Electric Power Systems Research 111 (2014) 62–70

Contents lists available at ScienceDirect

Electric Power Systems Research

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

A full demand response model in co-optimized energy and reserve market

G. Liu*, K. Tomsovic

Department of Electrical Engineering and Computer Science, The University of Tennessee, Knoxville, 1520 Middle Drive, Knoxville, TN 37996, USA

ARTICLE INFO

Article history:
Received 7 December 2013
Received in revised form 3 February 2014
Accepted 7 February 2014

Keywords:
Demand response
Bidding mechanism
Security constrained unit commitment (SCUC)
Spinning reserve
Electricity markets
Mixed integer linear programming (MILP)

ABSTRACT

It has been widely accepted that demand response will play an important role in reliable and economic operation of future power systems and electricity markets. Demand response can not only influence the prices in the energy market by demand shifting, but also participate in the reserve market. In this paper, we propose a full model of demand response in which demand flexibility is fully utilized by price responsive shiftable demand bids in energy market as well as spinning reserve bids in reserve market. A co-optimized day-ahead energy and spinning reserve market is proposed to minimize the expected net cost under all credible system states, i.e., expected total cost of operation minus total benefit of demand, and solved by mixed integer linear programming. Numerical simulation results on the IEEE Reliability Test System show effectiveness of this model. Compared to conventional demand shifting bids, the proposed full demand response model can further reduce committed capacity from generators, starting up and shutting down of units and the overall system operating costs.

Published by Elsevier B.V.

1. Introduction

The reliability and efficiency of power system operation have always been a high priority in competitive electricity markets. Reliable operation of power system necessitates a balance between the generation and demand at all times. This is challenging given the fact that both generation and demand can change rapidly and unexpectedly, e.g., due to reasons of loss of generation units, transmission lines outages and sudden load changes. When renewable energy resources, such as wind and solar, are introduced, this problem becomes even more difficult. As flexibility of conventional generators is restricted by technical constraints, such as ramp rates, maintaining power system reliability using only generation side flexibility becomes technically too constrained and potentially compromises efficiency [1].

Demand response (DR) is another approach to meet the need for flexibility. In fact, the importance of DR has been recognized and in several countries, it is implemented for obtaining reliable and efficient electricity markets [2–4]. DR can reduce the load at peak periods, which reduces the underutilization of generators with marginal costs [5]. In addition, DR can benefit individual customers by reducing their electricity charges through shifting consumption to lower price hours. Besides participation in energy markets, advances in control and communication technologies offer the possibility for DR to participate in reserve markets and provide contingency reserves during emergency conditions of the system by changing the normal consumption [6]. The additional scheduling flexibility introduced by DR facilitates more reliable and efficient power system operation, reduces transmission line congestion and mitigates price fluctuations and generally leads to significant gains in overall system benefits [7–9].

In order to better utilize DR, demand response providers (DRPs) have been introduced in the electricity markets as aggregators of small and widely dispersed customer responses [10]. The DRPs act as medium between Independent System Operators (ISOs) and small customers, bid the aggregated customer responses in the energy and/or reserve markets and schedule the responsive demand according to the result of market clearing. By this means, the flexibility of all customers, even small ones, can be exploited. Large customers satisfying certain requirements, such as minimum curtailment level, can participate as sole entities in the programs.

Considerable efforts have been devoted to incorporate DR into the market clearing process to achieve the most efficiency. In [6], a market model in which generators and consumers can submit offers and bids on both energy and reserve are proposed, but the network and multi-period constraints are neglected. In addition, the reserve constraint is deterministic in this model.

* Corresponding author. Tel.: +1 865 773 5812; fax: +1 865 974 5483.
E-mail addresses: gliu5@utk.edu, pillarl007@hotmail.com (G. Liu), tomsovic@utk.edu (K. Tomsovic).

http://dx.doi.org/10.1016/j.epsr.2014.02.006
0378-7796/Published by Elsevier B.V.

i	index of generators, running from 1 to NG
j	index of demand, running from 1 to ND
t	index of time periods, running from 1 to NT
k	Index of transmission lines, running from 1 to NK
m	index of energy blocks offered by generators (demand), running from 1 to NI (NJ)
ω	index of scenarios of generators, running from 1 to NW

Binary variables

u_{it}	1 if unit i is scheduled on during period t and 0 otherwise
u_{jt}	1 if demand j is scheduled on during period t and 0 otherwise

