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Commercial electric vehicle fleet scheduling for secondary frequency control

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ABSTRACT

The participation of plug-in electric vehicles (PEVs) in the frequency regulation has been subject of intensive research, but exclusively from the aggregator or individual car owner perspective. Therefore, optimization criteria have been restricted to aggregator's revenues and/or costs and car owner's utility and satisfaction. In a real life practice, the case of commercial PEV fleet is not rare, but the problem of its usage and scheduling for frequency regulation has not been addressed so far. This particular problem requires new criteria, besides costs and revenues, like the commercial service level and fleet owner electricity network capacity. Consequently, the multi-objective approach in the case of uncertainty is required, because of the stochastic nature of vehicle usage.

In this paper, a multi-objective decision-making methodology for the daily scheduling of PEV fleet is proposed. Objectives that have to be fulfilled simultaneously are the minimization of the costs incurred from being parked, maximization of the revenues offering secondary regulation and the maximization of the vehicle fleet charging station efficiency. The optimization is performed using the multi attribute utility theory that allows different decision maker's attitude towards risk. Possible revenues are calculated with day ahead energy costs, while the stochastic nature of vehicle usage is taken into account using queuing theory. Genetic algorithm is used for the minimization of multi-attribute utility function and daily scheduling of PEVs. Methodology is illustrated on a day ahead scheduling for small commercial vehicles fleet, giving the optimal time of grid connection of vehicles.

1. Introduction

1.1. Motivation

One of the main tasks of transmission system operators (TSO) is to maintain a real-time balance between generated and consumed electrical energy. This activity is essential for overall security of the power system and for proper functioning of integrated electricity markets. Balancing services differ in the terms of activation method and time domain of response and they are mainly based on generator's response. Besides classical generators, one of the propitious solutions is the utilization of plug-in electric vehicles (PEV) with batteries used as short-term energy storage. Depending on the imbalance direction, they are charged in the case of a power excess or discharged in the opposite case. PEVs are advantageous compared to classical generators due to their reaction to demand requests in real-time, low initial and standby costs per kWh, and temporarily high power [1–4].

Commercial PEV fleet (repair crews, delivery services) represents the important resource for frequency regulation, but the problem of its usage and scheduling has not been addressed so far. Optimization criteria have been restricted to aggregator's revenues and costs and car owner's utility and satisfaction. Particular problems, like the commercial fleet scheduling, require new criteria, besides costs and revenues, like the commercial service level and fleet owner electricity network capacity. Consequently, the multi-objective approach in the case of uncertainty is required, because of the stochastic nature of vehicle usage. Generally, the uncertainties include uncertainty of market prices, uncertainty of activated amount of reserve by ISO and uncertainty of PEV owners' behaviour [5].

In this paper, the problem of daily scheduling of PEV fleet is analyzed, with different objectives that have to be fulfilled simultaneously: the minimization of the costs incurred from being parked

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(not serving customers), the maximization of the revenues offering secondary regulation and the maximization of the vehicle fleet charging station load factor.

1.2. Literature review

The concept denoted as vehicle-to-grid (V2G) was first mentioned in 1997 [1] and has been subject to further intensive research [2–7]. An aggregator is necessary for the proper balancing service operation. This intermediary inserted between the vehicles offering different ancillary services and the grid system operator receives service requests from the grid system operator. Then, aggregator sends power commands to contracted vehicles using centralized of decentralized control [8–10]. The possible profitability of PEVs acting as regulating power has been treated in a number of previous studies. In [3], estimated profits are obtained for battery vehicles providing following types of ancillary services: peak load power, spinning reserves and regulation. Economic feasibility of V2G frequency regulation taking into account the battery wear is analyzed in [11–15]. In [16] the focus is essentially on the PEV contribution for primary reserves provision, while in [17] a bi-level problem is constructed, where in the upper-level, the objective of the aggregator is to maximize its profit through its interactions and in the lower-level the parking lot maximizes its own profit limited to the preferences of PEVs.

The study [18] analyses plug-in hybrid electric vehicles (PHEVs) as providers of regulating power in Germany and Sweden. The results indicate the maximum average profits on the German markets in the range 30–80 € (per month and vehicle), but no profit for the Swedish regulating power markets. The simulation result for the Portuguese market with average prices gives a net revenue of around 20 €/month and vehicle providing 3.5 kW of regulation services [19]. Results from the German market [20,21] show that providing negative regulation energy, which implies charging the PEV at a lower price, appears to be the most promising option related to the economic potential for both the secondary and the tertiary regulation energy market.

