An MCP Approach for Hydrothermal Coordination in Deregulated Power Markets

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Abstract: This paper proposes a new methodology for addressing the long term operation planning of a generation company, fully adapted to represent both its annual and hyperannual hydrothermal power generation scheduling in a competitive market. The method explicitly states the electricity generation market equilibrium by analytically formulating the equations that express the optimal behavior of the existing generation companies, considering the technical constraints that affect the scheduling of their units. The subsequent system of non-linear equations can be directly solved taking advantage of its Mixed Complementarity Problem (MCP) structure, which allows for the use of special complementarity methods. A hydrothermal coordination model based on the proposed methodology has been developed and implemented in GAMS. A case study is also presented to show its successful application to the large-scale Spanish electric power system.

Keywords: Power system planning, Generation scheduling, Competitive electricity market equilibrium, Complementarity.

I. INTRODUCTION

In deregulated power markets, electricity generation becomes an unbundled and liberalized activity in which both expansion and operation decisions no longer depend on administrative and centralized procedures –usually based on cost minimization schemes–, but rather on the managerial decisions of the generation companies looking to maximizing their own profits. As long as the market decides the actual operation of generation units, an important developmental effort is needed to design new models and tools that properly represent the electricity market equilibrium. The optimal energy scheduling of each company will depend not only on companies' production cost profiles and technical operation constraints but also on the market behavior resulting from the interaction of all market participants.

Interest in the research community regarding the development of hydrothermal scheduling models adapted to the new circumstances has grown and has been demonstrated as such in numerous publications [1]. Scott and Read [2] developed a medium term model with emphasis on hydro operation using dual dynamic programming. Bushnell [3] developed a model that achieves market equilibrium taking into account hydro scheduling decisions. More recently, Hobbs utilized the Linear Complementarity Problem (LCP) to model imperfect competition among electricity producers [4]. His model included a congestion pricing scheme for transmission. Wei and Smeers used a Variational Inequality (VI) approach for computing the market equilibria addressing the problem of transmission pricing [5]. Although modeling advances have been notable, limitations persist in tackling realistic power systems.

This paper proposes a new methodology for addressing the long term operation planning of a generation company also based on the Mixed Complementarity Problem, and fully adapted to represent both its annual and hyperannual hydrothermal power generation scheduling in a competitive market. This method states the market equilibrium by analytically formulating the equations that express the optimal behavior of the existing generation companies in a deregulated electricity market, considering the technical constraints that affect the energy scheduling among periods. This period coupling becomes essential in systems with a significant hydro component such as the Spanish one. The method properly models the physical behavior of a hydrothermal power generation system while considering the individual profit maximization goal of each company participating in the market.

The resulting system of equations can be directly solved taking advantage of its MCP structure, whose particularities allow the use of special resolution methodologies incorporated nowadays in commercial software packages, such as MILES and PATH solvers within GAMS.

This paper is organized as follows. Section 2 provides an overview of the method proposed. Section 3 outlines the notation used for the mathematical expressions. Sections 4 and 5 state the detailed mathematical formulation of the model. Section 6 describes an application of the model to the Spanish electric energy market and finally, section 7 provides the conclusions drawn from the study.

II. MODEL OVERVIEW

As long as market mechanisms in a deregulated context decide the actual operation of the generation units, the market equilibrium must be considered in order to properly model the optimal energy scheduling of one specific company. The market equilibrium defines a set of outputs such that no firm, taking its competitors' outputs as given, wishes to change its own output unilaterally. Modeling the market equilibrium requires the simultaneous consideration of each company's

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profit maximization objective, which constitutes the newest and most complicated issue of this kind of models.

The modeling of the market behavior hardly fits with the traditional cost minimization scheme, although there are models that give reasonable approximations based on this kind of approach [6]. Conceptually, the new structure better corresponds to various simultaneous optimizations –for each one of the participating companies, the maximization of its profits subject to its particular technical constraints– linked together through the market price resulting from the interaction of all of them. This scheme is shown in Figure 1, where z represents the operation profit of each company $e \in [1,\ldots,E]$, x the decision variables and the set of constraints h and g are particularized for each company. The electricity market is modeled by the demand function that relates the supplied demand to the electricity price.

