Applied Energy 133 (2014) 347–355

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Modelling demand response aggregator behavior in wind power offering strategies

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HIGHLIGHTS

- This paper proposes a new model to include DR in wind offering strategy.
- A wind power producer is able to trade DR with a DR aggregator.
- The DR aggregator behavior is modelled through a revenue function.
- A bilevel problem is formulated which is transformed into a linear problem.
- The outcomes indicate the usefulness of the proposed strategy.

ARTICLE INFO

Article history:
Received 2 May 2014
Received in revised form 25 July 2014
Accepted 30 July 2014
Available online 20 August 2014

Keywords:
Bilevel programming
Demand response
DR aggregator behavior
MPEC
Stochastic programming
Wind offering strategy

ABSTRACT

This paper proposes a new wind offering strategy in which a wind power producer employs demand response (DR) to cope with the power production uncertainty and market violations. To this end, the wind power producer sets demand response (DR) contracts with a DR aggregator. The DR aggregator behavior is modeled through a revenue function. In this way the aggregator aims to maximize its revenue through trading DR with the wind power producer, other market players and the day-ahead market. The problem is formulated in bilevel programming in which the upper level represents wind power producer decisions and the lower level models the DR aggregator behavior. The given bilevel problem is then transformed into a single-level mathematical program with equilibrium constraints (MPEC) and linearized using proper techniques. The feasibility of the given strategy is assessed on a case of the Nordic market.

1. Introduction

Determining an optimal offering strategy is the main challenge faced by a wind power producer. This is due to its power production uncertainty as well as market price volatilities. Research in the literature striving to present solutions for this issue mainly focuses on market studies [1–7] and joint operation problems [8–14].

Authors in [1] investigate a probabilistic bidding model for wind power producers. The concept of minimizing imbalance costs in wind offering strategies is investigated in [2,3]. Offering in various market floors including day-ahead, adjustment and balancing markets is addressed in [4]. Ref. [5] recommends the coalition of wind power producers to alleviate the wind power uncertainty. Researchers in [6] evaluate the offering strategy by price-maker wind power producers. Finally, offering strategy considering two models, i.e. naive use of wind production forecasts and stochastic programming, is addressed in [7].

A joint operation of wind power producers and storage systems is provided in [8–11]. The coordination of wind power producers and hydro power plants is studied in [12,13]. The coordination of wind power producers and thermal power plants is investigated in [14]. Demand response (DR) is now becoming matured around the world. Practical experience worldwide indicates this improved trend. For instance, refer to [15] for the European demonstration, [16] for the US experience and [17] for Italian programs. DR can also be employed by wind power producers as a hedging resource. The literature survey however indicates that relevant studies mostly focus on the coordination of DR and wind power producers to improve network and market operations [18–21].

This paper proposes a new offering strategy through which a wind power producer is able to trade DR with a DR aggregator in order to tackle the uncertainties associated with both power

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http://dx.doi.org/10.1016/j.apenergy.2014.07.108
0306-2619/

production and market prices. The wind power producer decides its offer in the day-ahead market while setting DR contracts with the DR aggregator. To this end, the DR aggregator behavior is modeled through a revenue maximization function in which the aggregator determines its DR trading shares with three main resources: the wind power producer in our study, other market players interested in DR, and the day-ahead market. A bilevel problem [22,23] is formulated in which the upper-level decision maker (leader) is the wind power producer while the lower-level problem is decided by the DR aggregator (follower). The overall problem is then transformed into a single-level mathematical program with equilibrium constraints (MPEC) by replacing the lower-level problem with its Karush–Kuhn–Tucker (KKT) optimality conditions [24]. In addition, the nonlinearities of the derived MPEC are linearized using the strong duality theorem [24] and the technique provided in [25]. A case study of the Nordic market is used to evaluate the validity of the proposed offering strategy. Uncertainties in each level are characterized using a set of finite scenarios. In addition, the risk is carried out using conditional value-at-risk (CVaR).

Overall, the contributions of the paper are as follows.

1. A new model is proposed to include DR in the offering strategy of a wind power producer. Accordingly, the wind power producer is able to participate in a day-ahead market while arranging DR contracts with a DR aggregator to lessen its risk.
2. The competition in the DR procurement is taken into account through modelling the DR aggregator behavior. To this end, a bilevel programming problem is formulated which is then rendered into a single-level linear MPEC using proper methods.

