Price Maker Self-Scheduling in a Pool-Based Electricity Market: A Mixed-Integer LP Approach

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***Abstract*— This paper addresses the self-scheduling problem faced by a price-maker to achieve maximum profit in a pool-based electricity market. An exact and computationally efficient mixed-integer linear programming (MILP) formulation of this problem is presented. This formulation models precisely the price-maker capability of altering market-clearing prices to its own benefits, through price quota curves. No assumptions are made on the characteristics of the pool and its agents. A realistic case study is presented and the results obtained are analyzed in detail.**

***Index Terms*—Electricity pool market, market power, mixed-integer linear programming (MILP), price maker.**

NOTATION

A. Functions

$\lambda_t(q_t)$ stepwise monotonically decreasing discontinuous function that, for every hour t, expresses the market-clearing price as a function of the price maker quota in that hour (see Fig. 1);

$c_{t,i}$ production cost for hour t of the ith unit belonging to the price maker;

R_t revenue of the price maker in hour t.

B. Constants

$b_{t,s}^{\max}$ megawatt size of step s of the price quota curve for hour t (see Figs. 2 and 3);

m number of units owned by the price maker;

n_t number of steps of the price quota curve in hour t;

$q_{t,s}^{\min}$ is the summation of power blocks from step 1 to step s-1 for hour t (note that $q_{t,1}^{\min} = 0, \forall\, t$; see Figs. 2 and 3).

T number of time periods considered;

$\lambda_{t,s}$ price corresponding to step number s of the price quota curve in hour t;

Π_i feasible operating region of unit i.

C. Variables

$b_{t,s}$ real variable representing the fractional value of the power block corresponding to step s to obtain quota q_t;

$p_{t,i}$ power produced by unit i in hour t;

q_t price maker quota in hour t;

$u_{t,s}$ binary variable that is equal to 1 if step s is the last step needed to obtain quota q_t in hour t and 0 otherwise.

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I. INTRODUCTION

The framework considered in this paper is a pool-based electricity market for energy. An auction mechanism to clear the market one day ahead on an hourly basis is assumed [1], [2]. No particular assumptions are made on generating companies; therefore, several price makers as well as several competitive fringe producers are market agents. The hourly load may be price elastic or not.

In the above context, this paper addresses the self-scheduling problem of a price maker, i.e., a generating company owning a portfolio of units that is capable of altering market-clearing prices. The objective function of this self-scheduling problem is to maximize the price maker profits. Once the optimal self-schedule is known, an appropriate bidding strategy to actually achieve this optimal schedule should be developed.

For every hour, it is assumed that the market-clearing price as well as the offer and demand curves are available once the market has been cleared. This is the case of several electricity markets like the market in mainland Spain [3], the former electricity market of California [4], and the electricity market of New England [5]. The above information is crucial because it allows small producers to forecast next-day market-clearing prices, and it also allows price makers to forecast their corresponding price quota curves. Note that several price makers can compete in the considered pool-based electricity market.

The price quota curve of a price maker for a given hour provides the market-clearing price as a function of the price maker quota (accepted production in that hour). This curve is described in detail in [1], [6]. Hourly price quota curves (also known as residual demand curves) allow formulating precisely the self-scheduling profit maximization problem that every price maker faces every day in a pool-based electricity market for energy.

This paper specifically addresses the day-ahead self-scheduling problem faced by a particular price maker. It provides an efficient yet simple mixed-integer linear programming (MILP) formulation that allows achieving the optimal solution for realistic case studies in moderate solution times. This LP formulation is exact in the sense that it is not an approximation of a nonlinear formulation, as is the case of the model presented in [7].

Market power and price maker behavior have been analyzed mostly in a single period context (therefore, not using 0/1 variables), and continuity has been assumed in functions and variables. Particularly relevant works are [8]–[11]. This paper provides a complementary approach that does not require continuity and considers a multiperiod setting. On the other hand, it extends the work reported in [6], specifically in providing an exact and efficient mixed-integer formulation, which guarantees the achievement of the optimal solution.

The remainder of this paper is organized as follows. Section II describes price quota curves, presents a nonlinear formulation of the price maker self-scheduling problem, and provides its equivalent mixed-integer linear formulation. In Section III, the results from a realistic case study are analyzed in detail. Section IV provides some conclusions. Finally, an Appendix is presented to describe the running cost and the feasible operating region for generating units.