Continuous variables

$p_{it}(m)$	power output scheduled from the mth block of energy offer by unit i during period t. Limited to $p_{it}^{\max}(m)$
$d_{jt}(m)$	power consumption scheduled from the mth block of energy bid by demand j during period t. Limited to $d_{jt}^{\max}(m)$
P_{it}	power output scheduled for unit i during period t
D_{jt}	power consumption scheduled for demand j during period t
R_{it}^U	scheduled up-spinning reserve for unit i during time period t
R_{it}^D	scheduled down-spinning reserve for unit i during time period t
R_{jt}^U	scheduled up-spinning reserve for demand j during period t
R_{jt}^D	scheduled down-spinning reserve for demand j during period t
$P_{it\omega}$	power output of unit i during period t in scenario ω
$D_{jt\omega}$	power consumption of demand j during period t in scenario ω
$r_{it\omega}^U$	deployed up-spinning reserve from unit i during time period t in scenario ω
$r_{it\omega}^D$	deployed down-spinning reserve from unit i during time period t in scenario ω
$r_{jt\omega}^U$	deployed up-spinning reserve from demand j during time period t in scenario ω
$r_{jt\omega}^D$	deployed down-spinning reserve from demand j during time period t in scenario ω
$r_{it\omega}(m)$	deployed spinning reserve from m-th block of energy offer by unit i during period t in scenario ω
$r_{jt\omega}(m)$	deployed spinning reserve from mth block of energy bid by demand j during period t in scenario ω
$L_{jt\omega}$	involuntary load shedding from demand j during period t in scenario ω. Limited to $L_{jt}^{\max}$

Constants

$\lambda_{it}(m)$	marginal cost of the mth block of energy offer by unit i during period t
$\lambda_{jt}(m)$	marginal benefit of the mth block of energy bid by demand j during period t
A_i	operating cost of unit i at the point of $P_i^{\min}$
B_j	consumption benefit of demand j at the point of $D_j^{\min}$
C_{it}^U	capacity cost offer of unit i during period t for providing up-spinning reserve
C_{it}^D	capacity cost offer of unit i during period t for providing down-spinning reserve
C_{jt}^U	capacity cost offer of demand j during period t for providing up-spinning reserve
C_{jt}^D	capacity cost offer of demand j during period t for providing down-spinning reserve
π_ω	probability of scenario ω
$VOLL_{jt}$	value of lost load from demand j during period t
$D_{jt}^{\max}$	maximum consumption of demand j during period t
$D_{jt}^{\min}$	minimum consumption of demand j during period t
$\lambda_{jt}^{\max}$	maximum bidding price of demand j during period t.
$\lambda_{jt}^{\min}$	minimum bidding price of demand j during period t
$-\alpha_{jt}$	price elasticity of demand j during period t
γ_j	recovery rate of demand j
Δt	duration of time period t
E_j	maximum energy consumption of demand j during the scheduling horizon
D_{jt}^F	fixed demand of demand j during period t
GSF_{ki}	generation shift factor to line k from unit i
GSF_{kj}	generation shift factor to line k from demand j
$F_k^{\max}$	transmission limit of line k
$\xi_{it\omega}$	health indicator of unit i during period t in scenario ω
$H_{t\omega}$	health indicator of system during period t in scenario ω

A probabilistic reserve model with demand-side participation is proposed in [11]. In this model, demand is able to submit bids of load reduction in the energy market and load shedding upon request through the reserve market. In [12], the price responsive demand shift bidding of consumers is introduced in a day-ahead market with network constraints. The ACOPF model is used in the formulation without considering unit commitment. The DR modeled with inter-temporal characteristics is incorporated into security constrained unit commitment (SCUC) for economic and security purposes in [13]. The DR is modeled as shiftable load and only participates in energy market in [12,13]. In [14], spinning reserve provided by DRPs and its associated cost function is formulated in a mixed integer linear form and incorporated in a two-stage stochastic SCUC. In [15], the demand recovery effect after deployment of spinning reserve from DR is further considered. It should be noted that DRPs only participate in spinning reserve market in [14,15].

The main contribution of this paper is to propose a full demand response model in which the DRP can submit duplex bids. Specifically, a consumer can bid energy as a price responsive shiftable demand in energy market, meanwhile, bid reserve coupled with its energy bids in reserve market. It should be noted that the principle of demand providing spinning reserve is different from that of generators. A consumer has the potential to provide spinning reserve as long as it is scheduled in the energy market, while a generator can provide spinning reserve only if it is not scheduled at full capacity. Based on this point, we make use of the flexibility of demand in the day-ahead time horizon through price responsive shiftable demand bids before any realization of system contingencies. In addition, the potential of rescheduling the scheduled demand in energy market when system experiences a contingency is further utilized by spinning reserve bids. In other words, the price responsive shiftable demand bids are DRPs' response to price in the first stage, while the spinning reserve bids are DRPs' response to