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A stochastic robust optimization approach for the bidding strategy of an electric vehicle aggregator

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ABSTRACT

This paper analyzes the bidding strategy problem of an electric vehicle aggregator that participates in the day-ahead energy market. The problem is formulated using a stochastic robust optimization model in which uncertainties in the day-ahead market prices and in the driving requirements of electric vehicles are modeled using scenarios and confidence bounds, respectively. The output of the proposed model is used to build the bidding curves to be submitted by the aggregator to the day-ahead market. We assume that the electric vehicle aggregator behaves as a price-taker in this market. A case study is analyzed to illustrate the main features of the proposed approach, as well as its applicability. We also compare the results with those achieved by considering other strategies. Results show that the proposed approach allows the aggregator to reduce the charging costs in comparison with other charging strategies. Moreover, the solution obtained is robust in the sense that driving requirements of electric vehicle users are met.

1. Introduction

1.1. Aim and approach

The number of electric vehicles (EVs) is expected to increase in the near future due to, mainly, two reasons. First, the maturity of their technology makes EVs available for long-distance trips, which was one of the main drawbacks in the past. Second, due to the reduction of CO_2 emissions and other greenhouse emissions if renewable energy sources are used to supply EVs [1]. This has motivated the use of incentive policies by some countries to encourage consumers to buy EVs instead of conventional vehicles, e.g., in Norway [2].

A large penetration of EVs supposes a big challenge. Traditional charging strategies consider that EV owners start charging their EVs as soon as they are parked and until the next trip or until the battery is full. In this sense, note that most of the population arrive at home/work at similar times. Thus, most EVs are expected to charge at the same time. If the number of EVs is very large, this may translate in a peak in the energy consumption at these times.

However, EVs are parked and available for charging most of the time. Thus, it would be possible to shift its charging to the most suitable time, e.g., to a time with low demand or with low prices. This would reduce the peak energy and/or would allow EV users to reduce their charging costs. Nevertheless, managing the charging of every individual EV has two problems. On the one hand, the limited flexibility of an individual EV. On the other hand, the high computation effort to deal with the management of a very large number of EVs. To overcome these two issues, it is generally convenient to use the figure of an aggregator, which can be seen as an energy management system (EMS) [3,4] in charge of an EV fleet. The aggregator manages the charging of these EVs and ensures that the driving requirements of EV owners are met.

The figure of an EV aggregator has been proposed and considered in the technical literature using different approaches, e.g., considering unidirectional [5,6] or bidirectional charging [7,8]. This bidirectional charging is usually known as vehicle-to-grid (V2G) and allows the EV aggregator to behave as a producer or as a consumer [9] depending on the market prices and the driving requirements.

Among the different problems faced by an EV aggregator, in this paper we focus on the problem of determining its bidding strategy in an energy market. In particular, we determine the bidding strategy of an EV aggregator that participates in a day-ahead (DA) energy market.

A key point at the time of determining the bidding strategy of the EV aggregator is the modeling the different sources of uncertainty that condition this bidding strategy. These uncertainties include

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Notation

The main notation used in this paper is stated below for quick reference, while other symbols are defined as needed throughout the text. A subscript t/ω in the symbols below denotes their values in the tth time period/ωth scenario.

Indices

t	time periods
ω	scenarios

Parameters

E^{A}/E^{D}	energy contribution/drop of EVs arriving to/departing from the EV aggregation [kWh]
E_{t_0}	initial energy content of the virtual battery representing the EV aggregation [kWh]
$\underline{E}^{max}/\bar{E}^{max}$	lower/upper bound for the maximum energy content of the virtual battery representing the EV aggregation [kWh]
$\underline{E}^{min}/\bar{E}^{min}$	lower/upper bound for the minimum energy content of the virtual battery representing the EV aggregation [kWh]
$\underline{P}^{+,max}/\bar{P}^{+,max}$	lower/upper bound for the maximum charging power of the virtual battery representing the EV aggregation [kW]
$\underline{P}^{-,max}/\bar{P}^{-,max}$	lower/upper bound for the maximum discharging power of the virtual battery representing the EV aggregation [kW]
Δt	time-step duration [h]
η^{+}/η^{-}	charging/discharging efficiency of the virtual battery representing the EV aggregation [%]

