Applied Energy 177 (2016) 625–635

Contents lists available at ScienceDirect

Applied Energy

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

Trading strategies for distribution company with stochastic distributed energy resources

Chunyu Zhang [a], Qi Wang [b], Jianhui Wang [c,*], Magnus Korpås [a], Pierre Pinson [b], Jacob Østergaard [b], Mohammad E. Khodayar [d]

[a] Department of Electric Power Engineering, Norwegian University of Science and Technology, Trondheim, Norway
[b] Center for Electric Power and Energy, Technical University of Denmark, Lyngby, Denmark
[c] Energy Systems Division, Argonne National Laboratory, Argonne, IL, USA
[d] Electrical Engineering Department, Southern Methodist University, Dallas, TX, USA

HIGHLIGHTS

- A market framework is presented for a proactive DISCO (PDISCO).
- Two-stage wholesale markets and stochastic distributed energy resources are involved.
- A one-leader multi-follower bilevel model is proposed.
- Continuous strategic offers and bids are achieved.

ARTICLE INFO

Article history:
Received 23 March 2016
Received in revised form 20 May 2016
Accepted 23 May 2016

Keywords:
Distributed energy resources (DERs)
Proactive distribution company (PDISCO)
Electricity markets
Bilevel game-theoretic model
Multi-period AC power flow
Mathematical program with equilibrium constraints (MPEC)
Mathematical program with primal and dual constraints (MPPDC)

ABSTRACT

This paper proposes a methodology to address the trading strategies of a proactive distribution company (PDISCO) engaged in the transmission-level (TL) markets. A one-leader multi-follower bilevel model is presented to formulate the gaming framework between the PDISCO and markets. The lower-level (LL) problems include the TL day-ahead market and scenario-based real-time markets, respectively with the objectives of maximizing social welfare and minimizing operation cost. The upper-level (UL) problem is to maximize the PDISCO's profit across these markets. The PDISCO's strategic offers/bids interactively influence the outcomes of each market. Since the LL problems are linear and convex, while the UL problem is non-linear and non-convex, an equivalent primal–dual approach is used to reformulate this bilevel model to a solvable mathematical program with equilibrium constraints (MPEC). The effectiveness of the proposed model is verified by case studies.

1. Introduction

Distributed energy resources (DERs) tend to occupy a high share in the distribution-level (DL) network [1,2]. In a deregulated environment, this stimulates the distribution company (DISCO) to preferentially procure DERs' generations at low prices. In the U.S., the recent initiative named the New York Reforming Energy Vision (NY REV) [3] has addressed the regulatory changes to liberate a DL market for cost-effective use of DERs. As indicated in the NY REV, a Distributed System Platform Provider (DSPP) will modernize its distribution system to create a flexible platform for new energy products and services, to improve the overall system efficiency. Resources provided could include distributed generation (DG), energy efficiency, predictive demand management, demand response (DR), microgrids (MGs), and more. This paper is partially motivated by the NY REV and aims to establish a real-time market framework for the PDISCO procuring the DL DERs and trading in the transmission-level (TL) wholesale markets. The DL resources are selected as stochastic DERs, such as wind turbines (WTs) and photovoltaic systems (PVs), while the proactive DISCO (PDISCO) can be considered as a DSPP to play an essential role in the hierarchical trading framework. To this end, the PDISCO gets an

* Corresponding author.
E-mail addresses: chunyu.zhang@ntnu.no (C. Zhang), qiwa@elektro.dtu.dk (Q. Wang), jianhui.wang@anl.gov (J. Wang), magnus.korpas@ntnu.no (M. Korpås), ppin@elektro.dtu.dk (P. Pinson), joe@elektro.dtu.dk (J. Østergaard), mkhodayar@smu.edu (M.E. Khodayar).

http://dx.doi.org/10.1016/j.apenergy.2016.05.143

Nomenclature

Sets and indices

i, j, B^{DS}, n, m, B^{TS}: index and set of distribution-level (DL) and transmission-level (TL) buses, respectively
ij, Λ^{DS}, nm, Λ^{TS}: index and set of DL feeders and TL lines, respectively
l, L, d, D: index and set of DL and TL demands, respectively
g, G: index and set of TL generators
k, K: index and set of DL DERs
t, T: index and set of time periods (e.g., hours per day)
ω, Ω: index and set of scenarios
$\mathcal{M}_L, \mathcal{M}_D$: mapping of the set of DL/TL demands onto the set of DL/TL buses respectively
$\mathcal{M}_G$: mapping of the set of TL conventional generations onto the set of TL buses
$\mathcal{M}_K$: mapping of the set of DERs onto the set of DL buses

