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A semi-cooperative decentralized scheduling scheme for plug-in electric vehicle charging demand

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ABSTRACT

The paper proposes a decentralized control scheme for scheduling the flexible charging demand of plug-in electric vehicles in residential distribution networks. This control scheme is designed for execution by a multi-agent system at two consecutive stages of static and dynamic scheduling. The distinctive attributes of the developed control scheme are (i) to realistically prioritize both the customers' and the utility's objectives, (ii) to incorporate the uncertainty in the forecasted demand, (iii) to account for customers' flexibility in their charging demand, and (iv) to specify a fair pricing scenario to all customers while protecting their privacy. The paper includes extensive numerical studies using a set of recorded real-world driving data, representing heterogeneous vehicular demand. In order to assess the efficacy of the proposed scheduling scheme, comparative assessments are also presented against an optimization-based charging scheduling scheme.

1. Introduction

Flexible demands such as charging batteries of plug-in electric vehicle (PEV) at the customer side of a smart power system have the potential to be scheduled in a manner to enhance the overall performance of the grid. Efficient utilization of existing infrastructure, peak load leveling, and frequency or voltage regulation are examples of applications where scheduling of the flexible demand presents considerable benefits [1,2]. Certainly, customer's response and participation play a critical role in realization of such benefits. Therefore, incorporation of customers' satisfaction in the planning procedure is essential.

It is clear that the attributes of such flexible PEV demands (i.e., intensity and timing of demand) depend principally on each individual customer's commute requirements, which do not necessarily align with the objectives of the utility. In fact, a main concern regarding vehicular loading is its adverse effects on overloading residential distribution networks. At the distribution level, grid assets such as transformers, have low spare capacity and their coincident factor [3] is high as each asset serves a relatively small number of customers; a large coincidence factor implies that the ratio of the observed peak demand of a small group of customers to the sum of their individual peak demands is large. At the same time home-charging offers convenience and (in many cases) cost-effectiveness for PEV owners, which implies that significant PEV charging is likely to occur at the seemingly most vulnerable parts of the network. Note that the magnitude of the charging load and also the vulnerability of certain locations in the network to this additional demand may vary from one network to another, which may need to be analyzed on an individual basis. The stochastic temporal and spatial nature of the charging demand aggravates the issue.

Several studies in recent years have identified the potential adverse consequences of unsupervised charging and have proposed alternative charging management schemes. To postpone the upgrading of network assets through enhanced utilization is the common goal among these schemes [1,4–8].

The methods developed for supervised charging in a smart grid environment can be broadly categorized as centralized and decentralized strategies [9–12]. In a centralized approach, the charging profile of all PEVs is determined by the central intelligence of the utility, which aims to achieve an optimal aggregated charging profile [4–7]. Centralized methods are generally suitable to address congestion management at a large scale and to manage incorporation of charging load in an environment where coordination with intermittent renewable sources may be required [11].

Although under a centralized scheme the customers can specify their strict charging objectives, a typical centralized decision mak-

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Nomenclature

AD	aggregated demand (forecasted) on target assets
B	base-load, uncontrollable demand
CP	critical point of demand
EC	effective desired charge
FD	flexibility degree
L	length of timeslots
MOL	maximum over-load
n	customer; $n \in \{1, \ldots, N\}$
NRC	summation of negative RC
OL	over-load of each customer
P	flexible charging demand
PZ/PF	flexible demand for $RD = 0/RD = 1$
POL	permitted over-load
RC	remaining capacity
RD	risk degree
RE	remaining energy
t	time slot; $t \in \{1, \ldots, T\}$
T_u/T_l	number of timeslots eligible for under-load/ over-load
UL	under-load of each customer

ing scheme (i) gives relatively more weight to maximized utilization and grid performance than to individual customer's satisfaction, and (ii) requires collecting and assessing large amounts of data from distributed PEVs. This involves an intensive computation and communication procedure/network, thus limiting its applicability for large numbers of PEVs.

