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A novel centralized charging station planning strategy considering urban power network structure strength

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ABSTRACT

Considering detrimental impact on grid by sizeable and unpredictable electric vehicles (EVs) loads, establishing centralized charging stations through swapping batteries can be the future competitive development orientations in EV industry. Optimal centralized charging station planning is not only pervasive enough to meet the requirement of EV charging, but also has the potential to improve the rationality of power grid structure as a distributed power station. In this paper, a novel centralized charging station strategy considering urban power network structure strength is proposed. Based on the analysis of time-space characteristic of load shifting in normal urban life, power supply moment balance index is defined to represent fluctuation of supply capability between peak and valley under certain structure. Meanwhile, the investment of charging stations and network loss are considered as part of objective function with moment balance index, aiming at improving urban power network structure with minimal economic cost. Case study on IEEE 123-bus test distribution system illustrates the validity of the strategy proposed.

1. Introduction

As is known to all, air pollution and other energy problems like depleting natural oil, rising petrol cost become intense increasingly with rapid development of urbanization and a boom in automobile industry. Electric vehicle as an alternative transport with clean energy is growing in popularity to conquer the problems mentioned before. Charging station is an essential infrastructure to guarantee EVs running normally, an outstanding placement of which is critical. Consequently, a great deal of interest has been directed towards charging station planning strategy.

The main emphasis of studies on electric vehicle charging station recently can be summarized into two categories: charging mode research and optimal object discussion. In terms of the former, different plug-in charging technologies are fully developed as EV charging control method in Ref. [1–5], which are also called vehicle-to-grid (V2G) charging technology. While in fact, charging schedule research under condition of V2G charging mode may become sophisticated and arduous to be implemented due to the randomness, disperstiveness and nondeterminacy of EVs' charging timing. Therefore, battery swapping charging strategy, namely battery-to-grid (B2G) charging mode, is proposed as effective means of eliminating uncertainty and large time cost associated with charging EV batteries. Ref. [6] presents one conclusion that battery-swap station is more suitable than plug-in charging station for public transportation in distribution system through the comparison study and optimal planning of these two charging types. In Ref. [7], an electric vehicle centralized charging station optimization model is introduced to mitigate long battery charging times and range anxiety under V2G mode obviously.

Meanwhile, the regional battery swapping demand prediction as the foundation of B2G mode to break out the dilemma of each EV's charging timing statistics should be as accurate as possible. Ref. [8] demonstrates a stochastic modeling and forecasting of area load demand for EV battery-swap station bases on four process variables to define the overall randomness of batteries' swapping and charging modes. Furthermore, other kinds of optimal operation and service scheduling strategy of the EV battery-swap station with B2G charging technology are designed for improving the controllability of EVs charging behavior in Ref. [9–12]. These studies fully expound the superiority and feasibility of B2G mode for meeting EV charging demand.

On the other hand, no matter V2G mode or B2G mode, service radius optimization, economic benefit maximization and load shifting compensation as decision elements which affect EV charging station location and capacity are also drawn much attention by different scholars. Ref. [13] designs a mobile charging service for expanding service radius and improving charging efficiency, which focuses on how to complete its charging duty better. Ref. [14,15] put their emphasis on the cost-effectiveness and power supply