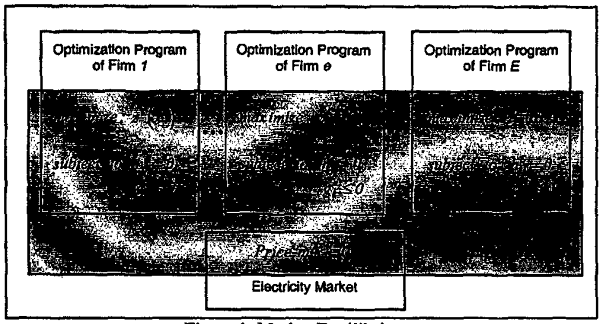

Figure 1. Market Equilibrium.

A. Model Statement.

The previous market equilibrium problem can be stated in terms of an MCP scheme by means of setting the first order optimality conditions of Karush-Kuhn-Tucker associated to the set of maximization programs (see figure 2).

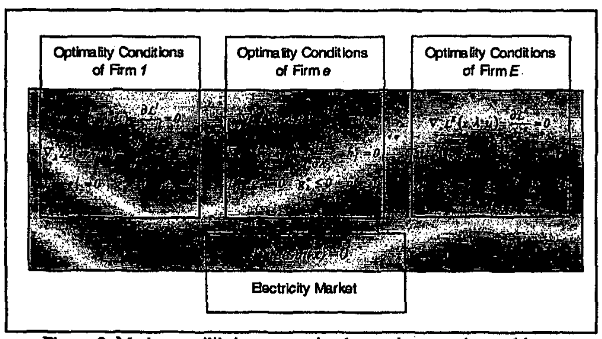

Figure 2. Market equilibrium as a mixed complementarity problem.

In figure 2, $\mathcal{L}$ represents the Lagrangian function of the corresponding optimization problem and λ and μ represent the dual variables associated to the set of h and g constraints respectively. The optimality conditions can be written down as three sets of equations. The first one cancels the gradient of the Lagrangian function with respect to the decision variables x. The second set (the gradient of the Lagrangian function with respect to the dual variables λ) coincides with the h equality constraints themselves. The third one is formed by the complementary slackness conditions associated to the inequality constraints g. Grouping together all companies' system of equations leads to a mixed complementarity problem formulation [7].

B. Generation System Representation

This hydrothermal coordination model considers a hyperannual scope divided into several periods and load levels. The periods coincide with months, while the grouping of the peak, plateau, and off-peak hours makes up the load levels.

The model considers in detail the particular characteristics of each type of generation unit: rated power output, quadratic fuel consumption, fuel purchases and the maximum size of the stockpiles for each thermal plant; rated power output and reservoirs limited capacity for the hydro units; and performance in the pumping and generation cycle for pumped units. In market operation models the modeling of the demand should consider the reaction of the quantity demanded to changes in the price. In the proposed model the total demand at each load level is a linear function of the price.

As a result of the previous model assumptions, the model presented in this paper is a mixed linear complementarity problem[1], which assures solution existence and uniqueness in the case that the thermal units' marginal costs are strictly monotone increasing [5].

III. NOTATION

In this section all symbols used in this paper are identified and classified, according to their use, into indices, parameters, variables and dual variables.

Table 1. Indices.

Index	Description
b	Pumped-storage[2] units
c	Thermal plants.
e	Firms.
h	Hydro and/or pumped-hydro units.
n	Load levels.
p	Periods.
T	Thermal units.

[1] A mixed linear complementarity problem is an MCP formed by linear equations.

[2] In this paper the following convention is used: a *pumped-hydro* unit is a pump-turbine, which has a large upper reservoir with seasonal storage capability that receives water from pumping and also from natural hydro inflows. On the other hand, a *pumped-storage* unit has a small upper reservoir filled with pumped water that allows only a weekly or daily cycle.

Table 2. Parameters.