On the other hand, in a decentralized approach, charging patterns of distributed PEVs are decided locally to firstly fulfill customer's desires; thus a decentralized strategy does not necessarily pursue the objective of the overall system's optimal operation [13–17]. Generally, the benefits of such strategies are (i) lower communication cost and computational complexity, (ii) fast response-time to the changes in the objectives and operational abnormalities, and (iii) better scalability. They also raise much less privacy concerns as customers' personal data, such as arrival and departure times, are usually not communicated within the network. Therefore, decentralized strategies are deemed more appropriate to address the problem of coordinated charging.

To implement decentralized strategies multi-agent system (MAS) frameworks have been widely employed, due to their inherent compatibility with decentralized schemes [18–21]. Depending on whether or not the agents (who execute the charging management scheme) cooperate with each other, several alternatives proposed in recent literature are classified as follows:

(1) *Non-cooperative strategies*: Every agent reacts to the change in a signal (usually electricity tariff) sent by the utility, and determines its own best charging profile. The key feature of strategies in this class is that each agent pursues only its own goals independently of the others. In one of the common approaches [13,18], agents engage in a dynamic game with the utility in several rounds until reaching an optimal settlement point. This certainly requires a highly reliable and complex communication network.

(2) *Cooperative or distributed strategies*: Agents cooperate with their neighboring agents, based on the consensus algorithm, to achieve an optimal solution for the entire group [22,23]. Although there is no need for the coordinator signal by the utility in this case, a peer-to-peer communication network is still required. Moreover, in such strategies some individual customers' objectives might be sacrificed for the sake of other members of the group.

This paper proposes a semi-cooperative decentralized scheme. The developed scheme is executed by a MAS framework such that agents indirectly cooperate with each other for the sake of better overall performance of the grid while pursuing only their own objectives (i.e., lower cost of charging). The utility will still have a simplified supervisory role, but the communication burden will be less than a game-based non-cooperative approach and the weight of the customers' objectives will be more than it would be in a distributed cooperative approach. The computation burden is also extremely relieved. The main contribution is in fact proposing a *satisficer* plan, which considers (i) the uncertainty of the forecasted demand, (ii) customers' unequal opportunity for off-home charging, and (iii) the necessity of establishing a fair pricing scenario.

The following section shows the attributes of the proposed scheme and describes its logic. Then in Section 3 the two stages of the scheme are described and their corresponding algorithms and formulations are presented. Section 4 is dedicated to simulation of a real-world case-study to which the proposed charging scheduling scheme is applied. Section 5 presents detailed comparative studies of the proposed scheme against a centralized optimization-based vehicular demand scheduling algorithm. This section shows the performance and merits of the proposed scheme in terms of achievement of the desired objective, immunity to uncertainties, and computational complexity. Section 6 presents discussions and conclusions.

2. Overview of the proposed scheme

The task of planning the flexible charging demand generally involves two parties: a utility service with diverse capacity infrastructure, and distributed customers with diverse demand attributes. In reality the objectives of these parties may not necessarily conform to one another; that is, a utility's objective could be to maximize its infrastructure's utilization in order to delay upgrades or addition of extra generation. Reasonable expectations of customers could, however, be to receive their entire charging demand within their desired time frame and with minimum cost. The aim of planning must, therefore, be to align the utility's and the customers' objectives as much as possible so that the final solution satisfies both parties to *an acceptable level*. Achievement of this goal requires both parties to indicate their acceptable satisfaction level.

It is important to note that the aggregated response and participation of customers are the main measures for a successful plan. A sound plan (or any energy regulation policy) must comprehensively address customers' concerns to convince the majority of them to participate; therefore, it must account for the human nature of decision making and energy consumption behavior. Several studies in this area have pointed out that since people mostly satisfice (good-enough option) rather than optimize (best option) while dealing with uncertainties and complexities, simplified strategies or policies will be more effective [24,25].

Plans designed for maximizing infrastructure utilization with a complex optimization procedure are too idealistic and highly prone to failure due to a large number of uncertain variables in this specific problem; that is, at a low level of a distribution network with a small number of customers, the actual demand could be noticeably different from the forecasted demand. Thus aiming to