The rest of the paper is structured as follows. Section 2 addresses the proposed wind offering strategy, where the mathematical formulation of the proposed bilevel problem is described. Then the equivalent linear formulation is presented in Section 3. Section 4 provides a case study with numerical results. Section 5 concludes the paper. Finally, appendices are addressed in the last section

2. Wind offering strategy

2.1. Framework

The following assumptions are made in the proposed strategy. First, it is assumed that the wind power producer makes offers in the day-ahead market while clearing imbalances in the balancing (regulating) market. Additionally, the given wind power producer is treated as similar to conventional power plants [26], where it is responsible for its bidding strategy and power production variation. Moreover, similar to [13], this paper determines the optimal offering quantities instead of presenting bidding curves which is investigated in [4]. A further assumption is that modelling technical DR programs through which the DR aggregator obtains DR from customers is not the focus of this paper. Finally, note that the DR flow can be either from the aggregator to players willing to trade DR or in the opposite direction. In this way, the DR aggregator maximizes its revenue when it is a DR seller and minimizes its cost when buying energy through DR contracts.

The proposed bilevel wind offering strategy is illustrated in Fig. 1. It is considered that the DR aggregator can trade DR with the wind power producer (WPP), other competitors that are willing to trade DR, and the day-ahead market. While parameters in each level are shown by dash line boxes and arrows, decision variables are represented using solid line boxes and arrows. The upper-level problem belongs to the wind power producer (WPP), where it aims to maximize its profit subject to the given constraints as well as the DR volume. Indeed, the obtained DR volume is determined by the DR aggregator in the lower-level problem, where it depends on the price that the wind power producer offers to the aggregator. Thus, the links between the upper-level and lower-level problems are the DR price offered by the wind power producer and consequently, the DR share that the aggregator provides to the wind power producer (double lines in Fig. 1).

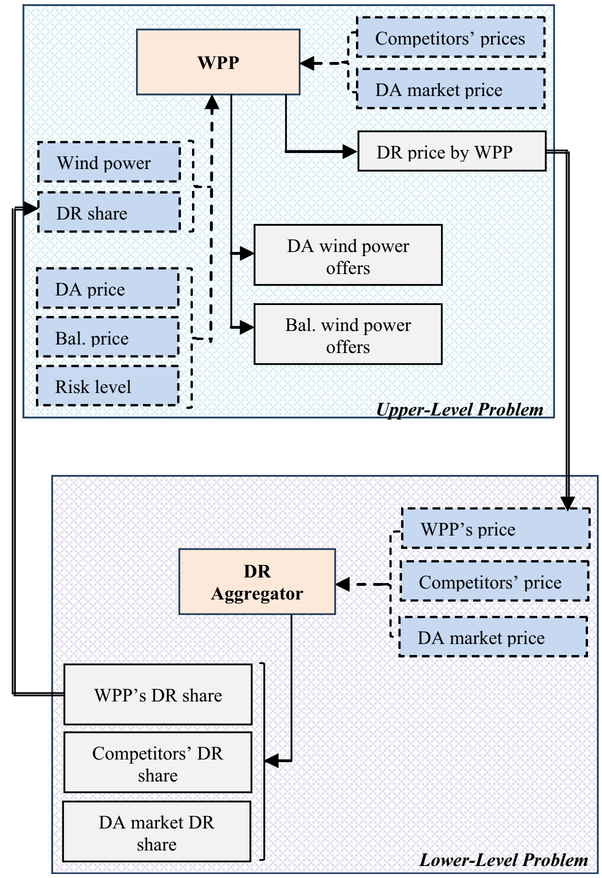

Fig. 1. The proposed bilevel wind offering strategy.

The procedure carried out in this strategy is as follows. The wind power producer determines its DR price while taking into account the DR prices offered by other competitors as well as the day-ahead (DA) market price (refer to upper-level problem, top right-hand side). Accordingly, the DR aggregator decides the share of each resource in the lower-level problem. Consequently, given the DR share obtained by the wind power producer, the producer makes its offer in the day-ahead and balancing markets. To this end, besides the price forecasts of DA and Balancing (Bal.) markets, the level of the risk taken by the producer is needed to be taken into account (refer to upper-level problem, bottom left-hand side). That is, depending on how risk averse the producer is, the energy portion to be sold in each market is determined.

Note that the above decisions are made while the problem is associated with the uncertainty of the following parameters: day-ahead market price, balancing market price, wind power production, and the DR price offered by other competitors. These uncertain parameters are represented using finite scenarios. Two distinct sets of scenarios are defined in this paper as follows.

Each upper-level scenario is represented by scenario w, which comprises the vectors of day-ahead price ($\lambda^{DA}(t,w)$), balancing price ($\lambda^{imb}(t,w)$) and wind power production $P^{w}(t,w)$.

$$scenario\, w = \{\lambda^{DA}(t,w), \lambda^{imb}(t,w), P^{W}(t,w)\} \tag{1}$$