Optimization of the Spanish Market Sequence by a Price-Taker Generating Firm

A. Franco, E. Lobato, L. Rouco, *Member IEEE*, A. Ugedo, J. Fernández-Caro, J. de-Benito, J. Chofre
and J. De-la-Hoz

***Abstract*—The Spanish electricity business, deregulated since January 1st 1998, has been organized in two different types of markets: (a) the energy markets (which include the day-ahead electricity market and 6 intradaily markets) and (b) the ancillary services markets (comprising the secondary and tertiary reserve markets and the deviation management markets). A generating firm must decide the generation resources to be distributed within each of the mentioned markets. This paper proposes a stochastic optimization model that decides the amount of resources to be distributed by a price-taker generating firm in each market of the generation business. The objective function maximizes the agent expected total profit. In addition, the model obtains the bid curves of the firm to be submitted to the hourly periods of each market. A case study illustrates the performance of the model proposed.**

***Index Terms*—generation scheduling, competitive electricity market, bidding strategies.**

I. NOTATION

The following symbols are used throughout the paper:

A. Sets

g : generator

h : hour

$scmd$: scenario of daily energy market

$scsr$: scenario of secondary reserve market

$scim_j$: scenario of intradaily market j

B. Parameters

$p_{h,scdm}^{DM}$: price of scenario $scmd$ of the daily market at hour h

$\rho_{h,scdm}^{DM}$: probability of scenario $scmd$ of the daily market at hour h

$\mathrm{E}[p_h^{DM}]$: expected price of the daily energy market of hour h

$p_{h,scsr}^{SR}$: price of scenario $scsr$ of the secondary reserve market at hour h

$p_{h,scim_i}^{IM_i}$: price of scenario $scim_i$ of the intradaily market i at hour h

$Q_{g,h}^{BIL}$: energy contracted with bilateral agreements by generator g in hour h

$P_{g,h}^{max}$: maximum output of generator g in hour h

$P_{g,h}^{min}$: minimum output of generator g in hour h

$\delta_{g,h}$: binary status of generator g in hour h

C. Variables

$Q_{g,h,scdm,scim1,scim2,scim2,scim3,scim4,scim5,scim6}$: final program of generator g in every hour h for the set of price scenarios available for each kind of market

$Q_{g,h,scdm}^{DM}$: energy offered by generator g in hour h of the daily market for scenario $scdm$

$Q_{g,h,scim_i}^{IM_i}$: energy sold by generator g in hour h of intradaily market i for scenario $scim_i$

$D_{g,h,scim_i}^{IM_i}$: energy that generator g offers to buy in hour h of intradaily market i for scenario $scim_i$

$UR_{g,h,scsr}$: up reserve band of generator g at scenario $scsr$ in hour h in the secondary reserve market

$DR_{g,h,scsr}$: down reserve band of generator g at scenario $scsr$ in hour h in the secondary reserve market

$\mathrm{E}[Q_{g,h}^{DM}]$: expected energy offered by generator g in hour h of the daily energy market

$\mathrm{E}[Q_{g,h}]$: expected energy produced by generator g in hour h

II. INTRODUCTION

The Spanish electricity business was deregulated in January 1st 1998. This new deregulated framework has been organized in two different kinds of markets [1]: (a) energy markets (which include the day ahead electricity market and 6 intradaily markets) and (b) ancillary services markets (comprising the secondary and tertiary reserve markets and the deviation management markets). The whole business is managed by two separate entities: the Market Operator (MO) and the System Operator (SO). The MO is on charge of clearing the energy markets, which activity rules are based exclusively on economic criteria. The SO is on charge of guaranteeing a feasible and secure operation of the power system. Thus, the SO is on charge of the management of the technical constraints and the ancillary services markets.

The Spanish electricity business has been organized in 24

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A. Franco (e-mail: afrancou@endesa.es) is currently with Carboex, S.L.U. (Endesa). C/Manuel Cortina 2, Planta 2.

E. Lobato (e-mail: Enrique.Lobato@iit.upco.es), L. Rouco and A. Ugedo are with the School of Engineering of Universidad Pontificia Comillas, C/Alberto Aguilera, 23, 28015 Madrid, Spain.

