to mitigate the voltage fluctuations caused by generation variations of distributed solar panels. In [10], a high efficient valley-filling strategy was proposed to determine the charging priority of EVs at each time slot. In [11], EV charging loads were separately scheduled by changing the charging times and locations. In [12], the operation of EV charging behavior was optimized by changing the charging time. In [13], the EV charging scheduling strategy of an aggregator was proposed by regulating the charging power in the charging process. In [14], the charging EV number in a certain period was calculated with the goals of peak-shaving and valley-filling. In [15], a double-layer smart charging strategy was developed. The first layer aims to determine the shortest path for EV users to reach a suitable charger. The second level controls the charging process in order to reduce the charging cost.

The above methods focus on adjusting the battery charging process of EVs. With the development of intelligent transportation systems [16], information and communication technology [17] and fast charging navigation system [18], the price mechanisms were applied to guide the EV charging behaviors.

In [19] and [20], the modeling of the EV driver's response to the charging price was discussed and the EV charging loads were shifted to the valley time period. In [21], the effect of prices on the fast charging behavior of EV users was analyzed. In [22], a proper charging pricing mechanism was designed to guide the EVs' charging behaviors. In [23], the load balancing of FCSs was achieved through a pricing mechanism, considering the quality-of-service targets and the spatial-temporal distribution of EVs. In [24], the fluctuation of renewable energy sources was balanced by adjusting the mobility behavior of EVs with the variations of price signals. The variable electricity prices are calculated based on marginal generation costs. In [25] and [26], it was assumed that the electricity was sold at the wholesale price to the EV users, ignoring FCS interests. And the electricity prices were optimized at the system level considering the operation of the power system and transportation system.

The existing researches have made good contributions to the optimization of EV fast charging load by the price incentives. The FCSs trend to privately-owned facilities [27,28] and collaborate with distribution networks. Although the charging pricing scheme of FCSs can be applied to improve the voltage quality of distribution networks, the profit of FCSs should be guaranteed when the loads are redistributed through the charging pricing scheme. For this reason, a charging pricing strategy of EV FCSs was proposed to minimize the total voltage magnitude deviation of distribution networks. The charging pricing scheme can be determined to minimize the total voltage magnitude deviation without decreasing the income of FCSs.

2. Framework of the proposed charging pricing strategy

The framework of the proposed charging pricing strategy is shown in Fig. 1, which consists of a simulation model of EV mobility and a double-layer optimization model.

The simulation model of EV mobility: The travel chain method [29], graph theory [30] and the Monte Carlo Simulation (MCS) are used to determine the EV fast charging demand considering the travel characteristics of users. The demand is transferred to the lower layer.

The lower-layer optimization model: According to the fast charging demand supplied by the simulation model and a given charging pricing scheme supplied by the upper layer, the selected FCS of each user is optimized to minimize the corresponding cost. The loads of FCSs and the EV recharging capacity of each user are determined and then transferred to the upper layer.

The upper-layer optimization model: The charging pricing scheme of FCSs is generated and optimized based on the charging loads of FCSs and the EV recharging capacity of each user supplied by the lower layer. The scheme is then transferred to the lower layer.

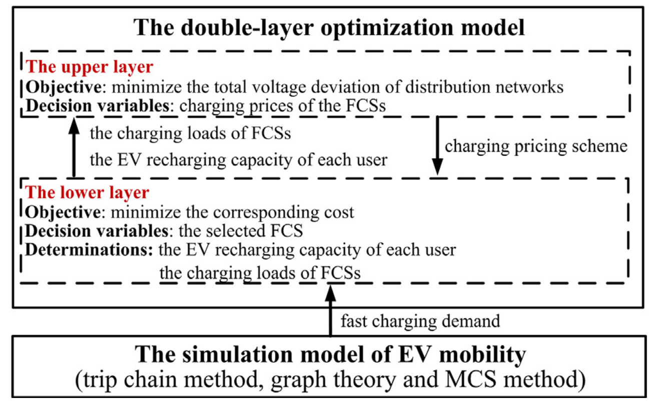

Fig. 1. The framework of the proposed charging pricing strategy.

3. The charging pricing strategy

3.1. The simulation model of EV mobility

The EV fast charging demand ***FC*** was predicted by the simulation model of EV mobility, considering the travel characteristics of users and the existing slow charging facilities in the urban area. ***FC*** was then transferred to the lower-layer optimization model.

3.1.1. Transportation network model

The extended graph is employed to describe the topology of the transportation network [30]. A graph ***G*** is an ordered pair, which consists of a set of vertices ***V*** connected by a set of edges ***E***. The vertices represent the nodes of the transportation network, while the edges represent the arterial roads and their flow direction. It is assumed that FCSs are built on the arterial roads to avoid the traffic jams. The extended graph includes the virtual vertices representing FCSs and the corresponding edges.

The distance matrix ***D*** is used to describe the distances between every two neighbor vertices of the extended graph. ***D*** is a $N_v \times N_v$ symmetric matrix and all diagonal elements are zero, where N_v is the total number of vertices in the extended graph and the element $D(v_i, v_j)$ represents the distance from vertex v_i to vertex v_j.

The impedance matrix ***IM*** is used to describe the driving time between every two neighbor vertices of the extended graph considering the traffic congestions. ***IM*** is determined by ***D*** and the average driving speed obtained from the history data of the traffic center. ***IM*** is a $Q_1 \times N_v \times N_v$ matrix, where Q_1 is the number of time intervals. And the element $IM(t_1, v_i, v_j)$ of ***IM*** represents the driving time from vertex i to j at the time interval t_1.

3.1.2. EV mobility model

The EV mobility is closely related with the travel characteristics of users, which is well described by the trip chain [29]. The concept of the trip chain has been widely applied in the travel demand forecast [31,32]. A trip chain is a time-ordered trip sequence which consists of locations and routes of daily trips. This chain can reflect the rules of user's activities in space. In this paper, only the private EVs are considered to forecast their fast charging demand, because other kinds of EVs (such as buses and enterprise owned vehicles) generally have the proprietary charging stations. Also the charging choices of these EVs used for public services are not easy to be changed. The activities of the private EVs are a series of movements and stops describing by the trip chain theory. The trip chain is composed of a spatial chain and a temporal chain.