Applied Energy 169 (2016) 663–681

Contents lists available at ScienceDirect

Applied Energy

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

A medium-term coalition-forming model of heterogeneous DERs for a commercial virtual power plant

Morteza Shabanzadeh, Mohammad-Kazem Sheikh-El-Eslami *, Mahmoud-Reza Haghifam

Faculty of Electrical and Computer Engineering, Tarbiat Modares University, Tehran, Iran

HIGHLIGHTS

- A medium-term coalition-forming scheme is proposed for commercial VPPs.
- Decision making on the optimal selection of VPP coalition members, bilateral and forward contracting, and pool involvement.
- VPP acts as an arbitrageur by exercising arbitrage between diverse energy trading floors.
- Stochastic programming approach applied to characterize the uncertainty and to derive informed decisions.

ARTICLE INFO

Article history:
Received 22 August 2015
Received in revised form 26 January 2016
Accepted 8 February 2016

Keywords:
Virtual power plant
Electricity market
Coalition forming
Distributed energy resources
Arbitrage
Risk management

ABSTRACT

Within a medium-term market horizon, this research work provides a methodology that allows a commercial virtual power plant (CVPP) to form an optimal coalition of heterogeneous distributed energy resources (DERs) based on weekly bilateral contracting, futures-market involvement, and pool participation. The established model aims at composing an optimal portfolio of available DERs and jointly takes into account the risk associated with the energy trading strategy of the CVPP. Perceiving the fact that pool prices have highly uncertain nature, a framework based on stochastic programming approach is utilized to model this decision-making problem. The proposed framework consists of two stages. The first stage deals with decisions regarding DERs optimal selection for the VPP coalition, the amount of agreed quantity in the bilateral negotiation, and the type and quantity selection of futures-market contracts as well. In the second stage, decisions are made based on the most plausible realizations of the stochastic prices in the day-ahead market. For a given pre-specified risk level on profit volatility, the main objective is to maximize the expected profit for the VPP manager over the planning horizon. The efficiency and applicability of the developed model is illustrated and analyzed by its implementation in a system with few heterogeneous DERs and through different scenarios, and finally thereby meaningful conclusions are duly drawn.

1. Introduction

1.1. Background and motivation

The planning and operation of electric power systems are undergoing fundamental changes stimulated by the pressing need to decarbonize electricity supply, to provide reliable and efficient use of green energy, and to take advantage of information and communication technologies (ICTs) [1]. The modernization of power systems toward the ultimate goals of the smart grid concept is perceived to be a means to attain reliability and efficiency with environmental compliance [2]. On the other hand, the design framework of the smart grid should be based upon the unbundling and restructuring of the power sector that have brought profound changes to electric power system operating and planning. Power industry liberalization with the introduction and institution of wholesale and retail electricity markets has gone hand-in-hand with the significant decentralization of these two tasks [3]. The agents trading on electricity markets are dispatchable generators, large consumers and various types of traders (e.g. retailers, aggregators, brokers, marketers, etc.), acting on behalf of non-eligible consumer groups. A key premise of trading rules in the competitive electricity markets is that all market participants should have substantial freedom to make various commercial arrangements with

* Corresponding author at: Faculty of Electrical and Computer Engineering, Tarbiat Modares University, P.O. Box 14115-143, Tehran, Iran. Tel.: +98 (21) 88220121.

E-mail address: aleslam@modares.ac.ir (M.-K. Sheikh-El-Eslami).

http://dx.doi.org/10.1016/j.apenergy.2016.02.058
0306-2619/

Nomenclature

– The main notation used throughout this paper is stated below, while other symbols are defined as needed

Acronyms

WPP wind power plant
PV photovoltaic units
ESS energy storage systems
FL flexible loads

Sets

T set of time periods (horizon time)
T_{peak} number of hours in peak-period contracts
$T_{offpeak}$ number of hours in off-peak-period contracts
N_s set of electricity price scenarios
N_{WPP} set of WPP candidates for the VPP coalition
N_{PV} set of PV candidates for the VPP coalition
N_{ESS} set of ESS candidates for the VPP coalition
N_{FL} set of FL candidates for the VPP coalition

Indices

t index of time periods running from 1 to T
c index of futures-market contracts
k index of standard power blocks in the futures-market contracts
h index for modeling of each contract duration time running from 1 to $\max\{T_{peak}, T_{offpeak}\} - 1$
i index of WPPs running from 1 to N_{WPP}
j index of PVs running from 1 to N_{PV}
e index of ESSs running from 1 to N_{ESS}
d index of FLs running from 1 to N_{FL}