J. Fernández-Caro, J. de-Benito, J. Chofre and J. De-la-Hoz are with Viesgo, S. L., C/Orense 11, 8ª planta, Madrid.

independent hourly scenarios for each day D. The daily energy market is the first one within the market sequence. It is cleared at 11:00 hour of the day before the day of analysis (day D-1) and covers the 24 hours of day D. Once the daily market has been cleared by the MO, the SO performs the technical constraint analysis, modifying the generation dispatch in order to guarantee a secure operation of the power system [2,3].

The secondary reserve market is performed once a day after the daily market and the technical constraint management, where the generating units sell the up and down band necessary to maintain the scheduled values of the system frequency and the interarea interchanges. The SO determines and publishes the system requirements of up and down band, receives the reserve bids and clears the secondary reserve market for the 24 hours of day D. For each agent, the ratio of up/down band cleared with all its units at each hour must equal the ratio of necessity of up/down declared by the SO.

Intradaily energy markets have been designed to ensure whatever adjustments may be necessary to obtain a feasible schedule of each market agent. They are called 6 times per day, each one covering a different time horizon.

Tertiary reserve markets are intended to reestablish the secondary reserve in use. Tertiary energy has been defined as the maximum energy increase and decrease that a generating unit can provide in a time interval of 15 minutes and can be maintained during at least 2 hours. The tertiary reserve market is only called and cleared if the available secondary reserve has been exhausted.

Finally, deviation management markets are only carried out if the SO predicts a significant positive or negative energy deviation between generation and demand for the following hours not covered by the next intradaily market. The deviation management market is convoked and cleared by the SO, who communicates the predicted deviations to the market agents.

TABLE 1 summarizes the market sequence of the Spanish electricity business and provides the time horizon covered by the energy markets managed by the MO and the ancillary services markets managed by the SO.

TABLE 1

TIME HORIZON OF THE MARKET SEQUENCE OF THE SPANISH ELECTRICITY BUSINESS

MARKET	ENTITY	CLEARING TIME	TIME HORIZON COVERED
Daily energy market	MO	11:00 hour day D-1	Hour 1 day D -> Hour 24 day D
Secondary reserve market	SO	16:00 hour day D-1	Hour 1 day D -> Hour 24 day D
Intradaily market 1	MO	19:35 hour day D-1	Hour 21 day D-1 -> Hour 24 day D
Intradaily market 2	MO	23:20 hour day D-1	Hour 1 day D -> Hour 24 day D
Intradaily market 3	MO	3:20 hour day D	Hour 5 day D -> Hour 24 day D
Intradaily market 4	MO	6:20 hour day D	Hour 10 day D -> Hour 24 day D
Intradaily market 5	MO	10:20 hour day D	Hour 12 day D -> Hour 24 day D
Intradaily market 6	MO	14:20 hour day D	Hour 16 day D -> Hour 24 day D
Tertiary reserve market	SO	X	Hour 1 day D -> Hour 24 day D
Deviation management market	SO	X	Hour 1 day D -> Hour 24 day D

In the new deregulated framework, market agents compete to sell their generation resources provided by their units. The bid curves submitted to each market are built in order to maximize the total expected profit of the agent. A bid curve consists of a set of non-decreasing quantity-price blocks for each hour covered by the target market.

Most strategic bidding approaches have been designed to optimize an agent's bid curve taking into account only the daily energy market [4-7]. In [8], an optimization tool has been developed to obtain independent optimal bidding curves for each energy and ancillary services markets in Spain. However, it builds independent curves for each market, ignoring the market sequence. A conceptual approach to optimize the market sequence has been explored in [9], but has not been applied in practice to the complete market sequence.

This paper proposes an optimization model that distributes the electric resources of a generating firm within the energy markets and the ancillary services markets. The model assumes that the generating firm acts as a price-taker in each one of the markets, taking as input data the technical and economic characteristics of the generating equipment (thermal, hydro and pumping units), the price forecasts for each market, and a set of strategic parameters selected by the generating firm. In addition, the model obtains the hourly energy-price bid curves for the energy, intradaily, tertiary and deviation management markets, and the hourly power-price up and down band bid curves for the secondary reserve market.

The paper is organized as follows. Section III overviews the model proposed in the paper. Section IV describes the objective function and the constraints governing the model. The performance of the tool is illustrated with a case study in section V. Implementation details are given in section VI. Finally, conclusions are presented in Section VII.

