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Optimal reserve market clearing considering uncertain demand response using information gap decision theory

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ABSTRACT

Responsive loads, according to their increasing penetration, short response rate and flexibility are important sources of reserve in the smart power systems. Although in recent years demand response (DR) contribution in the (reserve) electricity market has been widely accepted with an important role in the reliable and economic operation of power systems, due to uncertain availability, sheddability, and controllability of these sources their uncertain behavior is worth to be investigated. For this purpose, at first, a reliability-based unit commitment is solved and then the results are used to clear reserve market in the presence of uncertain responsive loads based on information gap decision theory (IGDT) concept. Responsive loads are considered as reserve providers which participate in the market by offering their price-quantity capacity bids to the reserve market. The proposed method does not minimize the reserve market clearing cost, but with regard to the minimum cost, assesses the risk aversion or risk-taking nature of different strategies and also measures the related risk/immunity cost. Using this method, the system operator can select the best strategy according to the desired risk level, taking into account demand side uncertainty. Proposed method has been simulated over the 24 bus IEEE Reliability Test System.

1. Introduction

Reliable operation of power system necessitates a reasonable level of reserve that could maintain system reliability in case of unforeseen events such as line/generator outage and sudden load change [1]. In conventional systems, the only source of spinning reserve were generation units. As flexibility of conventional generators is restricted by technical constraints, maintaining the power system reliability using only generation-side becomes too constrained. This problem becomes even more difficult, when renewable energy resources are introduced [2]. In recent years with smart grid advancements, DR has been introduced as an alternative to satisfy electricity supply availability. Demand response programs (DRPs) not only can improve reliability indices, but also can contribute in total cost reductions [3]. Recently, a massive focus has been made on incorporating demand side resources into the electricity market [4]. To this aim, and also to facilitate customer participation, versatile DRPs have been introduced by Federal Energy Regulatory Commission (FERC) to classify the many different features of the Demand Side Management (DSM) [5]. In addition, to eliminate the barrier of participating customers in electricity market, FERC issued an Order in 2008 [6], implies that ISO should accept bids from certified demand response resources to provide ancillary services.

Several countries have provided opportunities for customers to participate in DR programs [7–9]. In this regard, worthy researches have devoted considerable efforts to incorporate DR into the market clearing process to achieve the most efficiency. In [10], a market model in which generators and responsive loads can submit offers and bids on both energy and reserve markets is proposed, but the network and multi-period constraints are neglected and reserve is defined through a deterministic criteria. A new method is proposed in [11] that enables consumers maximize their benefit from DRPs based on their participation history. In [12], 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. A new economic model for price and incentive responsive loads based on the concepts of flexible price elasticity of demand and customer benefit function is proposed in [13] which can be used for load profile improvement as well as customer's satisfaction. Ref. [14] presents a procedure to derive the optimal offering strategy of a producer who owns a large number of generating units and can alter the formation of market clearing prices. Bilevel programming is used for problem modeling while considering uncertainty related to the demand bids and rival producers offering

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Nomenclature

Sets and indices

c	index of buses
d	index of distribution company
i	index of contingencies
J	index of generating units
k	index of responsive loads
L	index of transmission lines
l	index of price blocks
S	index of scenarios

Constants

m_{1i}	number of in service unit in contingency *i* which their single outage will not result in load interruption
mc_i	number of in service units in contingency *i*
N_g	number of generating units
N_S	number of scenarios
N_D	number of distribution companies
N_{DRk}	number of blocks offered by *k*-th responsive load
N_g^{ap}	number of in service units
N_L^b	number of transmission lines connected to bus b
N_D^d	number of buses located in the area of Disco *D*
nc_i	number of out of service units in contingency *i*
n_t	total number of system elements
n_s	number of out of service elements under scenario *s*
N_b	total number of buses
N_{gb}	number of generating units connected to bus b
N_{DR}	total number of responsive loads
L_b	demand at bus *b*
λ^{ref}	customer's offer base price
E	price elasticity of demand response resources
I_s^b	load curtailment indicator, 1 if occurrence state s cause to undesirable load curtailment and 0 otherwise
For_n	force outage rate of units
C_w	cost target for opportunity function
C_k	cost target for robustness function
DR_k^{Max}	maximum reserve capacity offered by k-th customer
TL	system total load
Up_k	capacity of the k-th unit
P_s	probability of scenario *s*

