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Self-scheduling and bidding strategies of thermal units with stochastic emission constraints

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ABSTRACT

This paper is on the self-scheduling problem for a thermal power producer taking part in a pool-based electricity market as a price-taker, having bilateral contracts and emission-constrained. An approach based on stochastic mixed-integer linear programming approach is proposed for solving the self-scheduling problem. Uncertainty regarding electricity price is considered through a set of scenarios computed by simulation and scenario-reduction. Thermal units are modelled by variable costs, start-up costs and technical operating constraints, such as: forbidden operating zones, ramp up/down limits and minimum up/down time limits. A requirement on emission allowances to mitigate carbon footprint is modelled by a stochastic constraint. Supply functions for different emission allowance levels are accessed in order to establish the optimal bidding strategy. A case study is presented to illustrate the usefulness and the proficiency of the proposed approach in supporting biding strategies.

1. Introduction

The electricity supply industry, despite growing renewable energy integration worldwide over the past decade [1], is still significantly dependent on conventional fossil fuel power plants [2]. These plants play a leading role in meeting a load demand and consequently assisting in system stability [3] due to their characteristics as a base load support. In 2012, 52% of the total power production in the European Union (EU) was derived from fossil fuel energy sources [4]. In that same year in Portugal, thermal power plants were responsible for about 46% of the total installed capacity [5]. Several environmental impacts at local, regional and global levels are attributed to the release of anthropogenic greenhouse gas emissions into the atmosphere. Nowadays, given the wide percentage share of thermal power plants, a need for explicit emission consideration is a power system concern. The well-known Kyoto Protocol [6] appeared in order to mitigate the climate changes and the rate of global warming. EU directive 2003/87/CE establishes a procedure for emission allowances imposing that all carbon emissions coming from the electricity supply industry must be economically treated at an auction [7]. The EU has subjected the electricity supply industry to other environmental limitations besides the aforementioned carbon emission allowances. The EU previously introduced a directive (2001/80/CE) on the emission standard of air pollutants for thermal power plants with a rated thermal input equal to or greater than 50 MW, irrespective of the type of fuel used. The standard stipulates limitations on the concentrations of air pollutant emissions due to thermal power plants, including SO_2, NO_2 and dust [8]. As an outcome in what regards carbon emission, the management of thermal power plants must be considered for different emission allowance levels traded until the auction's closing [9].

Throughout the world, the electricity supply industry is being driven toward a competitive framework, overriding the former traditional monopolistic scenery for this industry [10]. The competitive framework is intended for persuading the supply industry to operate under a high degree of economy for competition of deregulation [11], posing new challenging problems in order to obtain the best profit in the pool-based electricity market. One of the new challenging problems is the optimal schedule of the thermal units in order to support the bidding strategy submitted to the electricity market and taking into account the electricity price uncertainty and other requirements, such as: technical operating constraints on the thermal units required, for instance, to impose forbidden operating zones, ramp up/down limits, minimum up/down time limits, start-up/shut-down costs, and environment constraints required to ensure admissible emission allowance levels. The aforementioned optimal schedule of the thermal is defined

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Nomenclature

Sets and indexes

I, i set and index of thermal units
L, l set and index of piecewise linearisation segments for variable cost functions
M, m set and index of bilateral contracts
R, r set and index of segments of the piecewise emission function
Ω, ω set and index of electricity pool price scenarios
T, t set and index of hours in the time horizon

Constants

λ_{mt}^{bc} electricity price at hour t for bilateral contract m
$\lambda_{\omega t}^{b}$ electricity pool price at hour t for scenario ω
ρ_{ω} probability of occurrence for scenario ω
A_i fixed cost of thermal unit i at minimum power generated
Ae_i fixed emission of the thermal unit i
C_i shut-down cost of thermal unit i
EMS total emission allowances
F_i^l slope of segment l of the piecewise linear variable cost function of thermal unit i
Fe_i^r slope of segment r of the piecewise linear emission function of thermal unit i
J_i number of hours thermal unit i must be initially offline
K_i^{β} cost at the β-th interval of the start-up cost of thermal unit i
N_i number of hours thermal unit i must be online
p_{mt}^{bc} power at hour t for bilateral contract m
$p_i^{\min}$, $p_i^{\max}$ power generation of thermal unit i minimum and maximum value
RU_i, RD_i ramp-up and ramp-down of thermal unit i
SU_i, SD_i start-up and shut-down ramp rate of thermal unit i
$s_{\omega i0}$ number of hours thermal unit i has been offline at the beginning of the time horizon
T_i^l upper limit of segment l of the piecewise linear variable cost function of thermal unit i
UT_i, DT_i minimum up and down time of thermal unit i
$\boldsymbol{A}$ constraint matrix
$\boldsymbol{b}^{\min}$, $\boldsymbol{b}^{\max}$ vectors of lower and of upper bounds of constraints
$\boldsymbol{f}$ vector of coefficients for the linear term