III. MODEL STRUCTURE

A. General Overview

The optimization model proposed in this paper distributes the electric resources of a generating firm in order to maximize its expected total profit taking into account all the energy and ancillary services markets in the Spanish electricity business. The model assumes that the generating firm acts as a price taker in each market and that a set of price-probability pairs for every hour of each market is provided as input data. In addition, it builds the bid curve that the agent submits for every hourly period covered by each market. It should be noted that the same optimization model is applied to all the described markets (except the tertiary and deviation management markets).

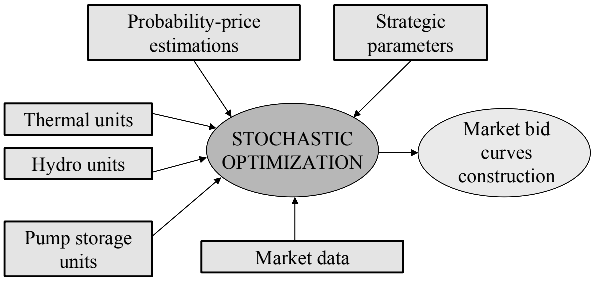

Fig 1. Structure of the proposed stochastic optimization model.

Fig 1 depicts the structure of the proposed model. Taking as input the technical and economic data of the thermal, hydro and pumping equipment of the generating firm, the set of probability-price estimations for the present and subsequent markets, the market results of the previously cleared markets and a number of strategic parameters of the firm, a stochastic optimization program is built to obtain the set of quantities that the agent offers at each estimated price in the hourly periods of the current market. The set of price-quantity pairs are joined to obtain the final bid curve that the agent submits for each hour of the present market.

B. Stochastic optimization

The stochastic optimization tree proposed in [4] has been extended to include the whole sequence of energy and ancillary services markets in the Spanish electricity business. Fig 2 depicts the structure of the tree, assuming that in each hour of each market three price scenarios are provided. The tree starts with the three price scenarios of the first hour of the daily market. The scenarios of the secondary reserve market are joined from the terminal leaves obtained in the last hour of the daily market (hour 24). Finally the intradaily hourly market scenarios are assembled sequentially, ending the tree with the scenarios for hour 24 of the sixth intradaily market.

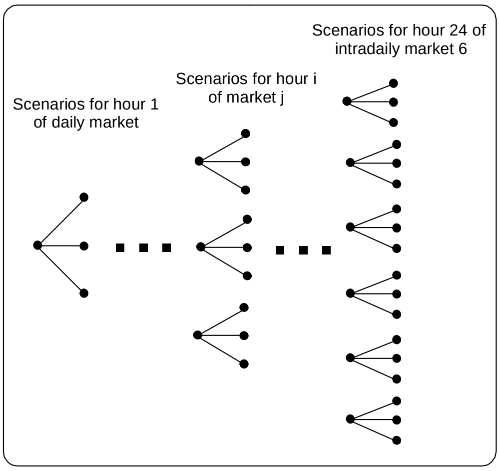

Fig 2. Structure of the tree of the stochastic optimization problem

Fig 3 shows the components of the stochastic optimization tree for the first two hours of the daily market. Each node represents the price $p^{DM}_{h,scdm}$ of scenario $scmd$ in hour h of the daily market, with its corresponding probability $\rho^{DM}_{h,scdm}$ (both are parameters). The decision variable at each node is the quantity of energy that a generator (for instance a thermal generator g) will submit $Q^{DM}_{g,h,scdm}$ at the node price. A path that goes from the starting node to an end node represents a feasible trajectory. Time related constraints will be applied to trajectories, while non time-related constraints will only include variables of a single node.

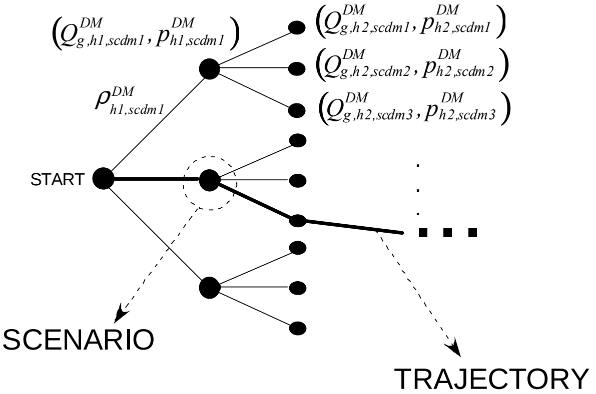

Fig 3. Decision variables and parameters at each node of the stochastic tree

The expected trajectory is built joining expected values of the price estimations of the hourly periods in each market. The expected energy output of each generator represents the decision variables of the nodes in the expected trajectory. Strategic time-related decision constraints are applied not to every feasible trajectory, but only to the expected trajectory.

