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Optimal placement of charging infrastructures for large-scale integration of pure electric vehicles into grid ☆

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A B S T R A C T

The optimal placement of charging infrastructures owns fundamental importance to the popularization of pure electric vehicles (PEVs). This paper focuses on the optimal configuration of centralized charging stations (CCSs) under the condition of large-scale integration of PEVs into grid. A mathematical model to formulate the optimal CCS placement problem is firstly established. Then the distribution discipline of CCSs in the optimum CCS configuration with minimum total transportation distance (TTD) is shed light on according to the mathematical model, and it in turn helps to identify the candidate CCS locations which turn out to be discrete, finite, fit for numerical calculation and reliable. Finally a further optimization model within the searching space of these candidate CCS locations is proposed to identify the optimum CCS configuration, and solved by a modified binary particle swarm optimization (BPSO) based on Taboo mechanism (TM). The resultant optimization method, named TM-BPSO, can make up the defect of premature convergence of the original BPSO to a certain extent. A large number of numerical examples verify the correctness of the proposed strategy and the applicability of the modified BPSO in this study.

1. Introduction

The pure electric vehicles (PEVs), utilizing electricity instead of diesel and gasoline as a propulsive engine element, are a kind of clean-energy transport with such advantages as high energy conversion efficiency, low noise, zero tailpipe emissions, independent on fossil fuels, and so forth [1]. Their large-scale application will effectively ameliorate current global concerns over environmental issues and petroleum paucity [2,3], and therefore many automotive manufacturers all over the world have begun to place increased emphasis on the development of PEVs [4]. Practically, the promotion of PEVs cannot be separated from the extensive spread of charging infrastructures for their exclusive and elementary electricity-supplying functionalities to PEVs, and researches on their configurations should be conducted in advance.

Compared with refueling facilities for gasoline vehicles (GVs), charging infrastructures entertain more existing forms and can be either the public built CCSs, or the scattered charging piles, or the common outlets in residential and workplace buildings. Moreover, in the current situation facing the growing shortage of land resources, a certain percentage of parking garages should be transformed to provide battery charging service for PEVs concurrently in the future, and thus become charging places, too. Among these four kinds of charging infrastructures, the optimum one for PEVs to recharge are residential or workplace buildings for the sake of convenience for performing charging, sufficiently long parking time for uninterruptedly charging, and less impact on power distribution system by adopting the normal charging mode with comparatively small charging power. And a certain number of PEV users can just charge their vehicles in residential or workplace buildings and gratify the power consumption of their daily travels by PEVs if they have short daily travel distance. However, some users may experience long daily travel distance which exceeds the cruising radius of PEVs, while some users may just forget to charge their vehicles with low state of charge (SOC) in those best charging sites beforehand. At these moments, outgoing PEVs will get battery-depleted halfway to destinations, and users have to resort to nearby CCSs or transformed public parking garages (TPPGs) for recharging. Therefore necessity exists for the construction of the other three kinds of charging infrastructures. This paper mainly concerns the optimal placement problem of CCSs, which will undertake much more public charging businesses than charging piles or TPPGs. In addition, TPPGs enjoy competitive relations with CCSs for their similar functions of running the public charging businesses and thus should be taken into the considerations of the CCS configuration.

Several important strides on this topic field have been performed in recent years [5–9], and they share a common ground that a number of candidate CCS locations are compared according

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to corresponding objective functions and constrains to finally identify the optimum CCS configuration. This signifies that the identification of candidate CCS locations enjoys a strong sense of essential importance for the optimal CCS placement and should be studied seriously. The current available literature provided two strategies for pinpointing candidate CCS locations. One strategy takes all continuous geographical points in a planning area as candidates CCS locations [5–7], and would probably stick the planning project in such a dilemma as being highly inefficient and complicated. And the other strategy just predetermines candidates subjectively [8,9], and do not offer any insight concerning the inclusion of the optimum CCS configuration into the predetermined candidate CCS locations. In light of such defects, this paper will put forward a new strategy with high efficiency and more reliability for identifying the candidate CCS locations.

In this study, CCSs are built within the road network (RN) in an area to be planned, with the objective to minimize the TTD by PEVs from all public charging points (PCPs) to corresponding CCSs or TPPGs, where PCPs are public points within the RN at which the residual battery capacities of outgoing PEVs get insufficient and need to recharge. Define actual distance (AD) between two points with the RN as the practical length of a path connecting the two points accounting for the tortuous nature of the path. And then in each recharge cycle, PEVs necessary to recharge at each PCP are assigned to the CCS or TPPG entertaining the shortest AD with the PCP. Based on these principles and explanations, the authors establish a mathematical model accounting for the distribution of PCPs and the structure of the RN to formulate the optimal CCS placement problem aimed at minimum TTD. Then the distribution discipline of CCSs in the CCS placement aimed at minimum TTD is shed light on based on the mathematical model, and it in turn helps to identify the candidate CCS locations. Finally a further optimization model within the searching space of these candidate CCS locations is proposed to identify the optimum CCS configuration, and solved by TM- BPSO.

