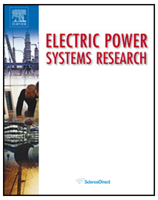
Electric Power Systems Research 119 (2015) 126–137

Contents lists available at ScienceDirect

Electric Power Systems Research

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



Robust unit commitment considering uncertain demand response

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ARTICLE INFO

Article history:
Received 1 July 2014
Received in revised form 2 September 2014
Accepted 3 September 2014
Available online 29 September 2014

Keywords:
Unit commitment
Price elasticity
Demand response
Uncertainty
Robust optimization
Locational Marginal Price (LMP)

ABSTRACT

Although price responsive demand response has been widely accepted as playing an important role in the reliable and economic operation of power system, the real response from demand side can be highly uncertain due to limited understanding of consumers' response to pricing signals. To model the behavior of consumers, the price elasticity of demand has been explored and utilized in both research and real practice. However, the price elasticity of demand is not precisely known and may vary greatly with operating conditions and types of customers. To accommodate the uncertainty of demand response, alternative unit commitment methods robust to the uncertainty of the demand response require investigation. In this paper, a robust unit commitment model to minimize the generalized social cost is proposed for the optimal unit commitment decision taking into account uncertainty of the price elasticity of demand. By optimizing the worst case under proper robust level, the unit commitment solution of the proposed model is robust against all possible realizations of the modeled uncertain demand response. Numerical simulations on the IEEE Reliability Test System show the effectiveness of the method. Compared to unit commitment with deterministic price elasticity of demand, the proposed robust model can reduce the average Locational Marginal Prices (LMPs) as well as the price volatility.

1. Introduction

Following the deregulation of power system, electricity prices in the wholesale market have at times experienced dramatic and rapid changes. This price volatility may arise from market power or an imbalance in supply and demand stemming from, for example, loss of generation units, unit ramping constraints, transmission lines outages or congestion and sudden load changes. When renewable energy resources, such as wind and solar, are introduced, this problem can become worse, e.g., frequent negative electricity prices occur in the western region of ERCOT [1]. Under these circumstances, demand response (DR) programs, which can change the energy consumption patterns of consumers, could improve market efficiency and reduce price volatilities. DR is implemented for obtaining reliable and efficient electricity markets in several countries [2–4].

Considerable efforts have been devoted to incorporating DR into the market clearing process to achieve the highest efficiency. In [5], an electricity market 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 [6,7], a price elasticity matrix (PEM) is proposed and taken into consideration when scheduling generation and setting the pool price. An iterative market clearing algorithm is used and the demand is adjusted in proportion to the difference between market clearing price and the reference price. In [8], a day-ahead market clearing tool is proposed for the load shifting behavior of consumers by submitting price sensitive bids. The effect of DR on the market is quantified and analyzed. In [9], price responsive demand shift bidding of consumers is introduced in a day-ahead market with network constraints. A linear price-elastic demand curve is used to represent the sensitivity of demand with respect to price. DR with inter-temporal characteristics is incorporated into a security constrained unit commitment (SCUC) for economic and security purposes in [10]. The price-elastic demand curve is approximated as a stepwise linear curve. DR participation in the spinning reserve market is also investigated in [11–13].

In order to eliminate the barrier of DR participating in electricity market, Federal Energy Regulatory Commission (FERC) issued Order No. 719 in 2008 [14]. By this order, FERC requires that ISOs/RTOs accept bids from qualified demand response resources to provide ancillary services. In addition, aggregators on behalf of small retail customers are allowed to bid DR directly into the organized markets. Currently, several ISOs/RTOs (e.g. California ISO, ERCOT, ISO-New England, Midwest ISO, PJM, and New York

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http://dx.doi.org/10.1016/j.epsr.2014.09.006
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Nomenclature

Indices and numbers

i	index of generators, running from 1 to N_G
j	index of demand, running from 1 to N_D
t	index of time periods, running from 1 to N_T
k	index of transmission lines, running from 1 to N_K
m	index of energy blocks offered by generators (demand), running from 1 to N_I (N_J)

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 to be reduced 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 $p_{it}^{\max}(m)$
$d_{jt}(m)$	demand reduction from the mth block of demand j's reduction curve during period t. Limited to $d_{jt}^{\max}(m)$
P_{it}	power output scheduled from unit i during period t
D_{jt}	demand reduction for demand j during period t
λ_{jt}	corresponding price when demand j during period t is reduced by D_{jt}
R_{it}	scheduled spinning reserve for unit i during time period t
$\tilde{\alpha}_{jt}$	a random variable of the slope of price elastic demand reduction curve of demand j during period t