II. Problem Formulation

A. Price Quota Curve Description

For a given hour, the quota of a price maker is the amount of power it contributes to serve the demand in that hour. If the price maker exercises its market power by retaining production, the market-clearing price increases. The curve that expresses how the market-clearing price (for the whole market) changes as the quota of the price maker changes is called residual demand curve [1] or, more directly, price quota curve. Note that different price makers competing in the same electricity market present different price quota curves.

The price quota curve for a given hour, corresponding to a price maker, is a stepwise monotonically decreasing curve that expresses the actual market-clearing price in that hour as a function of the market quota (total accepted production) of the price maker. Price quota curves are stepwise because (producer/consumer) bids are assumed to be blocks of power at given prices.

The 24 hourly day-ahead price quota curves of a given price maker provide all the market information it needs to self-schedule optimally, i.e., to maximize its benefits. That is, these curves embody the effects of all interactions with competitors and the market functioning rules. Once these curves are available, the price maker self-scheduling problem can be precisely formulated without further regard to the effect of competitors, i.e., the self-scheduling problem of any price maker can be formulated independently of the problems of other producers.

The functioning of a day-ahead electricity market is as follows. First, each producer, either price maker or price taker, uses a self-scheduling algorithm to determine its optimal self-schedule. Then, each producer uses a bidding strategy designed to achieve in the market that optimal schedule. Finally, the market operator uses a market-clearing procedure to determine the actual production of each producer.

The day-ahead price quota curves of a price maker can be obtained 1) by market simulation or 2) using forecasting procedures [1]. Both techniques are outside the scope of this paper, and therefore, the hourly price quota curves of the price maker considered are assumed to be known data.

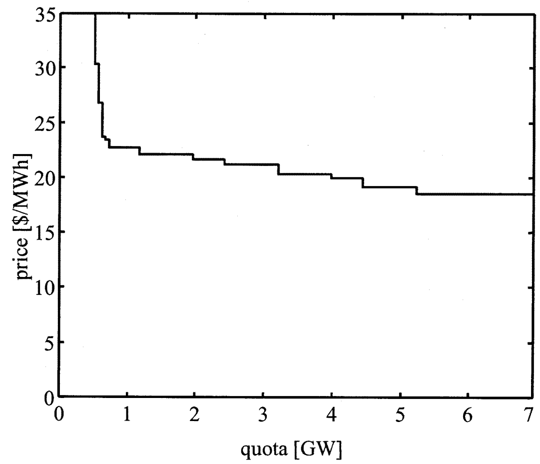

Fig. 1. Price quota curve.

For the sake of illustration, Fig. 1 shows a typical price quota curve.

B. Nonlinear Formulation

The natural formulation of the optimization problem that a price maker has to face is nonlinear, due to the products between the variables that appear in the objective function [6].

This formulation is

$$\underset{p_{t,i},\, q_t}{\text{maximize}} \quad \sum_{t=1}^{T} \left[\lambda_t(q_t)\, q_t - \sum_{i=1}^{m} c_{t,i} \right] \tag{1}$$

$$\text{subject to} \quad p_{t,i} \in \Pi_i, \quad i=1,\ldots,m, t=1,\ldots,T \tag{2}$$

$$q_t = \sum_{i=1}^{m} p_{t,i}, \quad t=1,\ldots,T. \tag{3}$$

The objective function (1) expresses the profit of the price maker over the planning horizon. The first term is the total revenue, and the second one is the total production cost, as formulated in the Appendix and in [12].

The set of constraints (2) enforces that every unit works within its feasible operating region over the whole planning horizon. A precise mixed-integer linear description of this feasibility region can be found in [12], [13], and in the Appendix.

The set of constraints (3) expresses for every hour the price maker quota as the sum of the power production of its units.

