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Coordinating plug-in electric vehicle charging with electric grid: Valley filling and target load following

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HIGHLIGHTS

- Proposed protocol effectively fills the overnight valley.
- Computation and communication efforts are very modest.
- Modified protocol can approach a desired target load.

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ABSTRACT

Plug-in electric vehicles (PEVs) shift energy consumption from petroleum to electricity for the personal transportation sector. This work proposes a decentralized charging protocol for PEVs with grid operators updating the cost signal. Each PEV calculates its own optimal charging profile only once based on the cost signal, after it is plugged in, and sends the result back to the grid operators. Grid operators only need to aggregate charging profiles and update the load and cost. The existing PEV characteristics, national household travel survey (NHTS), California Independent System Operator (CAISO) demand, and estimates for future renewable generation in California are used to simulate PEV operation, PEV charging profiles, grid demand, and grid net load (demand minus renewable). Results show the proposed protocol has good performance for overnight net load valley filling if the costs to be minimized are proportional to the net load. Annual results are shown in terms of overnight load variation and comparisons are made with grid level valley filling results. Further, a target load can be approached in the same manner by using the gap between current load and the target load as the cost. The communication effort involved is quite modest.

1. Introduction

Plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs) are typically classified under the category of plug-in electric vehicles (PEVs) [1]. PEVs have drawn interest from government, automakers, and the public due to the potential to reduce fossil fuel consumption, tailpipe emissions, overall greenhouse gas emissions, and operating cost [2]. A variety of research papers have evaluated PEV benefits quantitatively [3–6]. The California Advanced Clean Cars programs mandates 1.4 million zero-emission and PHEVs in California by 2025 [7]. However, a consensus has been reached that one of the hurdles for large deployment (or acceptance) of PEVs is the shortage of charging infrastructure or electric vehicle supply equipment (EVSE) [8,9]. The state and local governments, as well as automakers, have shown interest in building a sufficient charging network. Previous work has presented analysis of the allocation of charging infrastructure [4,9]. There, it is shown that with large PEV penetration, even with a reliable charging network, the majority of the charging activities occur at home with the current PEV characteristics and charging rates, due to the cheap night time residential electricity and the long dwelling time needed. Furthermore, charging time strategy has been showed to have the most significant impact on charging cost reduction and overall grid operation. Here we focus on the details of coordinating PEV charging, at home, with the electric grid.

The electricity demand and generation of the grid have to be balanced at all times to assure operational stability. Charging PEVs increases the electric demand and has the potential to change the demand curve, if PEV penetration becomes significant. The time needed to charge PEVs, for most travel demands, is less than the

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Notation

t_i	time slot i in the 48-h window, e.g., 12 am–1 am, 1 am –2 am,..., 11 pm–12 am
i	time slot number, e.g., 1,2,..., 48
Δt	time slot duration, e.g. 60 min (1 h)
$\Delta t_n(t_i)$	plugged in time in time slot i for vehicle n, known
n	PEV number
ta_n	home arrival time after the last trip for PEV n
$E(t_i)$	electric demand
$D(t_i)$	electric net load
$x_n(t_i)$	charging energy at each time slot for vehicle n, decision variable
$r_n(t_i)$	maximum charging energy at each time slot for vehicle n, known
$L(t_i)$	final load with PEVs charging
T_k	time when cost is updated
V_k	vehicle number when cost updated
T_{step}	time interval for cost function updating
V_{step}	vehicle number interval for cost function updating
k	kth step to update cost function
$s_k(t_i)$	aggregated charging profile for step k
$C_k(t_i)$	cost function for charging at step k
$R(t_i)$	maximum overall charging power at each time slot, known
$X(t_i)$	overall charging load at each time slot, decision variable
$\text{TL}(t_i)$	target load
$\text{TC}_k(t_i)$	cost function for charging at step k with target load

dwelling time overnight. Unlike day time charging, overnight charging can be flexible and can be managed so that, aggregated with overall demand, it results in lower generation cost and emissions. Generally, constant (or flat) demand curves are considered beneficial for cost and environmental consideration [10]. Typically, wind and solar generation are treated as negative demand since the power cannot be controlled in the same way as other forms of generation. So the net load, total demand minus renewable generation, is targeted to be flat or at least slowly varying. The problem can be simply stated as obtaining a charging pattern so that the final net load curve has the least variation over an extended time horizon, given an original net load curve from the grid and the total charging demand for numerous PEVs.

