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Optimal decentralized valley-filling charging strategy for electric vehicles

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ABSTRACT

Uncoordinated charging load of electric vehicles (EVs) increases the peak load of the power grid, thereby increasing the cost of electricity generation. The valley-filling charging scenario offers a cheaper alternative. This study proposes a novel decentralized valley-filling charging strategy, in which a day-ahead pricing scheme is designed by solving a minimum-cost optimization problem. The pricing scheme can be broadcasted to EV owners, and the individual charging behaviors can be indirectly coordinated. EV owners respond to the pricing scheme by autonomously optimizing their individual charge patterns. This device-level response induces a valley-filling effect in the grid at the system level. The proposed strategy offers three advantages: coordination (by the valley-filling effect), practicality (no requirement for a bidirectional communication/control network between the grid and EV owners), and autonomy (user control of EV charge patterns). The proposed strategy is validated in simulations of typical scenarios in Beijing, China. According to the results, the strategy (1) effectively achieves the valley-filling charging effect at 28% less generation cost than the uncoordinated charging strategy, (2) is robust to several potential affecters of the valley-filling effect, such as (system-level) inaccurate parameter estimation and (device-level) response capability and willingness (which cause less than 2% deviation in the minimal generation cost), and (3) is compatible with device-level multi-objective charging optimization algorithms.

1. Introduction

As alternatives to conventional vehicles, plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs) are expected to reduce petroleum-based energy consumption and greenhouse gas emissions. Consequently, their use is likely to expand drastically in the near future [1]. According to China's "Twelfth Five Year Plan", the number of EVs (PHEVs and BEVs) in Beijing will likely exceed 100,000 by 2017 [2].

As EVs comprise an increasing percentage of the vehicle population, unregulated charging behaviors (especially immediate charging after arriving home in the evening) will impact the power grid in two ways: (1) by increasing the peak load and local marginal prices (LMPs) and (2) by decreasing system reliability [5]. The control of EVs' charging loads, which is also essential to smart grids, becomes a feasible option for this issue [3]. The three potential ways of participating in a smart grid are load shifting, regulation, and spinning reserve [4].

Load shifting or valley-filling charging strategies have been widely reported. These studies focus on shifting the controllable EV load to less congested hours compared with that in an unregulated charging strategy. Valley-filling charging algorithms can be categorized into two broad classes on the basis of their EV charge patterns: centralized approaches [6–10] and decentralized approaches [11–13].

In a centralized approach, an imaginary centralized controller communicates with each EV, collects necessary information, solves specific optimization problems, and directly controls individual charging patterns. To reduce the dimensionality in the corresponding optimization problem, engineers frequently introduce aggregators between the power grid and EV owners, forming a decentralized hierarchical scheme [2,7,9,10]. Developing the computer/communication/control network and incentive program to implement this conceptual framework presents a major challenge [8]. Thus, centralized approaches are usually considered as long-term solutions to valley filling.

A decentralized approach offers more realistic alternative. In these approaches, EV owners determine individual charge patterns on the basis of an electricity pricing scheme or non-price instructions. The grid power demand can be altered by adjusting the electricity price, typically by a dual-tariff scheme [14]. While this time-varying pricing scheme encourages EV owners to charge their vehicles during valley hours, it introduces an undesirable second peak in the electricity load [3]. Zhongjing et al. [12] constructed

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a non-cooperative game strategy, in which each EV pursues a cost-minimizing charge pattern based on dynamic pricing schemes iteratively. This strategy drives a unique Nash equilibrium that results in the valley-filling charging effect. Although the algorithm allows autonomous charging behaviors, the iteration process requires a high-reliability bi-directional communication network between the power gird and EVs. Thus, similar to the abovementioned centralized strategies, this strategy is unsuitable for short-term applications. Ahn et al. [11] proposed an optimal decentralized charging strategy, in which the distributed EV chargers receive a simple command from the centralized grid controller, and thereby determine their individual charge patterns. This strategy behaves as the global optimal solution of a linear optimization problem, achieving near-optimal valley-filling effect. Such a command-based strategy requires no complex bi-directional network, but its valley-filling effect depends on the willingness of EV owners to relinquish charging autonomy for device-level objectives. The main challenge in such a decentralized algorithm is how to balance system-level with device-level objectives, which often constitutes a trade-off problem [3].