Parameter	Description
$A_{p,h}$	Hydro inflows for hydro unit h in period p [TWh].
$\overline{b}_b$, $\underline{b}_b$	Maximum and minimum capacity of pumped-storage unit b when pumping [GW].
$\overline{b}_h$, $\underline{b}_h$	Maximum and minimum capacity of pumped-hydro unit h when pumping [GW].
$C_{p,c}$	Contracted fuel purchase by thermal plant c at the beginning of period p [TWh].
$d_{n,p}$, $d'_{n,p}$	Power demand purchased in the market at price zero [GW] and constant slope of the demand function in load level n of period p [(k\$/TWh)/GW]
$D_{n,p}$	Duration of load level n of period p [kh].
$\overline{h}_{p,h}$, $\underline{h}_{p,h}$	Maximum and minimum capacity of pumped-hydro unit h in period p [GW].
$\overline{h}_b$, $\underline{h}_b$	Maximum and minimum capacity of pumped-storage unit b [GW].
k_t	Self-consumption coefficient of thermal unit t [p.u.].
$L_{p,e}$	Long term contract of firm e in period p [GW].
o'_t, o''_t	Heat rate (linear [kTcal/TWh] and quadratic [kTcal/(GW^2·kh)] terms) of thermal unit t.
$\overline{p}_t$, $\underline{p}_t$	Maximum and minimum rated capacity of thermal unit t [GW].
q_t	EFOR of thermal unit t [p.u.].
$\overline{R}_b$	Maximum hydro energy reserve of pumped-storage unit b [TWh].
$\overline{R}_{p,h}$, $\underline{R}_{p,h}$	Maximum and minimum hydro energy reserve of hydro unit h in period p [TWh].
$\overline{S}_{p,c}$, $\underline{S}_{p,c}$	Maximum and minimum fuel storage capacity of thermal plant c in period p [TWh].
u_t	O&M variable cost of thermal unit t [k\$/GW].
v_t	Fuel cost of thermal unit t [k\$/kTcal].
η_b	Performance of pumped-storage unit b [p.u.].
η_h	Performance of pumped-hydro unit h [p.u.].

Table 3. Decision variables.

Variable	Description
$b_{n,p,b}$	Power consumption by pumped-storage unit b in load level n of period p [GW].
$b_{n,p,h}$	Power consumption by pumped-hydro unit h in load level n of period p [GW].
$h_{n,p,b}$	Power generation by pumped-storage unit b in load level n of period p [GW].
$h_{n,p,h}$	Power generation by pumped-hydro unit h in load level n of period p [GW].
$p_{n,p,t}$	Power generation by thermal unit t in load level n of period p [GW].
$R_{p,h}$	Hydro energy reserve of hydro unit h at the beginning of period p [TWh].
$S_{p,c}$	Fuel storage level of thermal plant c at the beginning of period p [kTcal].

Table 4. Auxiliary variables.

Variable	Description
$g_{n,p,e}$	Total power generation sold in the market of firm e in load level n of period p [GW].
$\pi_{n,p}$	System marginal price in load level n of period p [k\$/TWh].

IV. HYDROTHERMAL SCHEDULING PROBLEM FOR EACH GENERATION COMPANY

This section states in detail the optimization problem that defines the generation companies behavior. Their goals are to maximize their own profits subject to the set of constraints[3] that limits their long term operation decisions.

A. Objective function

The objective of each generation company is to maximize its profits (market revenues minus costs) for the entire scope of the model.

$$\begin{aligned} \mathit{Maximize}: & \sum_p \sum_n D_{n,p} \cdot \pi_{n,p} \cdot g_{n,p,e} \\ & - \sum_p \sum_n \sum_{t \in e} D_{n,p} \cdot u_t \cdot p_{n,p,t} \qquad \forall\ e \quad (1) \\ & - \sum_p \sum_n \sum_{t \in e} D_{n,p} \cdot v_t \left(o'_t \frac{p_{n,p,t}}{k_t} + o''_t \left(\frac{p_{n,p,t}}{k_t} \right)^2 \right) \end{aligned}$$

Interperiod operating constraints

The interperiod operating constraints are those that regard resources planning across multiple periods. In particular, annual hydro energy scheduling, seasonal operation of pumped-hydro units and fuel scheduling are represented.

Hydro scheduling

The energy available during each period is limited by the hydro inflows and the initial and final reservoir levels of the period. The initial level of the first period and the final level of the last period are fixed data for the optimization problem.

$$\begin{aligned} & \sum_n D_{n,p} \left(h_{n,p,h} - \eta_h \cdot b_{n,p,h} \right) \qquad : \mu^R_{p,h} \quad \forall\ p,\ h \in e,\ e \quad (2) \\ & \quad \le A_{p,h} + R_{p,h} - R_{p+1,h} \end{aligned}$$

Fuel scheduling

This constraint models take-or-pay fuel purchasing contracts. It also allows the enforcing of domestic fuels consumption for strategic energy policy. The final fuel stock of each period is a function of the final stock at the previous

[3] Henceforth, μ denotes the dual variable of each corresponding constraint.

period, and of the purchases and actual consumption along the period. The initial and final levels for the whole scope are fixed data for the optimization problem.

$$\sum_n \sum_{t\in C} D_{n,p} p_{n,p,t} \geq C_{p,c} + S_{p,c} - S_{p+1,c} \quad : \mu^S_{p,c} \quad \forall\ p,\ c \in e,\ e \quad (3)$$

B. Intraperiod operating constraints

These constraints are internal to each period and represent weekly/daily operation of pumped-storage units and upper and lower limits of each generation unit.

