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Stochastic scheduling of aggregators of plug-in electric vehicles for participation in energy and ancillary service markets

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ABSTRACT

Plug-in electric vehicles are expected to play a major role in the transportation system as the environmental problems and energy crisis are being more and more urgent recently. Implementing a large number of vehicles with proper control could bring an opportunity of large storage and flexibility for power systems. The plug-in electric vehicle aggregator is responsible for providing power and controlling the charging pattern of the plug-in electric vehicles under its contracted area.

This paper deals with the problem of optimal scheduling problem of plug-in electric vehicle aggregators in electricity market considering the uncertainties of market prices, availability of vehicles and status of being called by the ISO in the reserve market. The impact of the market price and reserve market uncertainties on the electric vehicle scheduling problem is characterized through a stochastic programming framework. The objective of the aggregator is to maximize its profit by charging the plug-in electric vehicles on the low price time intervals as well as participating in ancillary service markets. The operational constraints of plug-in electric vehicles and constraints of vehicle to grid are modeled in the proposed framework. An illustrative example is provided to confirm the performance of the proposed model.

1. Introduction

The increased concerns about global warming and energy crisis effects have led to the widespread popularity of electric vehicles (EVs) [1]. Chivalrous government objectives for plug-in electric vehicles (PEV) promotion, growing PEV technology, PEV purchase motivations and PEV production cost saving all promise a large permeation share of PEVs in the future vehicle market.

In the early days of electricity markets, the generation units were the only participants of the power markets. As time passes demand side resources as well as aggregators contribute in the market as a virtual power plant in order to meet the power system demand and enhance the system reliability by providing ancillary services. The market share of electric vehicles is predicted to reach up to 30% of new sales by 2030 [2]. Since direct participation of small loads into the power markets is not feasible due to the current market rules, PEVs are aggregated by an agent that acts as a commercial middleman between the PEV owners and electricity market or independent system operator (ISO) of the transmission and distribution grid [3]. In addition, PEV aggregation can result in lower charging cost for PEV owners through managing and controlling batteries charging. PEVs are similar to an electric load when batteries are charging and vehicles receive energy from the network (grid-to-vehicle (G2V) mode). On the other hand, when the PEVs batteries are charged, a noticeable number of them can perform as a power generation unit and inject energy to the grid (Vehicle-to-grid (V2G) mode). In addition, PEVs in V2G mode, increase grid flexibility in order to integrate renewables, through implementing the vehicles as storage devices [4]. The concept of a PEV aggregator implementing bidirectional communications is discussed in Ref. [5]. Moreover, the aggregated PEVs due to their charging flexibility could be good candidates for providing ancillary services [6].

The participation of PEV aggregators in the power market implies the necessity of optimal scheduling for engaging these energy

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storage resources. Nowadays, owing to liberalized power markets, the PEV aggregators become subject to more volatile power prices and are enthusiastic to hedge against the risk of daily price instabilities. Forecasting the electricity market prices is of the foremost importance for aggregators in order to maximize their profit. The economic impact of the price forecasting errors in the scheduling problem of thermal and hydro producers is studied in Ref. [7]. Thus, an accurate price forecast and proper reserve market and vehicles modelling have a decisive impact on the decision making strategies of the aggregators to prospering participation in the power markets. Pool prices, availability of vehicles and the status of calling the players by ISO to deliver energy in the reserve market could be envisaged as random variables and stochastic optimization methods might be employed for obtaining the optimal schedules. Different methods have been presented for decision making in uncertain environment. In Ref. [8] a standard classification of uncertainty modelling methods for decision making process is presented. Possibilistic, probabilistic, hybrid methods, interval based analysis, robust optimization as well as Z-numbers have been assessed in Ref. [8]. An information gap decision theory (IGDT) based method is employed in Ref. [9] for determining the optimal bidding strategies of combined heat and power units considering market price uncertainty. Application of IGDT to risk-constrained self-scheduling of gencos has been investigated in Ref. [10]. In addition, in Ref. [11] risk-based bidding of large electric utilities using IGDT has been presented. A proper and common way for characterizing uncertainties is generating some plausible samples which are called scenarios [12]. In order to characterize the stochastic processes, perfect scenario generation and reduction with a proper tool is important. Autoregressive integrated moving average (ARIMA) model is of the widely employed and important time series models [13–15]. ARIMA is a time series analysis and modelling tool, which is also known as Box-Jenkins model, or differential autoregressive moving average (ARMA) model [16].

