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

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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 managment 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^B_{ij} at hour $i \in \mathcal{I} = \{1, 2, \ldots, 24\}$ of day D for each one of the $j \in \mathcal{B}$ *bilateral contracts*.
- This energy L^B_{ij} can be provided both by the real thermal units $\mathcal{T}$ and the GPU, that is:

$$\sum_{t \in \mathcal{T}} b^T_{itj} + b^G_{ij} = L^B_{ij} \quad j \in \mathcal{B}\,,\ i \in \mathcal{I} \tag{1}$$

The spot price

- The spot price λ_i^D is an 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 ($b^T_{it} = \sum_{j \in \mathcal{B}} b^T_{itj}$);
  - 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:

$$p^{T,s}_{it}(b^T_{it}, \lambda^{D,s}_i) = \begin{cases} p^{D,s}_{it} - b^T_{it} & \text{if } b^T_{it} \leq p^{D,s}_{it} \\ 0 & \text{if } b^T_{it} > p^{D,s}_{it} \end{cases} \quad \begin{matrix} \forall i \in \mathcal{I} \\ \forall t \in \mathcal{T} \\ \forall s \in \mathcal{S} \end{matrix} \qquad (2)$$

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

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.

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

Modellization of the thermal units

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

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

- 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 $\overline{p}^V$ 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

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

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

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

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

Final model

- 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*.

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

- 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.

Case study

- 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

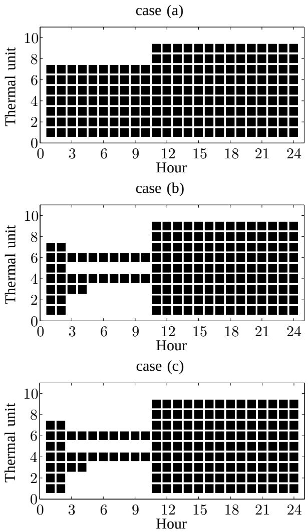
Case (a)	Case (b)	Case (c)
617.624,95 €	692.587,52 €	1.005.643,91 €

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).

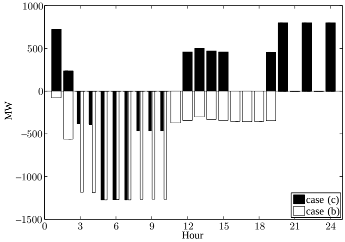
Case study

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

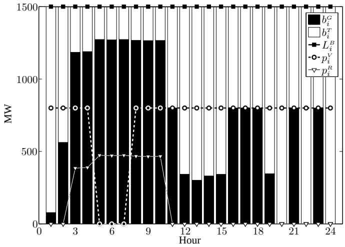


Case study

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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