Pumped-storage constraints

The first constraint establishes a balance between pumped and generated energy, while the second limits the energy that can be pumped in each period.

$$\sum_n D_{n,p}\left(h_{n,p,b} - \eta_b \cdot b_{n,p,b}\right) \leq 0 \quad : \mu^R_{p,b} \quad \forall\ p,\ b \in e,\ e \quad (4)$$

$$\sum_n D_{n,p} \cdot \eta_b \cdot b_{n,p,b} \leq \overline{R}_b \quad : \mu^{\overline{R}}_{p,b} \quad \forall\ p,\ b \in e,\ e \quad (5)$$

Variable bounds

The vast majority of the variables involved in the previous formulation are subject to the following bounds:

$$\underline{R}_{p,h} \leq R_{p,h} \leq \overline{R}_{p,h} \quad : \mu^{\underline{R}}_{p,h}; \mu^{\overline{R}}_{p,h} \quad \forall\ p,\ h \in e,\ e \quad (6)$$

$$\underline{S}_{p,c} \leq S_{p,c} \leq \overline{S}_{p,c} \quad : \mu^{\underline{S}}_{p,c}; \mu^{\overline{S}}_{p,c} \quad \forall\ p,\ c \in e,\ e \quad (7)$$

$$\underline{p}_t \leq p_{n,p,t} \leq \overline{p}_t \quad : \mu^{\underline{p}}_{n,p,t}; \mu^{\overline{p}}_{n,p,t} \quad \forall\ n,\ p,\ t \in e,\ e \quad (8)$$

$$\underline{h}_b \leq h_{n,p,b} \leq \overline{h}_b \quad : \mu^{\underline{h}}_{n,p,b}; \mu^{\overline{h}}_{n,p,b} \quad \forall\ n,\ p,\ b \in e,\ e \quad (9)$$

$$\underline{h}_{p,h} \leq h_{n,p,h} \leq \overline{h}_{p,h} \quad : \mu^{\underline{h}}_{n,p,h}; \mu^{\overline{h}}_{n,p,h} \quad \forall\ n,\ p,\ h \in e,\ e \quad (10)$$

$$\underline{b}_b \leq b_{n,p,b} \leq \overline{b}_b \quad : \mu^{\underline{b}}_{n,p,b}; \mu^{\overline{b}}_{n,p,b} \quad \forall\ n,\ p,\ b \in e,\ e \quad (11)$$

$$\underline{b}_h \leq b_{n,p,h} \leq \overline{b}_h \quad : \mu^{\underline{b}}_{n,p,h}; \mu^{\overline{b}}_{n,p,h} \quad \forall\ n,\ p,\ h \in e,\ e \quad (12)$$

C. Auxiliary constraints

For the sake of the clarity, the following equations have been stated. However, in the implementation, the total power generation and the price have been substituted by these expressions:

Total power generation of each firm

The total power generation of each firm represents the effective output that is sold on the market, therefore it excludes long term contract production already sold at a fixed price.

$$g_{n,p,e} = \sum_{t\in e} p_{n,p,t} + \sum_{h\in e} h_{n,p,h} - \sum_{h\in e} b_{n,p,h} - L_{p,e} \qquad \forall\ n,p,e \quad (13)$$

Price equation.