Constants

d_t duration of time period t (one hour)
λ^{PPA} sale price (or Strike price) of the PPA contract (€/MW h)
N^{min} the minimum number of the VPP coalition members
Q^{PPA}_{max} maximum volume that can be sold in the PPA. Defined by the customer willingness to contract (MW)
α per unit confidence level
β weighting factor to realize the trade-off expected profit versus CVaR

Parameters

π_s probability of occurrence of scenario s
$\lambda^{DA}_{t,s}$ day-ahead market price in period t and scenario s (€/MW h)
$\lambda^{DX,S}_{c,k}$ energy price of selling block k of futures-market contract c (€/MW h)
$\lambda^{DX,B}_{c,k}$ energy price of buying block k of futures-market contract c (€/MW h)
γ^{WPP}_i capacity offer price declared by WPP-owner i (€/MW-h)
γ^{PV}_j capacity offer price declared by PV-owner j (€/MW-h)
γ^{ESS}_e capacity offer price declared by ESS-owner e (€/MW-h)
γ^{FL}_d capacity offer price declared by DR-provider d (€/MW-h)
$TU_{c,h}$ duration of futures-market contract c minus one (h)
TC_{ct} a binary vector of which zero elements force futures-market contract c not to be selected
$\overline{P}^{WPP}_i$ equivalent capacity of WPP i during a medium-term period declared by its owner (MW)
$\overline{P}^{PV}_j$ equivalent capacity of PV j during a medium-term period declared by its owner (MW)
$P^{ESS,cap}_e$ capacity of the storage facility declared by ESS-owner e (MW)
$P^{FL,cap}_d$ upper limit for curtailing on FL d declared by its provider (MW)
$P^{chg,max}_e$ maximum specific ESS charging rate (MW)
$P^{dchg,max}_e$ maximum specific ESS discharging rate (MW)
η^{chg}_e charging efficiency of ESS e
η^{dchg}_e discharging efficiency of ESS e
$E_{e,0}$ initial energy storage of ESS e (MW h)
DOD_e depth of discharge window width declared by ESS owner e
cf_e contribution factor of ESS e which is obtained by dividing its length of the discharge cycle by 24 h
$Q^{Block}_{c,k}$ maximum power that can be sold/bought through the block k of futures-market contract c (MW)

Continuous variables

Υ^{VPP}_s the VPP medium-term profit in scenario s (€)
$P^{VPP}_{t,s}$ equivalent power of the VPP in period t and scenario s (MW)
Q^{PPA} the quantity of PPA contract as the percentage of customers' demand (MW)
x^{PPA} percentage of Q^{PPA}_{max} that the VPP is willing to supply through the PPA
$PC^S_{c,k,t}$ power sold through the k th block of futures-market contract c (MW)
$PC^B_{c,k,t}$ power bought through the k th block of futures-market contract c (MW)
$P^{DA}_{t,s}$ power traded in the day-ahead market in period t and scenario s; positive values for selling and negative values for purchasing (MW)
$P^{ESS}_{e,t,s}$ equivalent power of ESS e in period t and scenario s (MW)
$P^{curt}_{t,s}$ the amount of the VPP power production that can be curtailed in period t and scenario s (MW)
$PG^{chg}_{e,t,s}$ power charged to ESS e in period t and scenario s (MW)
$PG^{dchg}_{e,t,s}$ power discharged from ESS e in period t and scenario s (MW)
$E_{e,t,s}$ energy level of ESS e in period t and scenario s (MW h)
$P^{FL}_{d,t,s}$ the curtailment value of FL d in period t and scenario s (MW)

Binary variables

x^{WPP}_i 0/1 variable which is equal to 1 if WPP-owner i is chosen as a coalition member
x^{PV}_j 0/1 variable which is equal to 1 if PV-owner j is chosen as a coalition member
x^{ESS}_e 0/1 variable which is equal to 1 if ESS-owner e is chosen as a coalition member
x^{FL}_d 0/1 variable which is equal to 1 if DR-provider d is chosen as a coalition member
$u^S_{c,k,t}$ 0/1 variable that is equal to 1 if futures-market contract c is signed to sell energy and 0 otherwise
$u^B_{c,k,t}$ 0/1 variable that is equal to 1 if futures-market contract c is signed to buy energy and 0 otherwise
$u^{chg}_{e,t,s}$ 0/1 variable which is equal to 1 if ESS e is charged during period t and scenario s
$u^{dchg}_{e,t,s}$ 0/1 variable which is equal to 1 if ESS e is discharged during period t and scenario s