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Security-constrained self-scheduling of generation companies in day-ahead electricity markets considering financial risk

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A B S T R A C T

In this paper, a new security-constrained self-scheduling framework incorporating the transmission flow limits in both steady state conditions and post-contingent states is presented to produce efficient bidding strategy for generation companies (GENCOs) in day-ahead electricity markets. Moreover, the proposed framework takes into account the uncertainty of the predicted market prices and models the risk and profit tradeoff of a GENCO based on an efficient multi-objective model. Furthermore, unit commitment and inter-temporal constraints of generators are considered in the suggested model converting it to a mixed-integer programming (MIP) optimization problem. Sensitivity of the proposed framework with respect to both the level of the market prices and adopted risk level is also evaluated in the paper. Simulation results are presented on the IEEE 30-bus and IEEE 118-bus test systems illustrating the performance of the proposed self-scheduling model.

1. Introduction

By deregulation of electric power industry, electricity is traded as a commodity in the open electricity market environment [1]. In a day ahead electricity market based on the pool, generation companies (GENCOs) submit production bids to the independent system operator (ISO) and the bids are cleared based on the market-clearing procedure [2,3]. The objective of a GENCO is to maximize the value of profit from selling power and ancillary services in the competitive electricity market while meeting the prevailing equality and inequality constraints of its generating units and power system such as minimum on/off duration, generation capacity limits, ramping up/down limits of units and GENCO's demand constraint [4]. Thus, GENCOs require appropriate bidding strategy for a successful participation in the electricity markets [5–13]. Through this strategy, a GENCO can compete with its rivals in the electricity market and sell its products. Without an effective bidding strategy, a GENCO may encounter financial losses and even bankruptcy. Thus, devising such a strategy is an essential demand for producers in today electricity markets. This strategy should also be able to take into account the uncertainty of the forecasted prices with an appropriate risk management [2,4]. For power producers, the greatest risk posed by electricity pools is the financial consequence of fluctuating market prices. Therefore, GENCOs generation scheduling decision is associated with financial risks at the time of self-scheduling, which means any producer faces a tradeoff between maximum profit and minimum risk and a GENCO is interested in maximizing its profit while minimizing risk in a constrained power market. However, deterministic solution taking the expected price as given will not, in general, produce the correct expectation as it ignores price volatility [14].

To remedy this problem, different self-scheduling methods have recently been presented in the literature to develop bidding strategies for GENCOs considering price uncertainty and risk management. A risk-constrained bidding strategy was proposed in [15] for a GENCO to devise optimal bids in the day-ahead energy and ancillary services markets in which financial risk is modeled by including the expected downside risk as a constraint. A scenario-based approach for self-scheduling problem was presented in [16] that downside risk is employed as the risk measure. Also, the self-scheduling problem of a price taker power producer with special focus on risk modeling was analyzed in [17,18] in which the revenue is characterized as a random variable whose variance is a measure of risk. In [19], a stochastic profit maximization problem was presented in which price uncertainty is modeled using fuzzy numbers. An integrated bidding and scheduling algorithm with risk management for optimizing energy and reserve offer curves for a hydrothermal power producer is proposed in [20]. In [21], a bidding strategy is proposed for power producers that can trade in both day-ahead pool electricity market and future market spanning up to 1 year. Financial risk of the power producer is appropriately modeled through the conditional value at risk (CVaR) technique. A methodology is proposed in [22] for self-scheduling of