It has become clear that if there is a significant penetration of PEVs, some form of "smart" or scheduled charging protocol will be needed. The power requirement of a large number of PEVs at peak or near peak times can lead to significant challenges in cost, delivery through grid, and even in generation and ramping capacities. This has led to several approaches to address this problem. Generally, the main goal is to schedule and shift the charging demand of the PEVs to the late evening and very early morning when the overall demand is the lowest. These are often called 'valley filling' approaches since they are aimed at leveling the overall demand to reduce the need for shutting down and restarting of large power plants. Of course, depending on specific, and relatively uncertain, costs associated with ramping and other considerations, it is possible that valley filling is not the optimal solution. For example, results in Ref. [11] show that under certain combinations of level 2 charging, station penetration, and costs assigned to ramp rates, etc., one can design a more desirable (e.g., less costly) charging profile, though how such a global plan can be realized is unclear. Here, we focus on the decentralized approach to address this challenge, as centralized approaches are difficult to implement and unlikely to be accepted.

Among the decentralized approaches that have appeared recently, paper [12] first solves a centralized optimization problem that takes into account costs associated with CO_2 generation and/or other economic and environmental costs. Based on the obtained average charging power, it then develops an algorithm that yields a decentralized implementation. Papers [13,14] use non-cooperative game concepts to develop a global valley filling protocol, under the assumption that all BEVs have similar state of charge (SOC) and other properties, and are plugged in at the same time. Paper [15] removes the homogeneity assumption and allows varied SOC, max charge rate, etc. The approaches in Refs. [13–15] are aimed at solving the global valley filling problem through a decentralized, and iterative, approach. In each iteration, a 'price' structure is communicated to the fleet of PEVs, so that each vehicle can develop an optimal (with respect to the broadcasted cost) charging profile. These profiles are sent back to the central communication node or the grid operator (e.g., the ISO – Independent System Operator), who will aggregate the total demand, based on the individual profiles, and broadcast a new price. Under relatively minor assumptions, the algorithms have convergence proofs. While the results are quite impressive, there are some challenges. Both techniques require the total number of PEVs be available for participation in the iterations needed in the optimization ([15] has results for the asynchronous case as well). Such an iterative approach might require significant communication if the number of vehicles is large. More crucially, these techniques do not ensure each PEV is charging at the maximum charging rate, which is how PEVs are currently charged. Ref. [16] attempts to address the last concern by relying on a stochastic approach in which the start of the charging period is the decision variable in the optimization problem, given the charging rate and SOC – which yields the charging duration. Under mild assumptions, the proposed iterative algorithm converges with probability one. Papers [17] and [18] propose decentralized charging controls for PHEV to avoid transformer overloading, but cannot fill the overnight demand valley. Paper [19] utilizes system-wide or nodal price for PHEV in the distribution network, however, it requires non-convex optimization solving technique.

In this paper, we focus on the similar problem with somewhat a different tack. We propose two approaches that ensure charging occurs at the maximum power, as is required with the current charging technology (1.44 kW for level 1 and 3.3 kW for level 2 EVSE), and the partial charging rate will lead to efficiency drop of the converter [20]. As a key contribution, we attempt to minimize the amount of communication needed between the large fleet of PEVs and grid operator and do not require availability of all PEVs for initiating the charging time assignments. Similar to other approaches, it can be modified to address excessive ramp rates or possible intermittent renewable sources (with some reasonable prediction window).

The basic approach can be summarized as follows. We use a cost schedule that reflects the desirable 'valley' or 'valleys' for the PEVs to charge (by assigning low costs to such periods). This is shared with individual vehicles, each solving a simple linear program to identify the periods for charging (at peak power), which will be the lowest 'cost' – and overall demand – periods. The solution is then sent back to grid operator for updating the charge structure. Note that this is not an iterative technique – there is only one set of data