C. Linear Formulation

An alternative equivalent formulation of problem (1)–(3) that is linear is provided as follows:

$$\underset{p_{t,i},\, q_t,\, b_{t,s},\, u_{t,s}}{\text{maximize}} \quad \sum_{t=1}^{T} \left[\sum_{s=1}^{n_t} \lambda_{t,s} \left(b_{t,s} + u_{t,s} q_{t,s}^{\min} \right) - \sum_{i=1}^{m} c_{t,i} \right] \tag{4}$$

$$\text{subject to} \quad p_{t,i} \in \Pi_i, \quad i=1,\ldots,m,\ t=1,\ldots,T \tag{5}$$

$$q_t = \sum_{i=1}^{m} p_{t,i}, \quad t=1,\ldots,T \tag{6}$$

$$q_t = \sum_{s=1}^{n_t} \left(b_{t,s} + u_{t,s} q_{t,s}^{\min} \right), \quad t=1,\ldots,T \tag{7}$$

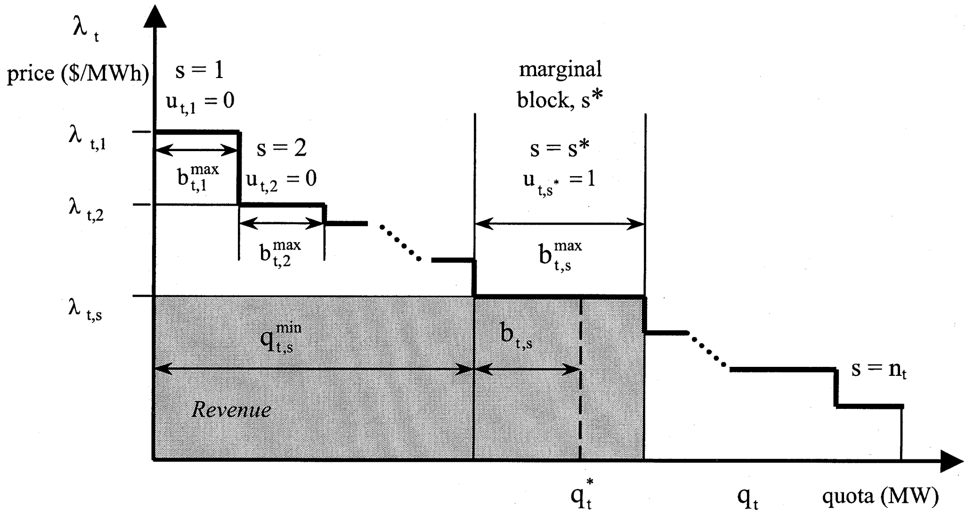

Fig. 2. Price quota curve: illustration of the linear formulation.

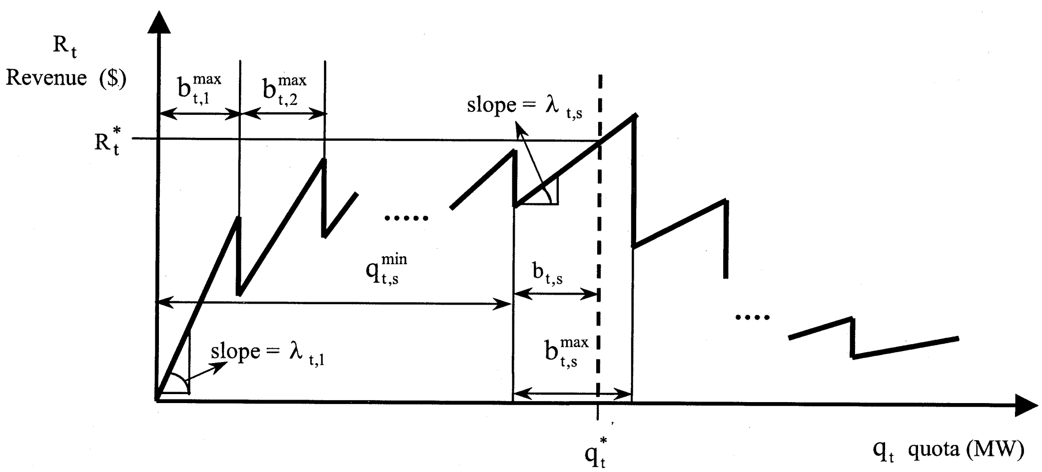

Fig. 3. Revenue versus quota.