The price is represented as a linear function of the total purchased power in the market.

$$\pi_{n,p} = d'_{n,p} \cdot \left(d_{n,p} - \sum_e g_{n,p,e} \right) \qquad \forall\ n,\ p \quad (14)$$

V. FORMULATION OF THE ELECTRICITY MARKET EQUILIBRIUM PROBLEM

Once the firm's optimization problems have been set (step represented in Fig. 1) the first order KKT optimality conditions must be derived (step repre4sented in Fig. 2)

A. Optimality conditions

Building the Lagrangian function of each firm's optimization problem and canceling its gradients with respect to the decision variables –since there are no equality constraints– leads to the following set of equality equations:

$$\begin{aligned}\frac{\partial \mathcal{L}_e}{\partial p_{n,p,t}} = & -D_{n,p} \cdot \left(\pi_{n,p} - g_{n,p,e} \cdot d'_{n,p} - u_t\right) \\ & + D_{n,p} \cdot v_t \cdot \left(\frac{o'_t}{k_t} + 2 \cdot \frac{o''_t}{k_t^2} \cdot p_{n,p,t} \right) \\ & + D_{n,p} \cdot \mu^S_{p,c}\ . \\ & - \left(\mu^{\overline{p}}_{n,p,t} - \mu^{\underline{p}}_{n,p,t} \right) = 0 \qquad \forall\ n,\ p,\ t \in e,\ e \end{aligned} \quad (15)$$

$$\begin{aligned}\frac{\partial \mathcal{L}_e}{\partial h_{n,p,h}} = & -D_{n,p}\left(\pi_{n,p} - g_{n,p,e} \cdot d'_{n,p} + \mu^R_{p,h}\right) \\ & - \left(\mu^{\overline{h}}_{n,p,h} - \mu^{\underline{h}}_{n,p,h} \right) = 0 \qquad \forall\ n,\ p,\ h \in e,\ e \end{aligned} \quad (16)$$

$$\begin{aligned}\frac{\partial \mathcal{L}_e}{\partial b_{n,p,h}} = & D_{n,p}\left(\pi_{n,p} - g_{n,p,e} \cdot d'_{n,p} + \eta_h \cdot \mu^R_{p,h}\right) \\ & - \left(\mu^{\overline{b}}_{n,p,h} - \mu^{\underline{b}}_{n,p,h} \right) = 0 \qquad \forall\ n,\ p,\ h \in e,\ e \end{aligned} \quad (17)$$

$$\begin{aligned}\frac{\partial \mathcal{L}_e}{\partial h_{n,p,b}} = & -D_{n,p}\left(\pi_{n,p} - g_{n,p,e} \cdot d'_{n,p} + \mu^R_{p,b}\right) \\ & - \left(\mu^{\overline{h}}_{n,p,b} - \mu^{\underline{h}}_{n,p,b} \right) = 0 \qquad \forall\ n,\ p,\ b \in e,\ e \end{aligned} \quad (18)$$

$$\frac{\partial \mathcal{L}_e}{\partial b_{n,p,b}} = D_{n,p}\left(\pi_{n,p} - g_{n,p,e} \cdot d'_{n,p}\right) + D_{n,p}\left(\eta_b \cdot \mu^{R}_{p,b} - \eta_b \cdot \mu^{\bar{R}}_{p,b}\right) - \left(\mu^{\bar{b}}_{n,p,b} - \mu^{\underline{b}}_{n,p,b}\right) = 0 \quad \forall\ n,\ p,\ b \in e,\ e \tag{19}$$

$$\frac{\partial \mathcal{L}_e}{\partial R_{p,h}} = -\mu^{R}_{p-1,h} + \mu^{R}_{p,h} - \left(\mu^{\bar{R}}_{p,h} - \mu^{\underline{R}}_{p,h}\right) = 0 \quad \forall\ p > 1,\ h \in e,\ e \tag{20}$$

$$\frac{\partial \mathcal{L}_e}{\partial S_{p,c}} = \mu^{S}_{p-1,c} - \mu^{S}_{p,c} - \left(\mu^{\bar{S}}_{p,c} - \mu^{\underline{S}}_{p,c}\right) = 0 \quad \forall\ p > 1,\ c \in e,\ e \tag{21}$$

B. Complementarity slackness conditions

As was previously established in section 2, in order to complete the set of non-linear equations that define the optimization problem of each company, the following three sets of equations must be added. First of all, the inequality constraints (2÷12) multiplied by their corresponding dual variables μ; next, the dual variables μ less than zero; and finally, the inequality constraints themselves.

C. Meaning of the optimality conditions

The optimality conditions provide useful information about the role of each type of power plant in firms' optimal energy scheduling policy.

The gradient of the Lagrangian function with respect to the thermal power generation equal to zero (15) reflects that the firm's maximum-profit is achieved when the firm's marginal revenue is equal to the firm's marginal cost. These equations correspond directly to the Cournot market equilibrium conditions.