Variables

$R_{DRk,l}$	amount of reserve which is provided by k-th responsive load
$R_{DRk,l}^{Max}$	size of power block l offered by k-th responsive load
$\rho_{k,l}$	price of l-th block of reserve bid offered by k-th responsive load
R_{gj}	reserve capacity offered by j-th generator
π_j	offered price at which generator j is willing to provide reserve capacity
u(j)	1 if unit is scheduled on and 0 otherwise
α,β	robustness/opportunity parameter
R_{gj}^{ap}	approved reserve capacity from j-th unit
R_{DRk}^{ap}	approved reserve capacity from k-th responsive load
F_L^s	line flow of line *L* under scenario *s*
LC_b^s	curtailed load from bus *b* under scenario *s*
P_{gj}^s	output power of unit *j* in scenario *s*
CLU_i	capacity of largest unit in the i-th contingency
CP_i	available capacity in the *i*-th contingency
EENS_d	expected energy not served of Dicso d
VOLL_d	value of lost load of Dicso d
ADR	total available demand response capacity
CDR_k	total cost of approved capacity from k-th responsive load
TSR	total spinning reserve
λ_i	unit j failure rate
R_{gj}^{Max}	maximum available free capacity of j-th unit
RR_j	j-th unit ramp rate
P_{gj}^{Max}	maximum power output of generator j
P_{gj}^{Min}	minimum power output of generator j
P_{gj}	output MW by j-th generator

Functions

$\widetilde{\beta}(\mathrm{C}_w)$	opportunity function
$\widetilde{\alpha}(C_k)$	robustness function

strategy.

In major common works, customers are considered as definite resources which participate to the market to improve market condition, but due to erratic nature of customers, demand-side participation will add uncertainty to the market operation. In other words, the actual response from customers could be different from the expected values. Therefore, considering demand-side uncertainty in the electricity market operation seems crucial.

Demand response uncertainty is considered in some studies and different aspects of uncertainty has been evaluated [15–17]. To model and simulate demand-side uncertainty, each research picks out a method. In [15] and [16] SCUC problem is conducted and customers are incorporated in the market. Ref. [15] by using different scenarios and [16] by an uncertain demand elasticity, has modeled demand-side uncertainty. Moreover, a robust unit commitment model is used in [17] to minimize the generalized social cost while considering uncertain demand elasticity. Wind power, as another uncertain source, is considered in [18] in which, strategic offering for a wind producer is investigated and uncertainty pertaining to wind production is modeled through a set of correlated scenarios using a bilevel model. In this regard, it is considered that wind producer behaves strategically in the day-ahead market, while decide to sell/buy its production deviations in the balancing market.

There are various uncertainty handling methods developed for dealing with the uncertain parameters such as Probabilistic, Possibilistic, Hybrid possibilistic–probabilistic, Robust optimization, Interval analysis and Information gap decision theory approach. The main difference between these methods is the way that is used for describing the uncertainty of input parameters [19]. These methods need exact uncertainty set, which requires more detailed information about the uncertain parameter. As an example, probabilistic methods need precise information about the probability density function of uncertain parameter while Fuzzy based methods require accurate membership function. As it is clear, each method has advantages and disadvantages accordingly, the best method is specified based on the availability of the input data or severity of the uncertainty [20].

A novel framework was proposed in [21] named Information Gap Decision Theory (IGDT), by which a range of robust decision making can be done. Effectiveness of this method in power system problems has already been evaluated in some fields such as energy procurement strategy for retailers [22], large consumers [23] and hydrothermal scheduling [24]. In this context, IGDT is used in [25–28] respectively for determining the optimal bidding strategy and self-scheduling of GenCos, operation strategy for combined heat and power units, and aiding the Distribution Network Operators (DNOs) in choosing the supplying resources.