$$0 \leq b_{t,s} \leq u_{t,s} b_{t,s}^{\max}, \quad s = 1, \ldots, n_t, \; t = 1, \ldots, T \quad (8)$$

$$\sum_{s=1}^{n_t} u_{t,s} = 1, \quad t = 1, \ldots, T. \quad (9)$$

The objective function (4) expresses the profit of the price maker: total revenue minus total costs. Figs. 2 and 3 illustrate the variables and constants needed to express linearly the price maker revenue as a function of its quota. Taking advantage of the stepwise nature of the price quota curve in every hour, the total revenue is expressed linearly using real variables $b_{t,s}$ and binary variables $u_{t,s}$, as illustrated in Fig. 2. Note that the revenue is the shadowed area in that figure. Fig. 3 also illustrates the above linear formulation. This figure expresses the price maker total revenue as a function of its quota. Observe the nonconvex and discontinuous nature of this function. Quota values that originate discontinuities on revenues do not lead to an ambiguous formulation, because the maximization of the objective function always leads to the highest revenue values.

The sets of constraints (5) and (6) are identical to sets (2) and (3), respectively. The set of constraints (7) expresses linearly the price maker quota in every hour as a function of variables $b_{t,s}$ and $u_{t,s}$, as illustrated in Fig. 2. The block of equations (8) expresses that the megawatt blocks of the price quota curve of every hour are nonnegative values, bounded above. The block of equations (9) states that only one variable $u_{t,s}$ is different from 0 in every hour. Thus, sets of equations (8) and (9) together enforce that only one variable $b_{t,s}$ is different from 0 in every hour. It should be noted that both formulations (1)–(3) and (4)–(9) are fully equivalent, and this allows saying that the linear formulation (4)–(9) is exact

III. Case Study

The considered electricity market includes one price maker producer owning 40 thermal units and different competitive fringe producers comprising 120 thermal units. It should be noted that mixed hydrothermal price makers can be analyzed in a similar way as thermal price makers. The differences among these analyses are simply related to the description of the feasible operating regions of the hydroelectric units. The market time horizon is 24 hours. Data for all units are based on the 1996 IEEE RTS [14] and are detailed in Table I. In this table, Type indicates the unit type (A, B, C, D, E, F, or G); PM/CF indicates the number of units corresponding to the price maker and the competitive fringe producers, respectively; $\overline{P}$ and

TABLE I
GENERATING UNITS DATA

Type	A	B	C	D	E	F	G
PM / CF	6 / 18	6 / 18	6 / 18	6 / 18	6 / 16	6 / 16	4 / 16
$\overline{P}$	12	76	100	155	197	350	400
$\underline{P}$	2.4	15.2	25	54.25	68.95	140	100
$C_1^{(*)}$	23.41	11.46	18.60	9.92	19.20	10.08	5.31
$C_2^{(*)}$	23.76	11.96	20.03	10.25	20.32	10.68	5.38
$C_3^{(*)}$	26.84	13.89	21.67	10.68	21.22	11.09	5.53
$C_4^{(*)}$	30.40	15.97	22.72	11.26	22.13	11.72	5.66
RR[MW/h]	12	76	100	155	180	120	400
SC($)	196	1353	1635	2173	2239	10190	NA$^{(**)}$
MUT (h)	4	8	8	8	12	24	NA$^{(**)}$
MDT (h)	2	4	8	8	10	48	NA$^{(**)}$

$^{(*)}$ Units: [$/MWh]. $^{(**)}$ NA: Not Applicable.

$\underline{P}$ indicate, respectively, the maximum and minimum power output; every C_j value provides the production cost of the block j of the unit (four-block piecewise convex cost curves are considered); RR gives both ramp-up and ramp-down maximum values; SC is the constant start-up cost; and MUT and MDT represent the minimum up and down times, respectively.

Price quota curves for the price maker are obtained simulating the market behavior as stated in [6]. They can also be obtained through forecasting procedures. However, it should be noted that they are exogenous data for the problem addressed in this paper. For the sake of illustration, the price quota curve faced by the price maker in hour 21 is shown in Fig. 1.

For this case study, problem (4)–(9) is solved using CPLEX 7.0 under the General Algebraic Modeling System (GAMS) [15] on an SGI R12000 (400 MHz) processor with 500 MB of RAM. The required CPU time is about 15 min.