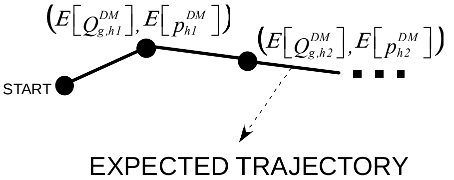

Fig 4. Expected trajectory of the stochastic tree

C. Performance modes

Eight different performance modes have been defined in the model:

- Daily mode: obtains the bid curves of the agent for each hour of the following day in the daily energy market.
- Secondary reserve mode: obtains the up and down band bid curves of the agent for each hour of the following day in the secondary reserve market.
- Intradaily mode 1 …. Intradaily mode 6: obtains the energy bid curves that the agent wants to sell and buy, for each hour covered in each intradaily market.

Lets consider the energy balance of a firm's generator g :

$$\begin{gathered}Q_{g,h,scdm,scim1,scim2,scim2,scim3,scim4,scim5,scim6} = \\ Q^{DM}_{g,h,scdm} + \\ (Q^{IM1}_{g,h,scim1} - D^{IM1}_{g,h,scim1}) + (Q^{IM2}_{g,h,scim2} - D^{IM2}_{g,h,scim2}) + \\ (Q^{IM3}_{g,h,scim3} - D^{IM3}_{g,h,scim3}) + (Q^{IM4}_{g,h,scim4} - D^{IM4}_{g,h,scim4}) + \\ (Q^{IM5}_{g,h,scim5} - D^{IM5}_{g,h,scim5}) + (Q^{IM6}_{g,h,scim6} - D^{IM6}_{g,h,scim6}) + \\ +Q^{BIL}_{g,h}\end{gathered} \tag{1}$$

$$0 \le UR_{g,h,scbs} \le P^{max}_{g,h} \cdot \delta_{g,h} - \mathrm{E}[Q_{g,h}] \tag{2}$$

$$0 \le DR_{g,h,scbs} \le \mathrm{E}[Q_{g,h}] - P^{min}_{g,h} \cdot \delta_{g,h} \tag{3}$$

The energy balance equation defined in (1) yields that the final program of generator g in every hour h for the set of price scenarios available for each kind of market is the sum of the energy sold in the daily market, the energy sold and bought in the 6 intradaily markets and the energy contracted with bilateral agreements. Equations (2) and (3) impose that the quantity of up and down band that generator g bids in each hour h at the price of scenario $scbs$ of the secondary reserve market can be obtained with the final expected program and the maximum and minimum generation limits of the unit.

For the daily mode, all of the terms in (1) are decision variables, and the bid curve of g for each hour is built from the pairs price-quantity $\left(Q^{DM}_{g,h,scdm}, p^{DM}_{h,scdm}\right)$ that result in the optimization problem.

In the secondary reserve mode, the daily energy market has already taken place already. Hence, the energy $Q^{DM}_{g,h,scdm}$ becomes a parameter equal to the generator market clearing in the daily market. The up/down band bid curve of the secondary reserve market is obtained joining the pairs up/down band-price $\left(UR^{SR}_{g,h,scsr}, p^{SR}_{h,scsr}\right)/\left(DR^{SR}_{g,h,scsr}, p^{SR}_{h,scsr}\right)$ that result in the optimization.

In the intradaily mode i, the daily energy market and the secondary reserve market, as well as the intradaily markets j (with $j<i$) have been cleared, and their results are constants in (1), (2) and (3). The bid curve of the energy to be sold in each hour h of intradaily market i is calculated joining the energy-price pairs $\left(Q^{IMi}_{g,h,scim_i}, p^{IMi}_{h,scim_i}\right)$. In the same way, the bid curve of the energy to be bought by generator g is built from the energy-price pairs $\left(D^{IMi}_{g,h,scim_i}, p^{IMi}_{h,scim_i}\right)$. A typical case occurs in the intradaily mode when a unit with energy cleared in the energy market breaks down in an hour h. The final program of generator g in hour h is fixed to zero, and the energy equation (1) yields that the unit must buy the energy scheduled.

