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Stochastic multi-objective programming for simultaneous clearing of energy and spinning reserve markets considering reliability preferences of customers

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ABSTRACT

Determination and procurement of required Spinning Reserve (SR) capacity have ever been major concerns in the power industry. In restructured power systems in various countries, Independent System Operators (ISO) determine the SR capacity requirements based on different criteria and procure the estimated SR on behalf of customers from SR market. In this paper a new stochastic joint energy and SR market clearing model is presented based on a multi-objective mixed integer nonlinear programming with three objective functions. In the proposed model the customers participate in SR market directly by declaring the Value of Lost Load (VOLL) and acquire the required SR. The responsibility of ISO to SR market is restricted to two proceedings; minimizing the total Expected Load Not Supplied (ELNS) of the power system and maximizing the post-contingency expected social welfare associated with the SR scheduling at the first and second objective functions. Meanwhile the pre-contingency offered cost is minimized at the third one. Simulation results from two test cases are presented to back up the conclusions.

1. Introduction

Spinning Reserve (SR), as one of the ancillary services, constitutes units synchronized with the system that can immediately supply energy to guarantee the normal operation of the system once a credible contingency takes place [1,2]. The design of efficient generation markets has been evolutionary process in most countries. In [3] various components of market design for energy and ancillary services are investigated. Due to interdependency of energy and SR markets, there are generally two forms for clearing energy and SR markets. In some markets, the simultaneous approach is applied for procuring energy and SR, while in other ones these two markets are cleared separately and sequentially [4,5]. Although the sequential approach is transparent and easy to implement, however experience shows that the generation resources are not properly scheduled and can lead to quite undesirable situations. So the simultaneous process would be the subject of research in this paper.

In the literature, before clearing the energy and SR markets, the ISO determines the SR requirements based on different criteria and thereinafter procures the required SR from SR market. Since SR auction is operated by the ISO, the ISO is the single buyer party to meet the reliability obligations. In a general sense, deterministic and probabilistic criteria are utilized by the ISO for determining the required level of SR. In deterministic approach, the SR capacity is often assumed to be fixed and equal to a specific percentage of the hourly system loads, or capacity of the largest online generator [6–13]. Rau [14] presents a mixed integer linear programming formulation for clearing the energy and ancillary services markets in which the required Automatic Generation Control (AGC), Ten Minutes Spinning (TMSR) and Non-Spinning Reserve (TMNSR) and Thirty Minutes Operating Reserve (TMOR) are assumed to be fixed and predefined. Although deterministic criterion is widely utilized in power industry, however the stochastic nature of the power system is ignored and thereinafter the market clearing solution would be generally suboptimal and may even be infeasible. On the contrary, stochastic security based approaches take into consideration the probability of occurrence of each contingency that influence the actual risk in the system. Therefore they can provide a more realistic evaluation of SR requirements [15–29].

On the other hand, it is obvious that energy is more valuable for some customers than others. Thus they are willing to pay more for higher reliability. With considering this fact, the SR requirements can be affected significantly by the reliability preferences of customers and it is so necessary to improve the operation of energy and SR markets with developing the techniques based on customer choice on reliability. In [15] a stochastic approach is used to clear energy and reserve markets simultaneously. However in the

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Nomenclature

Sets

N_g	set of all generators
N_b	set of all buses
N_l	set of all branches
N_s	set of all contingencies
N_d	set of all loads

Constants

$P_{g,i}^{\min}$	lower limit on a generator capacity in pre- and post-contingency states
$P_{g,i}^{\max}$	upper limit on a generator capacity in pre- and post-contingency states
$P_{ij}^{\max}$	capacity of line i–j in pre- and post-contingency states
$\mathrm{Rmp}_{g,i}$	maximum sustained ramp-up rate (MW/min) of unit i
VOLL_i	Value of Lost Load of DISCO i
$P_{d,i}$	power demand of DISCO i in energy market
$\rho_{cr,i}$	capacity reservation bid of generator i to SR market
$\mathbf{B}$	DC load flow matrix in the pre-contingency state
$\mathbf{B_i}$	ith row of matrix $\mathbf{B}$ corresponding to bus i
B_{ij}	corresponding element to ith row and jth column of matrix $\mathbf{B}$
$\mathbf{B^s}$	DC load flow matrix under contingency s
$\mathbf{B_i^s}$	ith row of matrix $\mathbf{B^s}$ corresponding to bus i
B_{ij}^s	corresponding element to ith row and jth column of matrix B^s
prob_s	occurrence probability of state s
prob_0	occurrence probability of normal operation state
n_{sys}	total number of components in the system
n_f	number of unavailable system components in state s
U_c	unavailability probability of component c