Optimal profit for the price maker producer is US $869,122. The production self-schedule for the price maker is illustrated in Figs. 4–6. Fig. 4 provides for the 24-hour time horizon: 1) the price maker hourly production (gigawatts), 2) the hourly total served demand (gigawatts), and 3) the hourly market-clearing price ($ per megawatt hour). The total hourly served demand is obtained after evaluating the optimal self-scheduling of every market participant. It can be observed that the market-clearing price is highly correlated with the served demand. However, that price is not correlated with the price maker production, and this is an indication that market power is being exercised. This lack of correlation can be used as a monitoring variable to assess market power.

Fig. 5 shows the quota of the price maker in percentage with respect to the total served power in every hour, and from Fig. 5 it is apparent that the price maker quota in percentage is higher in off-peak hours than in high-demand hours. This is again an indication that power is withheld in high-demand hours to keep the price high in these hours. This quota variation can also be used as a monitoring variable to appraise market power.

Fig. 6 provides specific information on the manner in which the price maker exercises its market power. The upper and lower solid plots represent the power range for which the price does not change. The $\times$ plot provides the price maker production in the marginal block of the price quota curve, i.e., the last block of this curve used by the price maker. Fig. 6 shows that, for some hours, (mostly high-demand ones) the marginal production (the

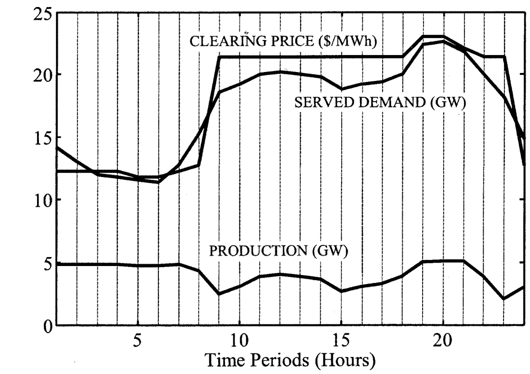

Fig. 4. Price maker production, served demand, and market-clearing price.

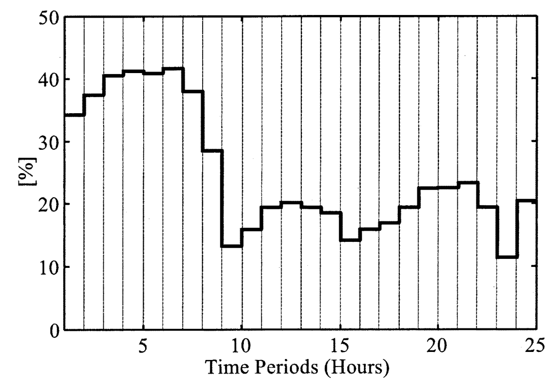

Fig. 5. Percentage of served power assigned to the price maker.

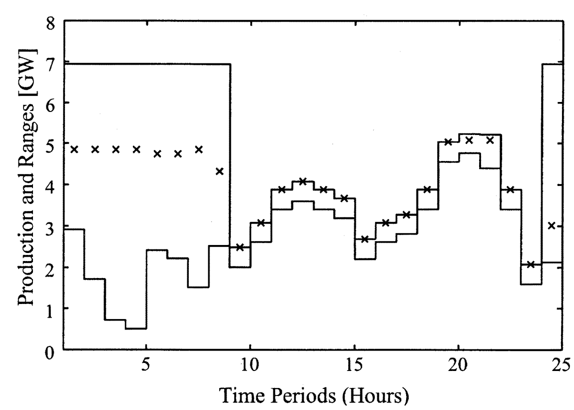

Fig. 6. Range of constant optimal price and price maker production.

production in the marginal block) of the price maker is in the upper limit of the range for the final price. This may mean that the price maker is withholding its production in those hours not to force the price down, and this is again a clear indication that the price maker is exercising its market power. Fig. 6 can be used as a monitoring tool to assess the exercise of market power.

On the other hand, during other hours, (i.e., hours 1–8, 21, 22, and 24) the optimal production is located somewhere between the lower limit and the upper limit that preserve the market-clearing price. There are three different reasons for that. In hour 8, this is so to meet the ramp-down constraint that becomes active between hours 8 and 9; it should be noted that the total production of the price maker begins to decrease in hour 8, when the demand rises. Secondly, in hour 24, the reason is to meet the ramp-up limit between hours 23 and 24. Finally, in hours 1–7, 21, and 22, the reason is that a relevant change in the price maker marginal cost occurs within the range of constant optimal price; note that hours 1–7 present a very wide range of constant optimal price. For example, in hour 4, the optimal price is US \$12.3/MWh, but the price maker only owns 4.858 GW of power cheaper than that price (see Table I); therefore, the price maker is only willing to offer that amount, because, if it offers more than 4.858 GW, its profit decreases.