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Nomenclature

List of symbols and abbreviations

A_E	power flow distribution matrix
ASAI	Average Service Availability Index
B	total daily battery swapping demand in the region
B_n	total daily battery swapping demand of EV under type n
$b_n(i)$	rounded up daily battery swapping demand of EV i
B2G	battery-to-grid
C	capacity of each battery
C_e	fix cost of one charging equipment
C_{Li}	land unit price of site i
C_{loss}	supply loss cost
C_o	operation cost of one charging equipment
C_{station}	construction and operation cost of centralized charging station
C_{100}	average power consumption of each 100 km distance
$D_n(i)$	daily driving distance of EV i under type n
EENS	expected energy not supply
EV	electric vehicle
$E(i)$	set of node which apply power to node i
G, D	generator source set and load demand set
G_{ab}, B_{ab}	conductance and susceptance between node a and b
G_s	number of units in the system
$L_{i,j}$	set of all the possible power supply paths from source i to load point j
$L_{ij,l}$	electrical distance of path l from source i to load point j
L_s	total line number in the system
$\overline{M}$	average value of all the power supply moment index
M_b	power supply moment balance index
$M(t)$	power supply moment index in time period t
N	total EV type number
n_i	number of charging equipment in station i
$n_{\max}$	maximum number of charging equipment in one station
N_p	total number of centralized station construction planning
N_s	total candidate building sites of stations
n_s	number of nodes in the system
P	power injection vector of each node
p_e	rated power of one charging equipment.
P_{Ga}, Q_{Ga}	active and reactive power generated on node a
$P_{Gk}^{\max}, P_{Gk}^{\min}$	upper and lower limits of active power output on generator k
$p_i(t)$	active power of centralized charging station i in time period t
$P_{i,j}(t)$	power supply set from generator source i to load demand point j in time period t
$P_{ij,l}(t)$	power supply quantity from generator source i to load demand point j on path l in time period t
P_l	active power flow on line l
P_{La}, Q_{La}	active and reactive load consumed on node a
$P_{\text{loss}}(t)$	active power loss in period t
$P_n(i)$	daily power demand of EV i
$Q_{Gk}^{\max}, Q_{Gk}^{\min}$	upper and lower limits of reactive power output on generator k
r	discount rate
S_e	floor space of one charging equipment
S_n	total sampling number of EV in the region
T_{day}	battery swapping circle
U_a	node voltage amplitude of node a
V2G	vehicle-to-grid
x_i	binary decision variable combined with station i
α_l	loss unit price
β	safety factor of charging facility operation
μ_b	mean value of electric bus daily driving distance probability function
μ_p	logarithmic mean value of electric private car daily driving distance probability function
σ_b	standard deviation of electric bus daily driving distance probability function
σ_p	logarithmic standard deviation of electric private car daily driving distance probability function
θ_{ab}	phase angle difference between node a and b
η_{from} and η_{to}	battery charging and discharging efficiency

stabilization as the judgment to different centralized charging station planning strategies with their respective battery charging schedules acting on the gird. Moreover, with regarding centralized charging station as battery energy storage system, a load shifting control method based on real time load forecast and dynamic programming is given by Ref. [16]. It provides a new point of view for the B2G charging technology research.

Actually, by using electrical energy for motion frequently, the increased demand for electrical energy brought by EVs cannot be underestimated. Since the centralized charging stations are responsible for the battery swapping of whole EV market, they are able to act as both a huge load and a large power source. In this sense, centralized charging station should play an essential role in electric energy transfer link of the whole grid as well as being a service device for EVs. However, most objective functions given previously only focus on the service attribute (to EV) to judge whether centralized charging station planning is efficient or not, ignoring the its power attribute (to grid), which may affect power flow distribution with different layout position and output arrangement. Optimal centralized charging station planning should be not only pervasive enough to meet the requirement of EVs charging, but also has the potential to improve the rationality of power grid structure as a distributed power station. Thus, the methods only considering service profit maximization at the cost of damage to the overall gird structure are not appreciated.

Directing at the weakness of the existing methods for setting the centralized charging station, a novel method taking power network structure strength into account is presented in this paper. Some basic problem researches about centralized charging station planning are introduced in Section 2, including battery swapping demand analysis of EVs and time-space characteristic of load shifting in urban city. After that, in Section 3, with definition of power supply moment balance index and other economic measure index, the objective function and constraints considering actual request are applied to optimize site selection and switch timing between charging and discharging of station with least operation cost increment. Then, the setting of relevant algorithms applied to solve the problem is provided in Section 4. The proposed methodology is tested using case study on IEEE 123-bus test distribution system in Section 5. Finally, the conclusions are shown in Section 6.

2. Basic research about centralized charging station planning

2.1. Background of battery swapping demand analysis

Generally, battery charging demand in most published EV charging strategy paper based on the background of V2G technology is