Bid curves for the tertiary and deviation management markets are built in a separate module that identifies the firm's free generating resources and offering them in accordance to the firm's selected strategy.

D. Liquidity constraints

An important issue to be considered is the liquidity of intradaily markets, i.e., an agent may not be able to sell its energy in an intradaily market if there is not a demand agent willing to buy it. With the described formulation of the model, the results obtained will try to assign the agent's resources to the market with the highest expected price.

Additional constraints need to be added in the model to limit the quantity to be sold in each market. Liquidity constraints are formulated as a maximum percentage of the total energy that every thermal, hydro and pumping unit can allocate in each market.

E. Building bid curves

The bid curve that a generator must submit to a market consists of a non-decreasing set of quantity-price blocks. It is obtained by locating a selected number n of segments between two consecutive optimal quantity-price pairs (a constraint is included in the optimization model to assure that optimal quantities in each market are non-decreasing with price). The price of each segment is determined imposing that the net area between the segments and the linear function that joins the two optimal pairs equals to zero [6]. Fig 5 illustrates the proposed method for obtaining the bid curve that generator g submits for hour h in the daily market, selecting n =2.

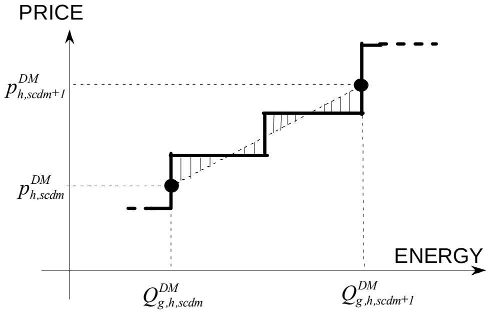

Fig 5. Method for building bid curves

In practice, some complex strategic parameters are included in the process of building the bid curve to adequate the bid to the firm's strategy.

IV. MODEL DESCRIPTION

A. Objective function

The model proposed in the paper maximizes the total expected profit (income minus cost) obtained by a price-taker generating firm with its thermal, hydro and pumping units.

The generation cost incurred by a thermal unit is modeled by its start up cost (start up decisions are given by a middle term model) and its variable cost.

The cost of a hydro unit is modeled with the water value curve. It should be noted that in deregulated electricity markets the water value at time t must be computed as the lost of future profit if the water is turbined at time t and is not saved for the future [10]. The relationship future profit-energy turbined by a hydro unit is modeled by a piecewise linear function as depicted in Fig 6. The slope of each segment λ_i is the marginal cost (c€/kWh) of water in each interval.

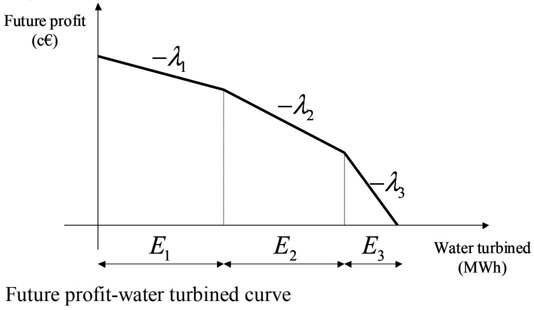

Fig 6. Future profit-water turbined curve

The cost of pumping units is computed taking into account the performance parameter of each pumping unit.

B. Constraints

The model includes the following constraints for each unit:

- Energy balance equation (1).
- Maximum and minimum technical output.
- Ramp rate constraints between two hours (only thermal units)
- Limits for the up and down band of the generators (equations (2) an (3)).
- Quantities sold at each hour of each market are increasing with price, and quantities bought at each hour of each market and decreasing with price.
- Liquidity constraints for each market.