This paper is organized into six sections. Section 2 describes the distribution of PCPs in a region to be planned. And the mathematical model for the optimal CCS placement, the distribution discipline of CCSs in the CCS placement aimed at minimum TTD and the determination of candidate CCS locations are presented in Section 3. Section 4 shows how to determine the optimum CCS configuration based on determined candidate CCS locations. And case studies and simulated results on a typical sub-region are presented in Section 5. Finally, the concluding remarks, on the application of the proposed strategy and the modified BPSO, is provide in Section 6.

2. Distribution of PCPs

Quantitative expression of the distribution of PCPs is a foundational issue to plan CCSs. This operation is difficult since strong randomness exists in the usage of vehicles so that any geographical point within the RN could be a PCP in principle and the required calculation for expressing all these PCPs is extremely huge. However, taking all these theoretical PCPs into the consideration of CCS placement is unnecessary and unwise since PEVs can get recharged in a large range of SOC and users could retain enough battery capacity to touch a CCS or TPPG around before the exhaustion of the batteries in their PEVs. For the sake of simplicity, this study only concerns those important PCPs, where most public outings by driving would transit under the condition of large-scale application of PEVs. And it should be noted that the proposed strategy for determining the optimum CCS placement in this study is applicable to the situations when much more discrete PCPs are concerned. These concerned important PCPs are aggregated sites of passenger or freight flow in a planning area, including wharfs, passenger/freight transportation centers, tourist spots, recreational centers, and so on, and they own a number of internal outlets but cannot afford the charging businesses of many a client. Let P_s represent the location of one PCP of this kind, and the number of PEVs to recharge at P_s, N_s, can be formulated as:

$$N_s = \varphi \cdot \omega_s \cdot \max(NP_s) \tag{1}$$

where NP_s is the total number of PEVs transiting P_s in a time instant and is a time-variant variable, and max (NP_s) is the maximum of NP_s within a week and utilized to meet the demand during the charging peak period here. Moreover, ω_s is the proportion of PEVs necessary to recharge among PEVs transiting P_s during the charging peak period, and φ is the synchronization factor and a constant less than 1. The charging peaks from all these important PCPs will not occur simultaneously, and φ is utilized to avoid overestimating the total number of PEVs necessary to recharge and can be approximately formulated as:

$$\varphi = \max(TNP) \Bigg/ \left(\sum_{s=1}^{TNS} \max(NP_s) \right) \tag{2}$$

where *TNS* is the total number of important PCPs in a region to be planned, and *TNP* is the total number of PEVs necessary to recharge from all these *TNS* PCPs at the same time instant and also a time-variant variable, and max (*TNP*) is the maximum of *TNP* within a week.

3. Distribution discipline of CCSs in the CCS placement with minimum TTD

The distribution discipline of CCSs in the CCS placement aimed at minimum TTD is obtained to determine the candidate CCS locations, and it is deduced based on a mathematical model which can formulate the optimal CCS placement problem and shown in Fig. 1. Let *RG* represent the region to be planned and CCS_α be a CCS that will be built within *RG*. And what Fig. 1 displays is just the sub-region covered by CCS_α. In the figure, *ab* is a road in the sub-region, and *a* and *b* are the two endpoints of it. *SA*, *SB* and *SC* are three sets of PCPs, and they together form another set of PCPs, namely Set_α, which contains all the PCPs served by CCS_α. *SA*, *SB* and *SC* are classified according to the distance between these PCPs and CCS_α. *SA* (or *SB*) comprises PCPs whose shortest ADs with *b* (or *a*) are no smaller than the sum of their shortest ADs with *a* (or *b*) plus d_{ab}, while *SC* comprises PCPs whose shortest ADs with *a* (or *b*) are larger than their shortest ADs with *b* (or *a*) and in the meantime smaller than the sum of their shortest ADs with *b* (or *a*) plus d_{ab}. d_{ab} is the length of *ab*. Moreover, PA_1 to PA_l are PCPs in *SA*, and da_1 to da_l are ADs between these PCPs with *a* correspondingly. PB_1 to PB_m are PCPs in *SB*, and db_1 to db_m are ADs between these PCPs with *b* correspondingly. PC_1 to PC_m are the locations of PCPs in *SC*, and dc_1 to dc_n are ADs between these PCPs with *a* correspondingly. And *l*, *m*

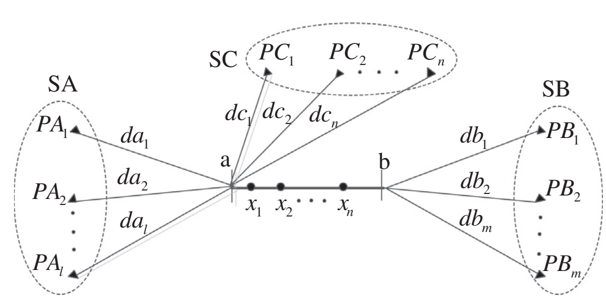

Fig. 1. The distribution of PCPs in the sub-region covered by CCS_α.