Variables

$P_{g,i}$	scheduled power generation for generator i in energy market
$u_{g,i}$	binary (0/1) variable denoting the off/on status of the generator i
$P_{r,i}$	scheduled spinning reserve for generator i in reserve market
$\boldsymbol{\delta}$	vector of nodal phase angles in the pre-contingency state
$\boldsymbol{\delta_g^s}$	vector of nodal phase angles under contingency s, according to *Generation decrement and load curtailment* implementation
$\boldsymbol{\delta_r^s}$	vector of nodal phase angles under contingency s, according to *SR generation and SR capacity subscription* implementation
$P_{g,i}^s$	generation decrement of generator i under contingency s
$P_{r,i}^s$	actual use of the scheduled SR of generator i under contingency s
$\mathrm{LNS}_{s,i}$	Load Not Supplied of DISCO i under contingency s
$\mathrm{AC}_{s,i}$	subscripted capacity of DISCO i under contingency s

Functions

$C_{g,i}(\cdot)$	energy bid function of generator i to day-ahead energy market

Parameters

ELNS_i	Expected Load Not Supplied of DISCO i under all contingencies
TELNS	total ELNS of the power system under all contingencies
TSR	total scheduled SR in power system
EAC_i	expected subscribed SR capacity by DISCO i under all contingencies
TEAC	total expected subscribed SR capacity by all DISCOs under all contingencies
RELNS_i	actual ELNS of DISCO i
RELNSC_i	imposed cost to DISCO i due to RELNS_i
TRELNS	total real ELNS of the power system
SSR_i	the contribution of DISCO i to total scheduled SR

mentioned research the reliability preferences of the customers are not considered in involuntary load shedding. The issue of the reliability preferences of customers, in the clearing procedure of energy and SR markets and the SR determination problem has so far investigated in several researches. In the mentioned works, the customers utilize two procedures to announce the reliability preferences. At the first procedure, the desired values of some probabilistic indices such as Expected Energy Not Supplied (EENS), Expected Load Not Supplied (ELNS) and Loss of Load Probability (LOLP) are declared as the reliability preferences by customers. The suggested proceeding is to schedule the SR capacity in such a way that the mentioned probabilistic indices should be within the desirable values [16–20].

However there are some drawbacks to implement that procedure. One is that it is complicated to set and justify desired values. In addition, if there is insufficient SR capacity in the system, then it may be impossible to satisfy a specified index upper bound. Meanwhile even if there was sufficient SR capacity available in the system, transmission lines flow limits would be another potential that may impede from satisfying the probabilistic indices inequalities constraints. Finally even if there are sufficient SR and transmission capacity in the system, involuntary load shedding will be applied until the indices inequalities become binding, which in general will be unacceptable to the consumers. In addition to the above expressed drawbacks, it can be stated that the main shortcoming of that scenario is that the effect of Value of Lost Load (VOLL) is not considered in involuntary load shedding of customers and consequently the SR scheduling is not based on cost-benefit analysis and so may be suboptimal. In other words, the desired values of indices should be satisfied even if the procurement cost of energy is more than value of load for customers. However at the second procedure, the aforementioned drawbacks are eliminated. The customers declare their desired reliability levels based on VOLLs and the optimum value for reserve is determined by trade-off between cost of reserve provision and benefit of EENS or ELNS reduction. In [21–23], the ELNS Cost (ELNSC) of all customers is penalized within the objective function based on their VOLLs. Refs. [24–27] develop the presented model in [21]. Wu et al. [24] represent the system reliability in the stochastic Security Constrained Unit Commitment (SCUC) by adding the cost of EENS to the objective function based on a fixed VOLL for the whole power system. Meanwhile the Loss of Load Expectation (LOLE) limit is augmented to the set of constraints. In [25–27] system security is taken into account in the market clearing procedure of the aggregated simultaneous multi-product auctions as the extra objective functions in the nonlinear constrained multi-objective optimization problem. In the proposed market clearing scheme in [25], augmented cost (offer generation cost and EENS cost) and security indices (branch overload, voltage drop, and voltage stability margin) are treated as competing objective functions. Refs. [26,27] retain the proposed multi-objective