IV. Conclusion

This paper provides a mixed-integer LP formulation for the self-scheduling problem faced by a price maker in a pool-based electricity market. This formulation is exact in the sense that it is equivalent to a "natural" nonlinear formulation of the problem. This linear formulation allows an efficient solution using a standard branch-and-cut solver. Extensive computational analyses based on realistic price makers in realistic markets have shown the appropriate functioning of the proposed formulation.

Appendix

The running cost of a thermal unit and its technical constraints are described in this Appendix. The running cost $c_{t,i}$ is expressed as

$$c_{t,i} = A_i v_{t,i} + vc_{t,i} + UC_i y_{t,i} + DC_i z_{t,i} \quad i=1,\ldots,m, \quad t=1,\ldots,T \tag{A1}$$

where A_i represents the fixed cost of unit i; $vc_{t,i}$ is the piecewise linear variable cost of unit i in hour t; UC_i denotes the startup cost of unit i; DC_i is the shutdown cost of unit i; $v_{t,i}$ is a 0/1 variable that is equal to 1 if unit i is online in period t; $y_{t,i}$ denotes the 0/1 variable that is equal to 1 if unit i is started up at the beginning of period t; and $z_{t,i}$ is the 0/1 variable that is equal to 1 if unit i is shutdown at the beginning of period t. Equations (A1) express the running cost of unit i in period t as the sum of a fixed term, different from zero if the unit is online, plus the variable cost, the startup cost, and the shutdown cost.

The piecewise linear variable cost $vc_{t,i}$ is formulated as

$$vc_{t,i} = \sum_{n=1}^{N} F_n(i) b_n(i,t), \quad i=1,\ldots,m, t=1,\ldots,T \tag{A2}$$

$$p_{t,i} = \underline{P}_i v_{t,i} + \sum_{n=1}^{N} b_n(i,t), \quad i=1,\ldots,m, t=1,\ldots,T \tag{A3}$$

$$0 \le b_n(i,t) \le \bar{b}_n(i), \quad n=1,\ldots,N \quad i=1,\ldots,m, t=1,\ldots,T \tag{A4}$$

where N is the number of blocks of the piecewise linear variable cost function; $b_n(i,t)$ represents the power produced by unit i in period t using the nth power block; $\bar{b}_n(i)$ is the size of the nth power block of unit i; $\underline{P}_i$ is the minimum power output of unit i; and $F_n(i)$ denotes the slope of block n of the variable cost of unit i.

Constraints (A2) express the variable cost of unit i in period t as the sum of the corresponding terms of the piecewise linearization. Constraints (A3) state that the power output of unit i in period t is the sum of the power generated using each block plus the minimum power output. Constraints (A4) set the limits of the power generated in each block. This power should be greater than zero and less than the size (in megawatts) of each block. This formulation assumes that the cost is monotonically increasing. Nonconvex costs can be easily modeled by using additional binary variables [12].

The feasible operating region Π_i is formulated through the following linear constraints, which are further described in [12]:

$$p_{t,i} \ge \underline{P}_i v_{t,i}, \quad i=1,\ldots,m, t=1,\ldots,T \tag{A5}$$

$$p_{t,i} \le \bar{P}_i (v_{t,i} - z_{t+1,i}) + z_{t+1,i}\mathrm{SD}_i, \quad i=1,\ldots,m, \quad t=1,\ldots,T \tag{A6}$$

$$p_{t,i} \le p_{t-1,i} + \mathrm{RU}_i v_{t-1,i} + \mathrm{SU}_i y_{t,i}, \quad i=1,\ldots,m, \quad t=1,\ldots,T \tag{A7}$$

$$p_{t-1,i} - p_{t,i} \le \mathrm{RD}_i v_{t,i} + \mathrm{SD}_i z_{t,i}, \quad i=1,\ldots,m, \quad t=1,\ldots,T \tag{A8}$$