In a competitive environment, the main objective of PEV aggregators is to maximize their profit while minimizing the corresponding risk. Typically, risk management could be carried out by means of risk measures, namely, the shortfall probability, expected shortfall, profit variance, value-at-risk (VaR) and conditional value-at-risk (CVaR) [12]. Currently, the CVaR is employed widely in problems related to electricity markets due to its linear formulation and also being a coherent risk measure [17].

1.1. Review of related works

Charging behavior of PEVs has been modeled in many recent works in order to maximize the aggregator profit. In Ref. [18], a charging regulation algorithm for unidirectional V2G is developed in order to modulate the set point of charging rate for each EV. In this work an aggregator profit maximization algorithm has been formulated with optional system load and price constraints similar to the smart charging algorithms. An aggregate battery model is proposed in Ref. [19] for an EV fleet. Impacts of market regulations on behavior of market players and EV owners are studied in Ref. [20]. Moreover, behavior of EV owners has been modeled in Ref. [20], considering type of the contract with aggregator. In Ref. [21], charging and discharging patterns of PEVs are optimized according to price variations of electricity market in order to maximize the social benefit of PEV participation as energy storage in the market. Moreover, in this literature, grid regulation ancillary service potential of the vehicle fleet has been calculated based on the outcomes of optimization problem. A novel approach for strategic bidding of Gencos in energy and spinning reserve markets has been proposed in Ref. [22]. In Ref. [23], the optimal energy management of micro grids including renewable energy sources, storage devices and plug-in hybrid electric vehicles (PHEVs) is studied using stochastic programming that considers the uncertainties using Monte Carlo simulation. A methodology for operations optimization to maximize hybrid energy systems economic value based on predicted renewable generation and market information is proposed in Ref. [24]. In addition, hybrid energy systems under variable energy generations/exploitations and flexible operations have been suggested to be an important element to permit higher penetration of clean energy generation, e.g., renewable and nuclear options, [25–27]. In Ref. [28] an optimal bidding algorithm is developed for unidirectional V2G model. Stochastic programming is used in Ref. [28] to formulate the EV aggregator optimization problem considering regulation market uncertainties. The problem of trading in the energy market for a load-serving entity that serves a load with significant PEV penetration has been addressed in Ref. [29]. In Ref. [29] the problem of energy trading in coordination with unidirectional V2G services is formulated as a mixed-integer stochastic linear program. In addition, in this work, the CVaR is used as a risk control measure. Short-term scheduling of aggregators employing unidirectional charging pattern is considered in Ref. [30]. Reference [30] focuses on risk constrained optimal participation of PEV aggregator in the day-ahead electricity market, employing CVaR risk measure.

The aggregator may participate as energy storage in both day-ahead and reserve markets in order to maximize the total benefit. Participation in the both markets has not been modeled in the above-mentioned works. In this regard, in the current paper the optimal scheduling of aggregators considering day-ahead and reserve markets has been formulated. The uncertainty nature of market prices, reserve market and available vehicles are modeled using stochastic programming formulation. ARIMA technique is employed to produce the electricity price scenarios. The daily and weekly seasonalities of the market prices and the hourly probability of being called by the ISO for delivering energy in the reserve market are considered in the scenario generation procedure. The battery degradation cost due to discharging the batteries in the market is envisaged, in order to have optimal scheduling. In addition, risk management problem has been employed considering CVaR risk measurement in the PEV aggregator scheduling process.

1.2. Paper highlights

(i) The optimal probabilistic scheduling problem of aggregators considering both day-ahead and reserve markets has been solved. In the proposed framework, the participation of PEVs in the markets has been studied considering the uncertainty of vehicles availability, and the battery degradation cost due to discharging the batteries in the market.
(ii) The pool prices uncertainty is envisaged as stochastic processes in the PEV aggregator scheduling problem. These random variables are forecasted implementing SARIMA models. In the scenario generation process, daily and weekly seasonalities of the electricity market prices have been modeled.
(iii) A new technique has been proposed for scenario generation process of the state of being called by the ISO. In the proposed model the hourly probability of being called by the ISO for delivering energy in the reserve market has been considered.
(iv) In the PEV aggregator decision making process risk management problem has been investigated considering CVaR risk measurement. In addition, the effect of risk measure weight in the V2G model has been studied.

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