In addition, the model formulates the following market constraints:

- Maximum and minimum share of the generating firm in the daily energy market
- Maximum and minimum share of the generating firm in the secondary reserve market
- Ratio of up/down band must equal the necessity of up/down band declared by the OS

V. CASE STUDY

The proposed model is used daily by Spanish utility Viesgo S. L. of Enel Group to configure the hourly generation bids submitted to each type of market. At present, generation assets of Viesgo S. L. comprise 7 thermal units, 1 hydro units and 1 pumping bid group (with 4 physical units). However, due to confidentiality reasons, the performance of the tool is illustrated in this section considering a fictitious non-real firm comprising 3 thermal units, 1 hydro units and 1 pump storage unit. It should be noted that some technical features have been modeled with high precision in the tool (for instance, each pumping physical unit is represented by an integer variable). For a firm with a higher number of assets, some simplifications in the modeling or the use of decomposition techniques could be required to solve the large resulting problem.

For the fictitious case proposed, the daily mode has been executed providing 7 price scenarios of the daily market for each hour, 3 price scenarios for each hour of the secondary reserve market and one price scenario for each hour of each intradaily market. The daily market price scenarios were 3.1, 3.32, 3.39, 3.46, 3.53, 3.61 and 3.82 c€/kWh. The optimization problem contained 34741 constraints, 13196 variables (216 corresponding to integer variables) and 235014 non-zero elements.

Bid curves for the daily energy market have been built selecting a number of 3 segments between each optimal quantity-price pair. Fig 7 shows the bid curve of thermal generator 1 (with a maximum output $P_{g,h}^{max}$ of 100 MW and a minimum output $P_{g,h}^{min}$ of 50 MW). The algorithm computes that for each price scenario of the daily market the optimal output of unit 1 is 100 MW. Thus, the unit offers the minimum output 50 MW at a price 0 (to assure that the minimum output will be cleared in the market) and locates 3 segments between the optimal pairs (50 MW, 0 c€/MWh) and (100 MWh, 3,1 c€/kWh). No energy blocks can be allocated between the optimal pairs (100 MW, 3.1 c€/kWh) and (100 MW, 3.32c€/kWh)-…-(100 MWh, 3.82 c€/kWh).

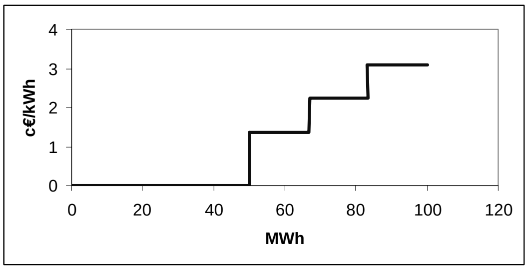

Fig 7. Bid curve of thermal unit 1 for hour 12 of the daily energy market

Once the daily market has taken place, the secondary reserve mode has been executed. The optimization problem for the secondary reserve mode (with 7 price scenarios for each hour of the secondary reserve market and one for each hour of each intradaily market) contained 14651 constraints, 10959 variables (804 of them integer) and 76824 non-zero elements. Assuming for hour 12 a the daily market clearing of 75 MW for thermal unit 1, maximum up band of unit 1 of 30 MW, a maximum down band of 20 MW for unit 1, Fig 8 depicts the up/down bid curve of the model assuming that 3 segments are located between each optimal pair.

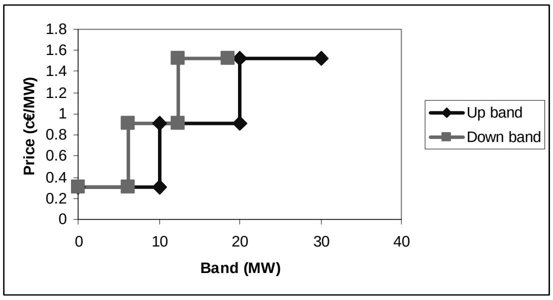

Fig 8. Up and down bid curve of thermal unit one for hour 12 of the secondary reserve market.

VI. IMPLEMENTATION

The interface of the optimization tool described in this paper has been coded in Visual Basic for Applications (VBA). The optimization modules have been built using GAMS (General Algebraic Modeling System) and solved using the CPLEX optimization software with mixed integer programming.

VII. CONCLUSIONS

The Spanish electricity business in Spain is organized in the energy markets and the ancillary services markets. Each agent must allocate its electric resources within each type of market in order to maximize its expected profit. This paper has proposed an optimization algorithm that distributes the electric resources of a price-taker generating firm within the energy and ancillary services markets, taking into account all the sequence of energy and ancillary services markets of the Spanish electricity business. The model builds the bid curves that the agent submits to each type of market.