Random variables

E^{max}/E^{min}	maximum/minimum energy content of the virtual battery representing the EV aggregation [kWh]
$P^{+,max}/P^{-,max}$	maximum charging/discharging power of the virtual battery representing the EV aggregation [kW]
λ	price in the DA market [$/MWh]

Optimization variables

E	energy content (state-of-charge) of the virtual battery representing the EV aggregation [kWh]
P	power bought from (if positive)/sold to (if negative) the DA market [kW]
P^{+}/P^{-}	Charging/discharging power of the virtual battery representing the EV aggregation [kW]

Acronyms

ARIMA	autoregressive integrated moving average
DA	day-ahead
EMS	energy management system
EV	electric vehicle
LP	linear programming
RO	robust optimization
VPP	virtual power plant
V2G	vehicle-to-grid

the market prices and the driving requirements of EV owners. To do so, in this paper we use scenarios to model the uncertainty in the market prices. This allows us to use a stochastic programming model [10]. On the other hand, we use confidence bounds to model the uncertainty in the driving requirements. This allows us to use robust optimization (RO) [11]. Thus, the bidding strategy problem is formulated as a hybrid stochastic robust model.

1.2. Literature review

The technical literature about bidding strategy problems is extensive. Many methods have been proposed for different entities, e.g., conventional power producers [12], demand-response aggregators [13], virtual power plants (VPP) [14], microgrids [15]. [12] proposes a bi-level model that allows representing the influence of the power producer on market prices. [13] compares stochastic and robust models for a demand-response aggregator. [14] proposes a stochastic model for a VPP participating in both energy and reserve markets. [15] proposes a hybrid stochastic robust model for a microgrid participating in the DA and real-time energy markets.

Besides these methods, different approaches to deal with the bidding problem of an EV aggregator have been proposed, e.g., [16–23].

Some of these methods consider the participation of EVs in both energy and capacity markets. [16,17] consider the participation of the EV aggregator in the DA and reserve markets. [18] proposes a stochastic approach and considers the participation of the EV aggregator in the DA and regulation markets. [19] analyzes the optimization of charging and frequency regulation capacity bids using a stochastic dynamic programming model. The problem is formulated in this case using a Markov decision problem. [20] proposes a stochastic mathematical programming with equilibrium constraints problem for the participation of EV aggregators in the DA and ancillary services markets.

Other methods consider the participation of EVs only in energy markets. [21,22] formulate the bidding problem in the DA market using a bi-level model, which explicitly represents the clearing of the DA market. [23] models the risk associated with the bidding decisions in the DA market using the conditional value-at-risk.

However, none of the above methods for EV bidding considers a robust approach. In these references, uncertainties are generally modeled using scenarios. Thus, the driving requirements of EVs may not be met if these scenarios are not properly generated.

Note that both [21] and this paper deal with the same problem, namely, the bidding strategy of an EV aggregator in the DA market. However, these two works have three main differences: (i) [21] considers that the EV aggregator is a price-maker while in this paper it is considered as a price-taker; (ii) uncertainties in [21] are modeled using scenarios, while in this paper we model uncertainties using both scenarios and confidence bounds; and (iii) [21] proposes a stochastic model, while in this paper we describe a hybrid stochastic robust model.

1.3. Contributions

The main contribution of this paper is to provide a new approach based on a hybrid stochastic robust model for the bidding strategy of an EV aggregator in the DA market.

On the one hand, stochastic programming has been widely used for offering strategy problems [9,12]. On the other hand, RO has been recently used in offering and bidding strategy problems of conventional units [24], concentrating solar power plants [25], and VPPs [26], since it constitutes a flexible tool that can be easily included in an EMS, e.g., in an EV aggregator in charge of an EV fleet.

However, to the best of our knowledge, there is no paper in the technical literature that combine stochastic programming and robust optimization for the bidding problem of an EV aggregation.

The advantage of the method proposed in this paper over other methods based solely on stochastic programming, e.g., [14], is that