Constants

$\lambda_{it}(m)$	marginal cost of the mth block of energy offer by unit i during period t
$mc_{jt}(m)$	marginal opportunity or alternative cost of the mth block of demand j's reduction curve during period t
A_i	operating cost of unit i at the point of $P_i^{\min}$
B_j	opportunity or alternative cost demand j when it is reduced by $D_j^{\min}$
C_{it}	capacity cost offer of unit i during period t for providing up-spinning reserve
$P_i^{\max}$	maximum output of unit i
$P_i^{\min}$	minimum output of unit i
$D_{jt}^{\max}$	maximum reduction of demand j during period t
$D_{jt}^{\min}$	minimum reduction of demand j during period t
$\lambda_{jt}^{\max}$	corresponding price when demand j during period t is reduced by $D_{jt}^{\max}$
$\lambda_{jt}^{\min}$	corresponding price when demand j during period t is reduced by $D_{jt}^{\min}$
$\lambda_{jt}^{\mathrm{ref}}$	reference price when demand j during period t is not reduced
α_{jt}	the slope of price elastic demand reduction curve of demand j during period t
e_{jt}^{m}	the mth elbow point of the piece-wise linear price elastic demand reduction curve of demand j during period t
$\Delta\alpha_{jt}$	deviation from the nominal slop of price elastic demand reduction curve of demand j during period t
D_{jt}^{F}	fixed demand of demand j during period t
D_{jt}^{ref}	reference responsive demand of demand j during period t without reduction
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
Γ_0	control parameter of robustness level

ISO) have provided opportunities for customers to participate in wholesale energy, capacity and ancillary services markets [15]. Taking New York ISO for example, DR resources may offer operating reserves, regulation, energy reduction and capacity service by participating into the Demand Side Ancillary Services Program, Day-Ahead Demand Response Program, Emergency Demand Response Program and Installed Capacity Special Case Resources Program [16]. By 2010, 31,695 MW of demand response are available in ISO/RTO markets, up from 17,146 MW at the end of 2006. Such gains represent 6.6% of 2008 peak demand within the regions combined [14].

In the above literature and market practice, DR directly bids into various markets and is modeled as a deterministic price-elastic demand curve. However, the actual price-elastic demand curve is uncertain and variable in time. In addition, consumers may modify their demand as prices change without being centrally dispatched. Therefore, power system scheduling, particularly unit commitment (UC), needs to be robust against the uncertainty in the price elasticity of demand. In recent years, significant contribution has been made by using the stochastic optimization models to solve UC problem under various uncertainties, in particular, under wind power output uncertainty [17–20]. A stochastic UC model is developed to determine the optimal reserve levels considering the volatile wind power in [21]. The impacts of large-scale wind power on system operating cost, realisability and environment are fully assessed in [22]. In [23], Benders decomposition technique is used to solve the stochastic UC problem. A chance-constrained two-stage stochastic UC with uncertain wind power output is proposed in [24]. Nevertheless, stochastic UC is rarely used in real system operation for two reasons. Firstly, the realization of uncertainty by a large number of scenarios dramatically increases the dimension of optimization model and reduces the solution efficiency. Secondly, the exact wind distribution is rarely available in short-term, such as day-ahead. For these reasons, robust optimization model, which requires less information of the uncertain parameter and has high solution efficiency, has been proposed to solve the UC problem with uncertainty recently. Two-stage robust UC models have been developed to solve the day-ahead UC problem under load uncertainty in [25,26], wind power output uncertainty in [27], generator and transmission uncertainty in [28] and market price uncertainty in [29]. For robust UC, the uncertainties are expressed by deterministic uncertainty sets neglecting their probability distributions and the worst case is optimized. Compared to stochastic UC, robust UC has relatively low dimension and high solution efficiency.

Considering the uncertainty of demand response, a scenario set of demand price elasticities is proposed in [30] to represent the stochastic DR, i.e., customers have different responses to the electricity prices in different scenarios, but the probability distribution of the demand elasticities is difficult to quantify. In [31,32], the price elasticity of demand is assumed to be varying within a given range. A robust UC approach is proposed to maximize the social welfare under the worst case joint wind power output and price-elastic demand curve scenario. This method allows for increased demand elasticity and results in a paradoxical reduction of total social welfare. This is because social welfare is not the right index of evaluating the economic benefit of system with demand