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Nomenclature

a_i, b_i, c_i coefficients of the quadratic fuel cost function of unit i
a_{mn}^k sensitivity factor for flow of transmission line between buses m and n with respect to injection of bus k in the normal (non-contingent) state
L set of line contingencies
$a_{mn}^k(L)$ sensitivity factor for flow of transmission line between buses m and n with respect to injection of bus k in the contingent state of the outage of transmission lines of L
$C_{i,t}^{Fuel}$ fuel cost function
$C_{i,t}^{Shutdown}$ shutdown cost of unit i at time t
$C_{i,t}^{Startup}$ startup cost of unit i at time t
C_i^{SD} constant shutdown cost of unit i
C_i^{SU} constant startup cost of unit i
D_t system demand at time t
$F(.)$ GENCO's expected profit (reward function)
F_{mn}^t flow of transmission line between buses m and n (line m-n) at time t
H_i^{up} number of hours that unit i must be initially online due to its minimum up time constraint
H_i^{down} number of hours that unit i must be initially offline due to its minimum down time constraint
i index of thermal unit ($i = 1,\ldots,NG$)
k index of bus ($k = 1,\ldots,NB$)
t index of time ($t = 1,\ldots,NT$)
j index of price scenario
NG number of thermal generating units
NB number of buses
NT number of time periods
NS number of price scenarios
P_i^{max} upper limit of real power generation of unit i
P_i^{min} lower limit of real power generation of unit i
$P_{i,t}$ real power generation of unit i at time t
$P_{k,t}^{NET}$ net power injection of bus k at time t
R_i^{up} ramp-up rate limit of unit i
R_i^{down} ramp-down rate limit of unit i
SUR_i startup ramp rate limit of unit i
SDR_i shutdown ramp rate limit of unit i
T_i^{down} minimum down time of unit i
T_i^{up} minimum up time of unit i
$z_{i,t}$ commitment state of unit i at time t (1 means on and 0 means off)
A LMP multiplier
$FLMP_{i,t}$ forecast LMP for unit i at time t

generating units to provide the proper tradeoff between maximum profit and minimum risk in the competitive market. Their proposed model uses CVaR as a measure of risk and taking into account long-term physical and financial contracts bargained, optimal hourly production of every generating unit is obtained as output of the optimization problem. A stochastic programming methodology is presented in [23] to determine profit-maximizing strategy for a thermal producer participating in a sequence of spot markets. The uncertainty sources of electricity prices are considered in [23]. A self-scheduling strategy based on stochastic programming is proposed for power producers in [24]. This strategy allows the producer to maximize its expected profit while controlling the risk of profit variability. However, network flow limits and security constraints are not considered in these research works, while the competition in an electricity market is constrained by available transfer capabilities and the level of transmission congestion. The ISO plans hour-ahead and day-ahead schedules and determines the optimal allocation of generation resources based on the possible network congestion [25–27]. In order to obtain successful generation bids, the GENCOs have to self-schedule their units by taking into account not only power flow constraints of the intact network, but also security constraints. This was motivated by the recommendation of the Northern Electric Reliability Council (NERC) that stressed the control area's responsibility to maintain sufficient ancillary services under $N-1$ contingency conditions [28]. To solve this problem, some self-scheduling research works consider security constraints in their models. In [28], a security constrained generation scheduling model for GENCOs is presented including transmission flow limits in both steady state and post-contingent states. However, this model does not take into account price uncertainty and financial risks of GENCOs. The other security-constrained self-scheduling methods based on DC network modeling are proposed in [29,30], wherein the reward is modeled as the expected profit and the financial risk is measured using the value at risk (VaR) and CVaR, respectively. However, none of self-scheduling models of [28–30] consider unit-commitment of the GENCO.

In this paper, a new security-constrained self-scheduling framework for GENCOs participating in the day-ahead pool based energy markets is proposed considering power flow limits of the intact network and security constraints in addition to the physical limits of generators. Moreover, price uncertainty and financial risks are modeled in the proposed framework using the efficient risk measure of CVaR. Furthermore, unit commitment of generators is taken into account in the suggested framework converting it to a mixed integer programming (MIP) model. Up to the authors' knowledge, the proposed self-scheduling framework is more comprehensive than the models presented in the previous research works in the area. To better illustrate this matter, a brief bibliography of different security-constrained generation scheduling (SCGS) models presented in the recent works is represented in Table 1, which better reflects the capabilities of the proposed model. The price uncertainty and financial risk handling method of each research work (if modeled) is also indicated in the table.

Another contribution of the paper is presentation of a new multi-objective framework for combining the reward function and risk measure. The proposed framework retains the important characteristic of linearity and explicitly models the tradeoff between reward and risk. Moreover, the sensitivity of the proposed

Table 1
A brief bibliography of some recent SCGS models.

Related reference	Price uncertainty and financial risk	Security constraints	Unit commitment
[8]			*
[15]	* Downside Risk		*
[16]	* Downside Risk		
[17]	* Variance of the Revenue		
[18]	* Variance of the Revenue		*
[19]	* Fuzzy Sets		*
[20]	* Price Variance		
[21]	* CVaR		
[22]	* CVaR		*
[23]	* No risk measure		
[24]	* CVaR		*
[28]		*	
[29]	* VaR	*	
[30]	* CVaR	*	
Proposed	* CVaR	*	*