VIII. ACKNOWLEDGMENT

The optimization tool described in this paper has been developed under the leadership of Spanish utility Viesgo S. L of Enel Group. The authors gratefully acknowledge the fruitful comments of J. Torné and all the personal staff of the energy management center of Viesgo. Thanks also to I. Hierro from IIT who helped in the development of the tool..

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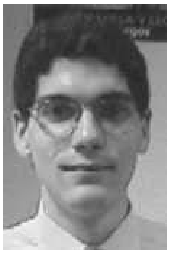
X. BIOGRAPHIES

Alvaro Franco Ugidos was born in Leon, Spain, in 1978. He received the degree of Industrial Engineer in 2001 from Universidad Pontificia Comillas, Madrid, Spain. From December 2001 to September 2002, he was a Researcher at the Instituto de Investigación Tecnológica, Universidad Pontifica Comillas. Actually, he is a gas analyst in Endesa and is pursuing a Bussiness Adminsitration Bachelor from UNED. His areas of interest include operation and economics in electric and gas power systems.



Enrique Lobato Miguélez was born in Burgos, Spain, in 1974. He received the degree of Electrical Engineer in 1998 and the PhD degree in 2002, from Universidad Pontificia Comillas, Madrid, Spain. Since June 1998, he is a Researcher at the Instituto de Investigación Tecnológica, Universidad Pontifica Comillas. His areas of interest include analysis, planning, operation and economics in electric power systems. He has participated in several research projects for different firms related with the energy industry.

Luis Rouco Rodríguez (Student Member 1989, Member 1991) obtained the Electrical Engineer degree and the Ph.D degree from Universidad Politécnica de Madrid in 1985 and 1990. He is Associate Professor of the School of Engineering of Universidad Pontificia Comillas. His areas of interest are modeling, analysis, simulation and identification of electric power systems. He has been visiting researcher at Ontario Hydro, MIT and ABB Power Systems.

Alejandro Ugedo Álvarez-Ossorio was born in Madrid, Spain, in 1979. He obtained an Industrial Engineer degree in 2002 from Universidad Pontificia Comillas, Madrid, Spain. Since September 2002, he is a Researcher at the Instituto de Investigación Tecnológica, Universidad Pontifica Comillas. His areas of interest include analysis, planning, operation and economics in electric power systems. At the present time, he is participating in a research project for a firm related with the energy industry.

Joaquín Fernández-Caro was born in Seville, Spain, in 1971. He received the degree of Mechanical Engineer in 1996. He started working in Saltos del Guadiana in 1997, in charge of the hydro scheduling. He moved to Spanish utility Endesa in the wholesale market bidding group, where he stood for 3 years till he moved to strategy. In 2001 he moved to Viesgo S. L. of Enel Group where he is actually on charge of the wholesale market operation and medium term planning.

Julián de Benito was born in Madrid, Spain, in 1972. He received the degree of Electrical Engineer in 1997. He started working in ABB Service, a branch of ABB AG, in 1998, working as a consultant in plant maintenance. In 1999, he joined Endesa, integrating the wholesale market bidding group. In 2001, he moved to Viesgo Generación S. L. of Enel Group, where he is in charge of the energy management center of Viesgo Generación.

Jorge de la Hoz Ardiz was born in Madrid, Spain, in 1975. He received the degree of Electrical Engineer in 1999 from Universidad Pontificia Comillas, Madrid, Spain. In 1999, he joined SchlumbergerSema as Energy Business Consultant in charge of Electricity and Gas Projects. In January 2002, he moved to Viesgo S.L. of Enel Group where he is in charge of the energy management and biding of Viesgo in the Spanish wholesale electricity market.

Javier Chofre Álvarez was born in Denia (Alicante), Spain, in 1973. He received the degree of Minus Engineer (Energy) in 1998 from Universidad Politécnica, Madrid, Spain. In 1998, he joined Tecnatom (Engineering Department) in ELCOGAS GICC Plant. In 2000, he was in charge of the O & M in CND Cogeneration Plant, in Dominican Republic. In January 2002, he moved to Viesgo S.L. of Enel Group where he is on charge of the energy management and biding of Viesgo in the Spanish wholesale electricity market.