Variables

P_{tg}^{G}: day-ahead offer of generator g at time t
R_{tg}^{UP}, R_{tg}^{DN}: day-ahead up and down regulation reserve capacities of generator g at time t
$r_{tg\omega}^{UP}, r_{tg\omega}^{DN}$: real-time up and down regulation power of generator g at time t for scenario ω
λ_t^{DDA}: day-ahead offering/bidding price of the PDISCO at time t
P_t^{DDA}, Q_t^{DDA}: day-ahead offering/bidding quantity of the PDISCO at time t (non-negative is offer, negative is bid)
$\lambda_{t\omega}^{DRT}$: real-time offering/bidding price of the PDISCO at time t for scenario ω
$P_{t\omega}^{DRT}, Q_{t\omega}^{DRT}$: real-time offering/bidding quantity of the PDISCO at time t for scenario ω (non-negative is offer, negative is bid)
$P_{td\omega}^{ST}$: TL load-shedding of demand d at time t for scenario ω
$\theta_{tn}^{0}, \theta_{tn\omega}$: voltage angles of bus n at day-ahead time t, and at real-time time t for scenario ω
$\lambda_{tn}^{DA}, \lambda_{tn\omega}^{RT}$: locational marginal price (LMP) at TL bus n at day-ahead time t, and at real-time time t for scenario ω
$P_{tk}^{DER0}, Q_{tk}^{DER0}$: active and reactive power procured from DER k at day-ahead time t
$P_{tl\omega}^{SD}, Q_{tl\omega}^{SD}$: active and reactive power of DL load-shedding for demand l at time t for scenario ω
$Q_{ti}^{C0}, Q_{ti\omega}^{C}$: reactive power from DL shunt compensator at bus i at day-ahead time t, and at real-time time t for scenario ω
$P_{t,ij}^{FD0}, Q_{t,ij}^{FD0}$: day-ahead active and reactive power flows through DL feeder i–j at time t
$P_{t,ij,\omega}^{FD}, Q_{t,ij,\omega}^{FD}$: real-time active and reactive power flows through DL feeder i–j at time t for scenario ω
$\delta_{ti}^{0}, \delta_{ti\omega}$: voltage angles of bus i at day-ahead time t, and at real-time time t for scenario ω
$V_{ti}^{0}, V_{ti\omega}$: voltage magnitudes of DL bus i at day-ahead time t, and at real-time time t for scenario ω

Parameters

$P_{tk\omega}^{DER}, Q_{tk\omega}^{DER}$: active and reactive power generation realization of DER k at time t for scenario ω
$\overline{P}_g^{G}, \overline{R}_g^{UP}, \overline{R}_g^{DN}$: maximum production, maximum up and down regulation reserve capacities of generator g
$C_g^{G}, C_g^{UP}, C_g^{DN}$: day-ahead generation cost, up and down regulation reserve costs of generator g
c_g^{UP}, c_g^{DN}: real-time up and down regulation cost of generator g
C_t^{DS}: operation cost of the PDISCO at time t
$\lambda_{td}^{TSD}, P_{td}^{TSD}$: day-ahead bidding price and consumption of TL demand d at time t
λ_t^{DER}: DER procurement price of the PDISCO at time t
λ_t^{DSD}: DL sale price at time t
$P_{tl}^{DSD}, Q_{tl}^{DSD}$: consumption of DL demand l at time t
$\overline{P}^{DS}$: active power injection limit for the PDISCO
$\lambda_t^{ST}, \lambda_t^{SD}$: TL/DL load-shedding price at time t
$\overline{P}_{nm}^{TS}$: capacity limit of each TL line nm
$\overline{S}, \overline{S}_{ij}$: capacity limits of the DL main substation and each DL feeder ij
$\overline{S}_k$: capacity limit of each DER k
$\underline{Q}_i^{C}, \overline{Q}_i^{C}$: reactive power limits of the DL shunt compensator at bus i
$\underline{V}_i, \overline{V}_i$: limits of voltage magnitude at DL bus i
τ_i: transformer tap ratio at DL bus i
B_{nm}: susceptance of the TL line nm
G_{ij}, B_{ij}, b_{ij}: conductance, susceptance and charging susceptance of the DL feeder ij

opportunity to strategically engage in the TL markets by rationally purchasing electricity from the DL DERs. In this situation, the DISCO's trading framework becomes more complex.

Associated with the smart grid technology, to participate in the day-ahead and real-time markets, for each time t, the DISCO has to make a trade-off on acquiring DERs' portfolio and trading strategy (offer/bid) to maximize its profit. Crossing the two-stage markets, the transactions between the DISCO and markets are characterized in a bidirectional fashion, implying the DISCO behaves as an active producer when providing offers, but as an active consumer when submitting bids. To highlight these features, this kind of DISCO is defined as a PDISCO in this paper. On the other hand, the PDISCO's trading strategies (offering/bidding prices and power quantities) are endogenously interrelated with the markets' outcomes (locational marginal prices (LMPs) and production/consumption quantities). Thus, the trading between the PDISCO and markets follows a typical gaming structure.

In order to capture the PDISCO's trading strategies, the PDISCO trading within markets can be formulated as a one-leader multi-follower game model, realized in a bilevel structure. Market-clearing procedures are indicated as the stage-based LL problems through DC power flow. The LL day-ahead market problem is to maximize the TL social welfare. In particular, in the real-time process, scenario-based methods [4] can be used to represent the stochastic outputs of individual DERs. Accordingly, an LL real-time market problem seeks to minimize the TL operation cost per scenario ω. The UL problem represents the profit maximization of the PDISCO, with the strategic offers/bids constrained by AC power flow. Note that the LL problems are linear and convex, while the UL problem is non-linear and non-convex. The primal–dual approach [5] is applied to reformulate the proposed bilevel model to a solvable mathematical program with equilibrium constraints (MPEC).

Few papers are available in the technical literature to discuss the DISCO trading within the TL markets. A static bilevel model is proposed in [6] to support a DISCO's operational decision with DGs and interruptible loads (ILs) in a competitive market, while the DISCO's offers/bids are ignored by the market objective. To optimize the DISCO's day-ahead acquisition, a static bilevel model [7] is