The gradient of the Lagrangian function with respect to the thermal power generation equal to zero (15) together with the gradient of the Lagrangian function with respect to hydro power generation (16, 18) shows that hydro scheduling tries to equalize the firm's marginal cost for high load levels within a period. This marginal cost is the water value of each hydro unit and it depends on the fuel cost structure of the hydro plant owner.

The gradient of the Lagrangian function with respect to the power consumption by a pumped unit equal to zero (17, 19) shows that the pumping power generation tries to equalize the firm's marginal cost for low load levels within a period.

Finally, the gradient of the Lagrangian function with respect to the hydro energy reserve equal to zero (20) shows that the interperiod hydro scheduling tries to equalize the water value between consecutive periods.

VI. NUMERICAL RESULTS

The model presented in this article was implemented in GAMS version 2.50. Two specific commercial solvers are available for large scale complementarity problems, MILES and PATH [8], which are based on a generalization of the classic Newton method, in which each subproblem is solved as a linear complementarity problem using an extension of the Lemke´s algorithm.

Our model has been applied to the Spanish Electricity Market, in which four main firms compete. The system meets a maximum peak load close to 30000 MW and a yearly energy demand of 175770 GWh, and the average hydro energy available is 30176 GWh. Demand is modeled as a linear function of the price with 20 ($/MWh)/GW slope. The annual scope (1999) of the model has been divided into twelve periods (months) with 5 load levels for each one.

There are 82 thermal generators grouped into 42 thermal plants. The hydro units have been grouped into 28 equivalent units plus 10 other pumped-storage units. A detailed description of the Spanish electricity system can be found in [9].

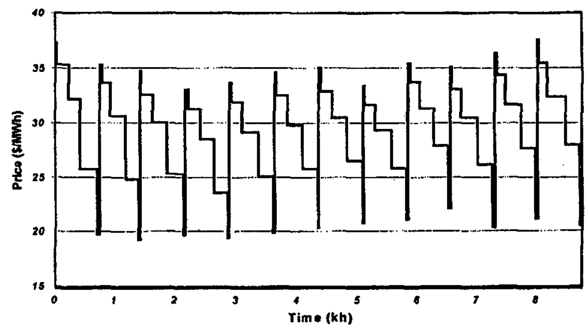

Figure 3. Prices of the case study.

Figure 3 shows the system marginal price obtained from the model, which exhibits double seasonality. The first one is due to the different demand levels within a period. The other one is explained by the annual hydraulic inflows seasonality.

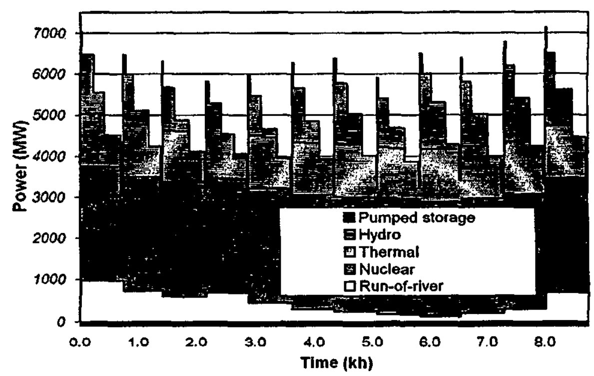

Figure 4. Technology-detailed output of Iberdrola.

Figure 4 shows a technology-detailed output of the firm with the highest hydro production. Although the model has been run for the average hydraulic inflow scenario, the shown results are very promising as they are close to the actual Spanish Market results.

The size of the presented problem is 8691 variables, and it is solved using PATH in approximately 120 seconds on a PC Pentium-II 233 MHz with 64 MB.

VII. CONCLUSION

This paper presents a new methodology based on the mixed complementarity problem for the development of hydrothermal coordination models within the context of deregulated electricity markets. A detailed mathematical formulation of the proposed model is also stated. This model is able to maximize the producer surplus of each firm for a large power system, taking into account all kinds of operation constraints and multiple hydro reservoir scheduling.

The mathematical model has been developed and implemented in GAMS taking advantage of the specific solvers designed to deal with complementarity problems. The successful application to the large-scale Spanish market presented in this article shows that the model is capable of representing real electric power systems.

In order to improve the long term hydrothermal coordination –specially in power systems with a high level of hydro component–, the source of uncertainty due to the stochastic nature of hydraulic inflows will be addressed in future researches.

VIII. ACKNOWLEDGEMENTS

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X. BIOGRAPHIES

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