$$\sum_{t=1}^{G_i} (1 - v_{t,i}) = 0, \quad i=1,\ldots,m \tag{A9}$$

$$\sum_{\ell=t}^{t+\mathrm{UT}_i-1} v_{\ell,i} \ge \mathrm{UT}_i y_{t,i}, \quad i=1,\ldots,m, \quad t=G_i+1\ldots T-\mathrm{UT}_i+1 \tag{A10}$$

$$\sum_{\ell=t}^{T} (v_{\ell,i} - y_{t,i}) \ge 0, \quad i=1,\ldots,m, \quad t=T-\mathrm{UT}_i+2,\ldots,T \tag{A11}$$

$$\sum_{t=1}^{F_i} v_{t,i} = 0, \quad i=1,\ldots,m \tag{A12}$$

$$\sum_{\ell=t}^{t+\mathrm{DT}_i-1} (1 - v_{\ell,i}) \ge \mathrm{DT}_i z_{t,i}, \quad i=1,\ldots,m, \quad t=F_i+1,\ldots,T-\mathrm{DT}_i+1 \tag{A13}$$

$$\sum_{\ell=t}^{T} (1 - v_{\ell,i} - z_{t,i}) \ge 0, \quad i=1,\ldots,m, \quad t=T-\mathrm{DT}_i+2,\ldots,T \tag{A14}$$

$$y_{t,i} - z_{t,i} = v_{t,i} - v_{t-1,i}, \quad i=1,\ldots,m, t=1,\ldots,T \tag{A15}$$

$$y_{t,i} + z_{t,i} \le 1, \quad i=1,\ldots,m, t=1,\ldots,T. \tag{A16}$$

where

$$G_i = \min\left[T, \left(\mathrm{UT}_i - U_i^0\right) v_{0,i}\right]; \tag{A17}$$

$$F_i = \min\left[T, (\mathrm{DT}_i - S_{0,i})(1 - v_{0,i})\right]. \tag{A18}$$

In the expressions above, $\bar{P}_i$ is the capacity of unit i; SD_i is the shutdown ramp limit of unit i; RU_i represents the ramp-up limit of unit i; SU_i is the startup ramp limit of unit i; RD_i is the ramp-down limit of unit i; UT_i is the minimum up time of unit i; DT_i is the minimum down time of unit i; U_i^0 expresses the time periods unit i has been online at the beginning of the market horizon (end of period 0); $v_{0,i}$ provides the initial commitment status of unit i (1 if it is online, 0 otherwise); and $S_{0,i}$ represents the time periods unit i has been offline at the beginning of the market horizon (end of period 0). For unit consistency, it should be noted that time periods of one hour are considered.

Constraints (A5) and (A6) set the lower and upper limits of the power output, respectively. The upper limit is restricted by the maximum capacity of the unit in normal operation and by the shutdown ramp rate if the unit is shutdown in the next period. It should be noted that the power output becomes zero if the unit is offline, i.e., if binary variable $v_{t,i}$ is equal to zero.

The set of constraints (A7) imposes the ramp-up rate limit as well as the startup ramp rate limit. Analogously, ramp-down and shutdown ramp rate limits are enforced by constraints (A8).

Equations (A9)–(A11) represent the linear expressions of minimum up-time constraints. The set of equations (A9) is related to the initial status of the units. G_i is the number of initial periods during which unit i must be online to meet the minimum up-time requirement. If unit i does not declare any initial status, G_i is assumed to be equal to zero. The set of equations (A10) is used for the periods following G_i, and it ensures the satisfaction of the minimum up-time constraint during all the possible sets of consecutive periods of size UT_i. Finally, the set of equations (A11) is needed for the last $\mathrm{UT}_i - 1$ periods, i.e., if a unit is started up in one of these periods, it remains online during the remaining periods. Similarly, (A12)–(A14) provide the formulation of the minimum down-time constraints. Equations (A12)–(A14) are identical to (A9)–(A11) just by changing $v_{t,i}$, $z_{t,i}$, DT_i, and $S_{0,i}$ by $(1 - v_{t,i})$, $y_{t,i}$, UT_i, and U_i^0, respectively.

Finally, constraints (A15) and (A16) are necessary to model the startup and shutdown status of the units and to avoid the simultaneous commitment and decommitment of a unit [13].

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