The system-level objective of the overnight charging scenario is to realize a valley-filling charging effect that reduces peak load and overall generation cost. At the device level, this charging strategy are usually to optimize the individual charging patterns to minimize electricity cost and battery degradation [16]. Sikha et al. developed a varying current decay (VCD) charge pattern for a lithium ion cell. VCD enables faster charging and lower capacity fade than conventional constant current/constant voltage (CC–CV) charge patterns [17]. To maximize the useful lifetime of lithium ion cells, Rahimian et al. optimized charging currents as a function of cycle number [22,23]. Liu et al. adopted the Taguchi method in an optimization technique for designing rapid charge patterns [24]. Applying the power loss model to the battery and charger, Wang proposed that electricity cost could be minimized by efficiency-optimized charge patterns [18]. Benedikt et al. investigated the trade-off between two competitive optimizations: cost and battery lifespan [19]. Adopting a first-principles electrochemistry based battery model [25], Bashash et al. optimized the PHEV charge pattern in terms of battery longevity and energy cost [16]. They used a multi-objective genetic optimization algorithm to balance the two conflicting device-level objectives. The resulting Pareto fronts of this algorithm described the trade-off between energy cost and battery health. Although these abovementioned device-level charging algorithms generate different "optimal" charge patterns, they possess one common feature: they require charging autonomy at the device level.

An ideal valley-filling charging algorithm satisfies the following three criteria.

1. *Coordination*: An optimal valley-filling effect is achieved by the aggregated charging load of all EVs connected in the grid.
2. *Practicality*: No reliance on a bidirectional communication/control network.
3. *Autonomy*: Allowing device-level charging autonomy and appropriate balance between competing objectives at two levels.

To the best of our knowledge, none of the existing valley-filling charging strategies [7–13] possess all three characteristics. This study proposes a novel decentralized optimal valley-filling charging strategy that fulfills these three criteria. The fundamental design is an optimized day-ahead two-dimensional time-power-varying pricing scheme for dynamic electricity use.

The pricing scheme is transmitted from the centralized grid broadcaster via a unidirectional communication network and is received by the intelligent chargers installed in the EV. Thereafter, the chargers determine their individual charge patterns. When EV owners optimize the varying device-level objectives, the grid automatically achieved optimized or near-optimized valley-filling charging effect. Therefore, the proposed strategy realizes multi-level optimization.

The paper is organized as follows. Section 2 describes the system and defines the optimization problem for the proposed valley-filling charging strategy. Section 3 introduces the fundamentals of the proposed strategy; namely, the pricing scheme and its design. Section 4 verifies the robustness of the proposed strategy in a series of simulations. The conclusions are presented in Section 5.

2. System description and problem definition

Fig. 1 shows the schematic of the grid–EVs system for the proposed valley-filling charging strategy. In this system, the charging behaviors of an EV fleet are indirectly coordinated by a pricing scheme. The EV owners are expected to optimize their individual charge patterns in response to the pricing scheme, enabling the aggregated charging load $P_{EV,agg}(t)$ to achieve a valley-filling effect.

The parameters of the grid–EV system are discussed in Sections 2.1 and 2.2. Using Beijing as an example, the valley-filling charging optimization problem is defined in Section 2.3. A preliminary analysis of the problem is provided in Section 2.4. The detailed pricing scheme based on the optimization problem is proposed in the next chapter.

2.1. Grid demand and generation cost

Fig. 2 shows the variation of typical grid power demand with time of day in Beijing. Data were collected at 15-min intervals during the summer and winter of 2011. This study uses the summer profile as an example, assuming that an accurate day-ahead forecast of non-EV power load $P_{nonEV}(t)$ is available [11].

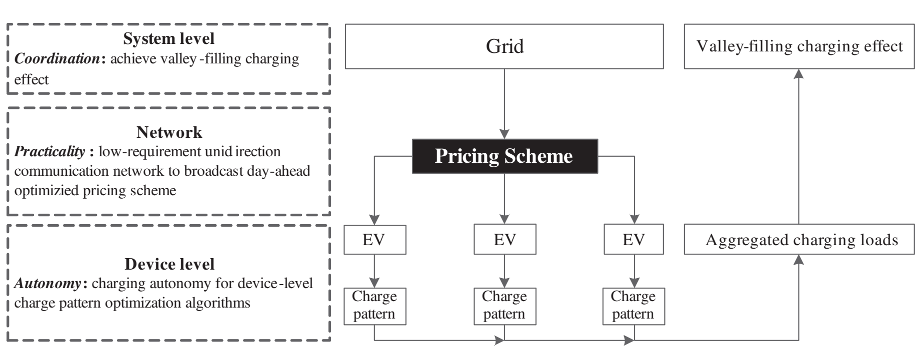

Fig. 1. Schematic of proposed grid–EVs system.