Continuous variables

$p_{\omega it}$ power generation of thermal unit i at hour t for scenario ω
$p_{\omega it}^{\max}$ maximum available power of thermal unit i at hour t for scenario ω
$p_{\omega t}^{b}$ power to bid in the pool-based electricity market at hour t for scenario ω
$\delta_{\omega it}^{l}$ segment l power of thermal unit i at hour t for scenario ω
$\delta e_{\omega it}^{r}$ segment r power related to the emission of thermal unit i at hour t for scenario ω
$b_{\omega it}$ start-up cost of thermal unit i at hour t for scenario ω
$d_{\omega it}$ linearised variable cost function of thermal unit i at hour t for scenario ω
$E_{\omega it}$ total emissions of thermal unit i at hour t for scenario ω
$F_{\omega it}$ total operating cost of thermal unit i at hour t for scenario ω
$\boldsymbol{x}$ vector of decision variables
$\boldsymbol{x}^{\min}$, $\boldsymbol{x}^{\max}$ vectors of lower and upper bound on variables

Binary variables

$t_{\omega it}^{l}$ equal to 1 if power generation of thermal unit i at hour t for scenario ω exceeds segment l
$u_{\omega it}$ commitment decision of plant i at hour k for scenario ω
$y_{\omega it}$ decision to start-up the plant at hour t for scenario ω
$z_{\omega it}$ decision to shut-down the plant at hour t for scenario ω

as a self-scheduling problem and is the subject of the work presented in this paper.

Apart from the pool-based electricity market provided by the market environment, participation in bilateral contracts is a potential current reality benefit for thermal power producers in order to hedge against price uncertainty [12]. Hence, additional modelling must be included in the self-scheduling problem to capture the current reality of the management of those thermal power plants. Also, in a pool-based electricity market a producer with higher capacity availability levels can heavily influence the closing electricity price, i.e., has market power. Likewise, a price-taker producer has a capacity level that is unable to have a significant influence in the electricity price, i.e., a price-taker as a single producer is not capable of exercising market power, hence they act like price-takers by considering fixed prices when devising their bidding strategies [13]. Price-takers are the producers considered in this paper, participating in pool-based electricity market and in bilateral contracts.

Price uncertainty has become a relevant matter to be tackled and research has developed a scheme based on modelling via a set of scenarios in order to support the decisions of power producers against this uncertainty [14]. Uncertainty can be considered by stochastic programming approaches in order to avow solutions that are not desirable [15], i.e., solutions showing potential achievement of small profits or major costs [16].

A review of the literature on self-scheduling problems for price-taker thermal power producers reveal that this problem has been widely treated as deterministic one, ignoring the random events observed in the electricity market [17–21]. Hence, those treatments cannot provide for a convenient level of precautions on the decisions that are not appropriated, because the one certainty in the present framework for price-taker thermal power producer is uncertainty. Optimisation methods for solving the self-scheduling problem have been addressed, from since the priorities list method [22] to the classical mathematical programming methods until the recently reported artificial intelligence methods [23]. Although, easy to implement and requiring a small processing time, the priority list method does not take into account fundamental consideration of nowadays management for thermal power producer. Hence, this method does not ensure an economic solution near a global optimal one, i.e., a higher operation cost is to be expected [24]. Classical methods include dynamic programming (DP), Lagrangian relaxation-based techniques and mixed-integer programming [25]. DP methods are flexible but suffer from the "curse of dimensionality", a limitation due to the increase in the problem size related to the number of thermal units to be committed. This is due to the number of necessary states for modelling the thermal behaviour of thermal unit during the time horizon [26], implying an eventual widespread use of computation memory and processing time. Although Lagrangian relaxation [27] can overcome the previous limitation, it can lead to an infeasible solution, so, it requires the satisfaction of the violated constraints using heuristics, undermining the optimality.

Artificial intelligence (AI) methods based on artificial neural networks [28], genetic algorithms [29], evolutionary algorithms [30] and simulating annealing [31], have also been applied.