At an aggregator level, flexible and practical charging strategies are proposed by controlling the attached PEV chargers [22]. In [23], the proposed methodology considers the regulation up/down, spinning and non-spinning reserve jointly with the energy service minimizing the VPP's operation cost. In [24], the unidirectional V2G has been explored, while this approach has been extended to bidirectional V2G, and to a combined provision of regulation and reserve in [25,26]. The aggregator maximizes the profit and optimizes PEV owners' revenue by applying changes in tariffs to compete with other market players for retaining current customers and acquiring new owners [27].

In these studies, the problem of optimization of V2G assets or vehicle scheduling has been treated as one-dimensional problem, with the maximization of aggregator revenues as the sole objective. The analyzed sources of aggregator revenues were the revenues from selling regulation and spinning reserve capacity, regulation energy and the revenues from selling energy to PEVs.

In [28], the two-stage optimization of the charging/discharging decisions by maximizing PEV owner satisfaction and then minimizing system-operating costs is presented. However, a PEV scheduling problem often involves trade-off on cost and CO_2 emissions, while also pursuing welfare maximization, battery cost minimization, grid support (e.g. peak shaving, or power deviation minimization in aggregator level), battery state of charge (SOC), etc. PEV optimization and modelling should include multi-objective optimization in order to be realistic. Research in [29] considered a multi-objective optimization, in the unit commitment scheduling problem formulation with both capital and operational costs. In [30] multi-objective optimization algorithm using a heuristic technique to maximize V2G revenue and to improve system reliability by minimizing the system disruption cost as well as reducing the power loss is presented. An objective function in [31] consists of electricity generation, imported/exported power costs and revenue components, and the environmental-credit components that are assigned to each PEV. In [32] authors considered charging cost, power losses, and departure penalty, and [33] divided the charging task into two parameters involving maximum revenue dynamic charge scheduling and minimum cost dynamic charge scheduling, with an upper bound of cost designed to trade-offs aggregator revenue with customer benefit. The power purchase, generation and emission cost are minimized using the generalized Benders decomposition method from a distribution network side, where the Pareto optimal solution for economic cost and emission cost is achieved [34]. The optimal allocation of available vehicles on a day-ahead basis using the queuing theory and a fuzzy multi-criteria methodology has been determined in [35]. A more detailed comprehensive review of other computational scheduling methods for integrating PEVs in power systems is given in [4,36].

Although multi-objective oriented, previous studies take into account the vehicle owner benefit from the aggregator or individual car owner perspective. The aggregator schedules vehicles with the maximization of his profit, while the fleet owner perspective, concerning its revenues and the availability of vehicles remains neglected. While the aggregator needs as much vehicles as possible connected to the network, the fleet owner has to balance between the service quality and the revenues from ancillary services offered by PEVs. Some fleets operate in a demand-responsive mode (the fleet has to be deployed and managed in real-time [37]), but many of them have to perform tasks that may be known well in advance or that are sometimes repetitive.

The stochastic nature of driver's attitude and car usage represents a great problem in the reserve capacity allocation. Vehicle driving patterns and available regulation capacity have been investigated in [38] using queuing theory and $M/M/\infty$ model for the estimation of each vehicle charging and discharging time. However, this approach calculates available energy implicitly, not being aware of required driving distance for each vehicle. Usually, PEV charging demand prediction model takes daily driving patterns and distances as an input to determine the expected charging load, and the probability density function of arrival and departure times based on the historical data is used. With large numbers of vehicles, the distribution yields a normal distribution, and the total achievable power capacity from each PEV is represented by normal probability distribution in [39–41]. In [27,42,43] lognormal distribution function is utilized to generate the probabilistic daily driven distance, and scenarios based on time series of uncertain variables are generated using Roulette Wheel Mechanism [27].

Another source of uncertainty is the probability of being called to generate energy in the spinning reserve market. In [44], this probability is modelled with Poisson distribution, while the more usual approach is to estimate this probability by the ratio between actually daily dispatched energy and potential contracted energy [1–3,45,46].

In our approach, we are eliminating the uncertainty concerning EV charging by setting fixed time interval for PEV connection. In the proposed methodology, the uncertainty estimation of driving patterns is transferred from the aggregator to the PEV fleet owner. The PEVs arrival and departure times are fixed, and fleet owner minimizes the service waiting time by estimating expected calls for services and service execution time.

1.3. Research objectives and contributions

The main goal of this paper is optimal day-ahead schedule of PEVs charging from the fleet owner perspective. Vehicles are used