

Optimal Thermal and Virtual Power Plants Operation in the Day-ahead Electricity Market

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This work was supported by the Ministerio de Educación y Ciencia of Spain under Project
DPI2005-09117-C02-01

May 29, 2008

Introduction and motivation

- ▶ The new rules of the Iberic electrical energy production market operation (June 2008) bring new challenges in the modeling and solution of the production market operation.
- ▶ The Royal Decree 1634/2006 imposes to Endesa and Iberdrola to hold a series of five auctions offering virtual power plant (VPP) capacity to any party who is a member of the MIBEL.
- ▶ This work develops an stochastic programming model for a Generation Company (GenCo) to find the optimal management of a VPP in the day-ahead market under the most recent bilateral contracts regulation rules of Iberic energy market.

Introduction and motivation

- ▶ The VPP capacity means that the buyer of this product will have the capacity to generate MWh at his disposal.
- ▶ The buyer can exercise the right to produce against an exercise price that is set in advance, by paying an option premium.
- ▶ The energy resulting from the exercise of the VPP options can be used by buyers both:
 - ▶ To contribute to the covering of the national and international bilateral contracts prior to the day-ahead market; or
 - ▶ To sell it to the day-ahead market.
- ▶ In this last case, the unmatched VPP energy, if any, can be sold through national bilateral contracts after the day-ahead market.

Introduction and motivation

- ▶ The model allows a price-taker generation company to decide
 - ▶ The unit commitment of its thermal units;
 - ▶ The economic dispatch of the bilateral contracts between the thermal and generic programming units; and
 - ▶ The optimal bid for both thermal and generic programming units, observing the Iberic peninsular regulation.
- ▶ Maximizing the expected profit from its involvement in the spot market, bilateral contracts and virtual power plan capacity.

Optimization model

- ▶ Consider a GenCo with a set of \mathcal{T} thermal generation units (coal, nuclear, fuel, gas, combined cycle) and a generic programming unit (GPU).
- ▶ The GPU is the unit that management the VPP options, and can be integrated into the energy production system.
- ▶ Assume that the GenCo has agreed to physically provide the energy amounts L_{ij}^B at hour $i \in \mathcal{I} = \{1, 2, \dots, 24\}$ of day D for each one of the $j \in \mathcal{B}$ *bilateral contracts*.
- ▶ This energy L_{ij}^B can be provided both by the real thermal units \mathcal{T} and the GPU, that is:

$$\sum_{t \in \mathcal{T}} b_{itj}^T + b_{ij}^G = L_{ij}^B \quad j \in \mathcal{B}, i \in \mathcal{I} \quad (1)$$

The spot price

- ▶ The spot price λ_i^D is a stochastic variable with the characteristics of a financial time series.
- ▶ This random variable is discretized on a fan of scenarios $\lambda^{D,s}$ with probabilities $P^s = P(\lambda^{D,s})$ for all scenarios $s \in \mathcal{S}$.
- ▶ The spot market has been characterized by an auto-regressive integrated moving average model ARIMA.
- ▶ Once the model has been fitted, there has been done many simulations of it in order to obtain many possible scenarios of prices.
- ▶ Finally the set of scenarios has been reduced preserving at maximum the characteristics of the simulated tree.

Modellization of the thermal units

- ▶ Regarding the thermal unit t , the model proposed performs three basic decisions for each hourly auction $i \in \mathcal{I}$:
 - ▶ Its commitment (binary variable u_{it});
 - ▶ The energy assigned to each bilateral contract ($b_{it}^T = \sum_{j \in \mathcal{B}} b_{itj}^T$);
 - ▶ The optimal selling bid.
- ▶ Under the price-taker assumption and MIBEL rules, the matched energy at scenario s resulting from the clearing of the day-ahead market can be expressed as:

$$p_{it}^{T,s}(b_{it}^T, \lambda_i^{D,s}) = \begin{cases} p_{it}^{D,s} - b_{it}^T & \text{if } b_{it}^T \leq p_{it}^{D,s} \\ 0 & \text{if } b_{it}^T > p_{it}^{D,s} \end{cases} \quad \begin{array}{l} \forall i \in \mathcal{I} \\ \forall t \in \mathcal{T} \\ \forall s \in \mathcal{S} \end{array} \quad (2)$$

where $p_{it}^{D,s}$ is a constant that depends on the characteristics of the thermal unit and the spot price at scenario s , $\lambda_i^{D,s}$.

