Applied Energy 218 (2018) 520–532

Contents lists available at ScienceDirect

Applied Energy

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

A decentralized trading algorithm for an electricity market with generation uncertainty

Shahab Bahrami[a,1], M. Hadi Amini[b,*]

[a] Department of Electrical and Computer Engineering, University of British Columbia, Vancouver, BC, Canada
[b] Department of Electrical and Computer Engineering, Carnegie Mellon University, Pittsburgh, PA, USA

HIGHLIGHTS

- A decentralized energy trading algorithm is proposed considering the integration of renewable energy resources.
- Our method optimizes the cost of load aggregators and profit of the generators.
- The proposed optimization problem minimizes as the risk of shortage in the renewable generation.
- A risk measure called the conditional-value-at-risk (CVaR) is used to model uncertainty of renewables.
- The simulation results validate the effectiveness of the proposed decentralized algorithm.

ARTICLE INFO

Keywords:
Renewable Energy Resources
Price-responsive load aggregator
Power market
Conditional value-at-risk (CVaR)
Generation uncertainty
Controllable load
Decentralized algorithm

ABSTRACT

The uncertainties in renewable power generators and the proliferation of price-responsive load aggregators make it a challenge for independent system operators (ISOs) to manage the energy trading in the power markets. Hence, a centralized framework for the energy trading market may not be remained practical for the ISOs mainly due to violating the privacy of different entities, i.e., load aggregators and generators. It can also suffer from the high computational burden in a market with a large number of entities. Instead, in this paper, we focus on proposing a *decentralized* energy trading framework enabling the ISO to incentivize the entities toward an operating point that jointly optimize the cost of load aggregators and profit of the generators, as well as the risk of shortage in the renewable generation. To address the uncertainties in the renewable resources, we apply a risk measure called the conditional value-at-risk (CVaR) with the goal of limiting the likelihood of high renewable generation shortage with a certain confidence level. Then by considering the risk attitude of the ISO and the generators, we develop a decentralized energy trading algorithm with some control signals that properly coordinate the entities toward the market operating point of the ISO's centralized approach. Simulation results on the IEEE 30-bus test system show that the proposed decentralized algorithm converges to the solution of the ISO's centralized problem in a timely fashion. Furthermore, the load aggregators can help their consumers reduce their electricity cost by 18% on average through managing their loads using locally available information. Meanwhile, the generators can benefit from 17.1% increase in their total profit through decreasing their generation cost.

1. Introduction

One of the foremost goals of the future smart grid is to provide the necessary infrastructures toward integration of renewable generators (e.g., wind turbine and photovoltaic (PV) panel) as the environmentally friendly alternatives for the fossil fuel-based power plants. Meanwhile, the infrastructure in the smart grid can facilitate the participation of the demand side in the energy management programs such as the demand response (DR) [1,2].

Independent system operators (ISOs) usually perform comprehensive analysis (e.g., optimal power flow and unit commitment) to optimally dispatch the available generation portfolio in order to supply the load demand. Nevertheless, there are challenges in performing energy market analysis in a centralized fashion, especially in a grid with

* Corresponding author. Department of Electrical and Computer Engineering, Carnegie Mellon University, Pittsburgh, PA 15213, USA.
E-mail addresses: shahab_bahrami@yahoo.com (S. Bahrami), hadi.amini@ieee.org (M.H. Amini).
URL: http://www.hadiamini.com (M.H. Amini).
[1] Shahab Bahrami graduated from the Department of Electrical and Computer Engineering, University of British Columbia in 2017.

https://doi.org/10.1016/j.apenergy.2018.02.157
Received 7 November 2017; Received in revised form 22 February 2018; Accepted 23 February 2018

Nomenclature

y_h	arbitrary scaler y in time slot h.
$\boldsymbol{y}$	arbitrary vector $(y_h, h \in \mathscr{H})$.

Variables and parameters for generator j

$p_{j,h}^{\text{conv}}$	conventional unit's output power
$p_{j,h}^{\text{ren}}$	predicted renewable generation
$\hat{p}_{j,h}^{\text{ren}}$	actual renewable generation
β_j	confidence level of the generator

Variables and parameters for load aggregator i

$l_{i,h}$	total load demand
$\boldsymbol{x}_i$	profile of load demands
$\boldsymbol{x}_{a,i}$	demand profile of load a
$x_{a,i,h}$	demand of load a
$\boldsymbol{x}_{a,i}^{\text{des}}$	desirable profile of load a
$\mathscr{H}_{a,i}$	scheduling horizon of load a

Other variable and parameters

$\delta_{b,h}$	voltage phase angle of bus b
$p_{r,s}^{\max}$	maximum power flow limit for line $(r,s) \in \mathscr{L}$
$b_{r,s}$	admittance of line $(r,s) \in \mathscr{L}$
ϵ^q	step size in iteration q

renewable generators and price-responsive load aggregators. First and perhaps most importantly, the centralized market analysis by the ISO can violate the entities' privacy in a competitive energy market, e.g., by revealing the demand information of the load aggregators and operational cost of the generators. Second, the uncertainty in the privately-owned renewable generators puts the generation-load balance at risk. Third, the centralized market analysis can be computationally difficult in large power grids, especially when the number of decision variables dramatically increases by participating the price-responsive load aggregators and small-scaled renewable generators in the competitive energy market.