Modellization of the thermal units

- ▶ The non-differentiable expression (2) can be incorporated into the optimization model through an equivalent set of mixed-linear constraints.

$$\left. \begin{aligned} p_{it}^{T,S} &= p_{it}^{D,S} u_{it} + v_{it}^S - b_{it}^T \\ p_{it}^{D,S} (z_{it}^S + u_{it} - 1) &\leq b_{it}^T \\ b_{it}^T &\leq p_{it}^{D,S} (1 - z_{it}^S) + \bar{p}_t (z_{it}^S + u_{it} - 1) \\ 0 \leq p_{it}^{T,S} &\leq p_{it}^{D,S} (1 - z_{it}^S) \leq p_{it}^{D,S} u_{it} \\ 0 \leq v_{it}^S &\leq (\bar{p}_t - p_{it}^{D,S}) (z_{it}^S + u_{it} - 1) \\ p_{it}^S &= p_{it}^{T,S} + b_{it}^T \\ b_{it}^T &\in [0, \bar{p}_t] \\ z_{it}^S &\in \{0, 1\} \end{aligned} \right\} \begin{array}{l} \forall i \in \mathcal{I} \\ \forall t \in \mathcal{T} \\ \forall s \in \mathcal{S} \end{array} \quad (3)$$

Modellization of the thermal units

- ▶ The Eq. (4) are used to formulate the minimum up and down times for thermal unit t .

$$\left. \begin{aligned} u_{it} - u_{(i-1)t} - e_{it} + a_{it} &= 0 & \text{(a)} \\ a_{it} + \sum_{j=i}^{\min\{i+t_t^{\text{off}}, |\mathcal{I}|\}} e_{jt} &\leq 1 & \text{(b)} \\ e_{it} + \sum_{j=i+1}^{\min\{i+t_t^{\text{on}}, |\mathcal{I}|\}} a_{jt} &\leq 1 & \text{(c)} \\ u_{it}, a_{it}, e_{it} &\in \{0, 1\} \cap \mathcal{U}^T \end{aligned} \right\} \begin{array}{l} \forall i \in \mathcal{I} \\ \forall t \in \mathcal{T} \end{array} \quad (4)$$

- ▶ where \mathcal{U}^T is the initial feasible set of those variables.

Modellization of the generic programming unit

- ▶ Through the GU the GenCo has at its disposal up to \bar{p}^V MWh of capacity at a price λ^V , and also the possibility of buying and selling energy from the pool.
- ▶ The optimal decisions involving the management of the GPU are, for each hourly auction of the day-ahead market,
 - ▶ The "generation" of the VPP (p_i^V),
 - ▶ The energy $b_i^G = \sum_{j \in \mathcal{B}} b_{ij}^G$ to be allocated to bilateral contracts,
 - ▶ The optimal selling and buying bid to the pool, which depends on the scenario.
- ▶ Once again, under the price-taker assumption the optimal selling and buying bid functions for the GU can be developed and used to derive the expressions of the *matched sold* ($p_i^{S,S}$) and *matched bought* ($p_i^{B,S}$) energy at each scenario $s \in \mathcal{S}$.

Modellization of the generic programming unit

$$p_i^{S,S}(b_i^G, p_i^V) = \begin{cases} [p_i^V - b_i^G]^+ & \text{if } s \in \mathcal{M}_i^S \\ 0 & \text{if } s \notin \mathcal{M}_i^S \end{cases} \quad \forall i \in \mathcal{I}$$
$$p_i^{B,S}(b_i^G, p_i^V) = \begin{cases} \min\{b_i^G, \bar{p}^V - p_i^V\} & \text{if } s \in \mathcal{M}_i^B \\ 0 & \text{if } s \notin \mathcal{M}_i^B \end{cases} \quad \forall s \in \mathcal{S}$$

- ▶ In case the energy b_i^G exceeds the maximum VPP capacity \bar{p}^V a mandatory accepting-price buying bid $p_i^{R,S}$ must be placed:

$$p_i^{R,S}(b_i^G) = \begin{cases} [b_i^G - \bar{p}^V]^+ & \text{if } s \in \mathcal{M}_i^B \\ 0 & \text{if } s \notin \mathcal{M}_i^B \end{cases} \quad \forall i \in \mathcal{I}$$
$$\quad \forall s \in \mathcal{S}$$

- ▶ These non-differentiable expressions can be formulated through an equivalent set of mixed-linear constraints.

- ▶ Additionally, any GU operating in the MIBEL must satisfy at each hour $i \in \mathcal{I}$ that the net energy balance of the GU must be zero, with the help, if necessary, of the so called *bilateral contracts after de day-ahead market*.

$$p_i^V + p_i^{B,S} + p_i^{R,S} + b_i^{B,S} = p_i^{S,S} + b_i^{S,S} + b_i^G \quad \forall s \in \mathcal{S}, \forall i \in \mathcal{I}$$

- ▶ The objective of the producer is to maximize the expected profit from its involvement in the spot market, bilateral contracts and virtual power plan capacity.
- ▶ The model corresponds to a mixed quadratic two-stage stochastic programming problem.

Case study

- ▶ The model was solved with real data of a Spanish generation company and market prices.
 - ▶ 25 Day-ahead market price scenarios;
 - ▶ 24 hours of study;
 - ▶ 10 thermal units;
 - ▶ 2 bilateral contracts;
- ▶ The model was tested for three different cases:
 - (a) A GenCo without GPU;
 - (b) A GenCo with GPU but without VPP capacity; and
 - (c) A GenCo with GPU and VPP capacity.
- ▶ The model has been implemented and solved with AMPL/CPLEX 11.
- ▶ The CPU time using a Dell Optiplex 745 with two processors at 2.13 GHz and 2 Gb of RAM memory is approximately 200 s.

- ▶ The mathematical characteristics of the model.

| Case | Constraints | Real variables | Binary variables |
|------|-------------|----------------|------------------|
| (a) | 41464 | 17340 | 6720 |
| (b) | 45064 | 17988 | 7344 |
| (c) | 48088 | 18636 | 7368 |

- ▶ The expected profit values for all study cases

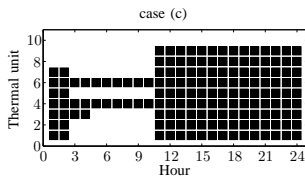
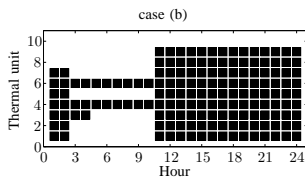
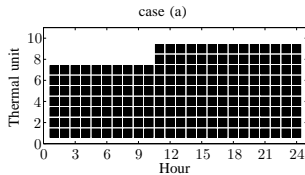
| Case (a) | Case (b) | Case (c) |
|--------------|--------------|----------------|
| 617.624,95 € | 692.587,52 € | 1.005.643,91 € |

Case study

- ▶ The results show that the worse profit is obtained with case (a), where the thermal units are responsible to cover bilateral contracts, losing an opportunity to obtain a greater profit selling its energy to the day-ahead market.
- ▶ Case (b) obtains a greater profit than case (a), due to the possibility of being able to buy cheaper energy in the day-ahead market to cover the bilateral contracts and to avoid the use of expensive thermal units.
- ▶ The greater profit is obtained in the case (c) where the VPP capacity is used to sell in the day-ahead market and to cover part of the bilateral contracts, using the same advantages of the case (b).

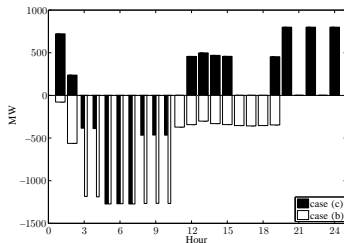
Case study

- ▶ Unit commitment of the thermal units for all study cases.

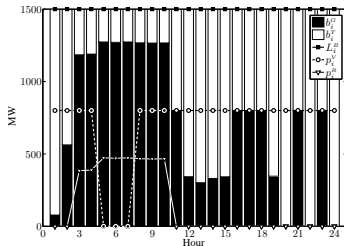


Case study

Sold and bought optimal bid of the GPU for the study cases B and C.



Operation planning for study case (c).



Conclusions

- ▶ The main contributions of this paper are:
 - ▶ A new model for the optimal thermal bid function and matched energy who takes into account the presence of bilateral contracts.
 - ▶ The mathematical modellization of the generic programming units and the Virtual Power Plants.
 - ▶ The modellization of the optimal bid functions and matched energy of the GPU.
 - ▶ The inclusion in the optimization model of the bilateral contracts after the day-ahead market.
 - ▶ The consideration of the most recent regulations of the MIBEL energy market.

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