There have been some efforts in the power system operation literature to tackle the above-mentioned challenges. Qadran et al. [3] studied the application of DR in combined gas networks and power systems. According to Drysdale et al. [4], the flexible load demand needs three major criteria for the participants: identifiability, accessibility, and being useful. We divide the related works into three threads. The first thread of the literature is concerned with the participation of the price-responsive loads in the DR programs and addresses the entities' privacy issues thorugh designing decentralized energy planning algorithms using the evolutionary game [5], stochastic game [6], Stackelberg game [7], dual decomposition method [8], multi-agent system [9], multi-agent systems [10,11], and hierarchical bidding [12]. These approaches, however, may not be easily implementable in practice, since they ignore the physical constraints imposed by the topology and operation of the power network. In order to achieve an accurate estimation of the load demand, a multi-time-scale method is developed in [13] that outperforms the available forecasting methods. The second thread of the literature is concerned with considering the power flow constraints in the decentralized system planning procedure using different techniques such as the primal-dual algorithm [14], convex relaxation [15–17], quadratic programming [18], alternating direction method of multipliers (ADMM) [19–21], diagonal quadratic approximation [22], and Lagrange relaxation method [23–25]. In these works, nevertheless, the uncertainty issues related to the integration of the renewable generators have remained as a primary challenge. The third thread of the literature is concerned with addressing the uncertainty issues by using chance-constrained optimization [26–28], successive constraint enforcement [29], fuzzy system [30], stochastic optimization [31,32], and risk management [33–37]. The proposed models include the power flow constraints and deal with the uncertainty issues. However, they are implemented in a centralized fashion, and thus cannot address the privacy and computational complexity concerns.

In this paper, we focus on extending the works in the above-mentioned threads of the literature by designing a decentralized energy trading algorithm in a day-ahead electricity market with renewable energy generators and active participation of load aggregators in the DR programs. The ISO, load aggregators, and generators use the smart grid's communication infrastructure to execute the proposed distributed algorithm and jointly optimize the profit (for the generators) from selling electricity and the cost (for load aggregators) of purchasing electricity. Each entity solves its own optimization problem using the locally available information. Hence, the privacy of each entity is preserved. Compared to our previous work [38], the main challenge is to consider the uncertainty in the renewable generation and design proper control signals among the ISO, generators, and load aggregators that enforce the proposed decentralized algorithm to converge to the optimal solution of the centralized problem of the ISO. The main contributions of this paper are as follows:

- *Risk evaluation*: Inspired by the works in [33,34], we deploy a penalty term based on the conditional value-at-risk (CVaR) into the objective functions of both the ISO's centralized problem and the generators' local problem in order to address the uncertainties of the renewable generation. It enables the generators with renewable plants to sell electricity and gain profit, while limiting the risk of high generation shortage within a certain confidence level. The ISO can also reduce the risk of generation-load mismatch based on its own risk attitude. We discuss how to deal with the different risk attitudes of the ISO and the generators. It is worth noting that the systemic-risk oriented methods for network fragility assessment in other types of multi-agent dynamical networks have been widely investigated by researchers in control network area [39,40].
- *Decentralized algorithm design*: To protect the privacy of the entities, as well as reducing the computational complexity, we propose a decentralized algorithm based on the Lagrange relaxation method [23,24] that can be executed by the entities to trade in the competitive energy markets. A load aggregator schedules the customers' loads, and a generator determines its risk minimizing generation level. Meanwhile, the ISO can meet the network physical constraints, thus achieving a triple-win result.
- *Performance evaluation*: Simulation results on a modified IEEE 30-bus test system show that the proposed decentralized algorithm provably converges to the optimal solution to the centralized problem of the ISO in about 45 iterations. The proposed algorithm also benefits both the load aggregators by reducing their cost by 18%, the generators by increasing their profit by 17.1% and decreasing the peak-to-average ratio (PAR) by 15%. When compared with the centralized approach, our algorithm has a significantly lower running time, as the entities can execute the algorithm in a parallel fashion.

The rest of this paper is organized as follows. Section 2 formulates the ISO's centralized problem. In Section 3, we propose a decentralized algorithm to determine the energy market equilibrium. Section 4 provides simulation results, followed by Section 5 that concludes the paper.