Paper accepted for presentation at 2009 IEEE Bucharest Power Tech Conference, June 28th - July 2nd, Bucharest, Romania

Dispatch of Head Dependent Hydro Units: Modeling for Optimal Generation in Electricity Market

S. J. P. S. Mariano, M. R. A. Calado, *Member, IEEE,* and L. A. F. M. Ferreira

***Abstract*—Deregulation and liberalization of electric power industry, among other things, has created new requirements for the market participants. The power system engineer, operator, and, in general, the market participant is being faced with requirements for which he does not have adequate training and the proper software tools. In this framework, among others, a pure hydro-generation company has to (1) operate its hydro units, throughout the operating day, trying to fulfill the market clearing schedule, and modify the program in the intra-day energy markets if necessary (or more suitable) as real-time operation is getting closer and (2) make the offers for the regulation service market. In this scenario the Dispatch of Head Dependent Hydro Units is a problem that must be solved before dealing with the hourly hydro resource scheduling for energy and reserve optimization.**

***Index Terms*—Hydroelectric power generation, hydroelectric generators, optimization methods, electricity market.**

I. Nomenclature

J	total number of hydro resources
I	total number of curves
q_{ji}	water discharge in (m^3s^{-1}) by unit *j* in curve *i*
$q_{ji}^{\max}$	maximum water discharge in (m^3s^{-1}) by unit *j* in curve *i*
$q_{ji}^{\min}$	minimum water discharge in (m^3s^{-1}) by unit *j* in curve *i*
p_{ji}	power generated in (MW) by unit *j* in curve *i*
$p_{ji}^{\max}$	maximum generating capacity in (MW) of unit *j* in curve *i*
$p_{ji}^{\min}$	minimum generating capacity in (MW) of unit *j* in curve *i*
$p_{j}^{\max}$	maximum generating capacity in (MW) of unit *j* (whatever the curve *i*)
$p_{j}^{\min}$	minimum generating capacity in (MW) of unit *j* (whatever the curve *i*)
P	total power generated in (MW) by plant (power demand)
Q	total water flow through the committed units
h_i	head in (*m*) in curve *i*
u_j	decision variable for unit *j*
U_j	set of admissible decisions in unit *j*
$\mathscr{L}$	Lagrange function
λ	Lagrange multiplier
α_{ji}	constant of quadratic approximation of unit *j* in curve *i*
β_{ji}	constant of quadratic approximation of unit *j* in curve *i*
γ_{ji}	constant of quadratic approximation of unit *j* in curve *i*

II. Introduction

ELECTRICITY industry restructuring has received government priorities worldwide while restructuring policies are debated at all levels internationally. The preliminary experiences have shown that the establishment of electricity market is going to be specific to legislations, cultures, economy, and electricity operations and practices in participating nations [1].

Portugal is also moving towards a competitive electricity market with the presumption that the competition will result in technological progresses, better services, higher efficiency and enhanced reliability, as well as less costly delivery of electricity to customers.

In this context and within the competitive environment [1]-[3], such as the Norwegian case [4] or concerning Portugal and Spain given the Iberian Electricity Market, a hydro generating company (H-GENCO) is usually an entity owning generation resources and participating in the electricity market with the ultimate goal of maximizing profits, without concern of the system, unless there is an incentive for it [5]. The system-wide balance of supply and demand is assumed to be managed by an Independent System Operator (ISO), which maintains the system security and reliability.

The optimal management of the water available in the reservoirs for power generation, regarding future operation use, delivers a self-schedule and represents a major advantage for the H-GENCO to face competitiveness given the economic stakes involved. Based on the self-schedule, the H-GENCO is able to submit bids with rational support to the electricity market. Thus, for deregulation applications, Short Term Hydro Scheduling (STHS) solution is very important as a decision support for problem solution to (P1) elaborate a daily operation plan of its hydro resources in order to asses the available energy that could be offered in the day-ahead market and to (P2) build the competitive hourly bids to sell that energy, and submit them to the market operator [6]-[10].

Dynamic programming (DP) is among the earliest methods applied to the STHS problem [11]. Although DP can handle the nonconvex, nonlinear characteristics present in the hydro

978-1-4244-2235-7/09/$25.00 ©2009 IEEE

model, direct application of DP methods for cascaded hydro systems is very difficult to implement due to the well-known DP curse of dimensionality, more difficult to avoid in short--term than in long-term optimization without losing the accuracy needed in the model [12]. Artificial intelligence techniques have also been applied to the STHS problem [13], [14]. However, a significant computational effort is necessary to solve the problem for cascaded hydro systems, particularly, with a time horizon of 168 hourly intervals. Also, due to the heuristics used in the search process only suboptimal solutions can be reached. A natural approach to STHS is to model the system as a network flow model, because of the underlying network structure subjacent in cascaded hydro systems [15]. For cascaded hydro systems, as there are water linkage and electric connections among plants, the advantages of the network flow technique are salient. Hydroelectric power generation characteristics are often assumed as linear or piecewise linear in hydro scheduling models [16]. Accordingly, the solution procedures are based on linear programming (LP) or mixed-integer linear programming (MILP). LP is a well-known optimization method and standard software can be found commercially. MILP is very powerful for mathematical modeling and is applied successfully to solve large-size scheduling problem in power systems. Hence, MILP is becoming often used for STHS [17], where integer variables allow modeling of start-up costs and discrete hydro unit-commitment constraints. However, LP typically considers that hydroelectric power generation is linearly dependent on water discharge, thus ignoring head--dependency to avoid nonlinearities. This is nowadays not appropriated for a realistic modeling of run-of-the-river hydro plants. The discretization of the nonlinear dependence between power generation, water discharge and head, used in MILP to model head variations, augment the computational burden required to solve the STHS problem. For instance, the selection of the best under-relaxation factor in [18] is empiric and case-dependent, rendering some ambiguity to these methods.

Hydro scheduling is in nature a nonlinear optimization problem. A nonlinear model has advantages compared with a linear one. A nonlinear model expresses hydroelectric power generation characteristics more accurately and head--dependency on STHS can be taken into account. In the past, there were considerable computational difficulties to directly use nonlinear programming (NLP) methods to this sort of problem [19]. The cascaded hydraulic configuration coupled with the head change effect augments the problem dimension and the complexity. As a result of the nonlinear nature of the problem, computational limitations prevented a direct optimization or simplifications of the model were imposed. However, with the advancement in computing power and the development of more effective nonlinear solvers in recent years, this disadvantage has much less influence. We have shown as a recently new contribution, [6] and [7], that this disadvantage is mitigated by applying a nonlinear approach to a realistically-sized hydro system, respectively, with three and seven cascaded reservoirs, which was not possible with earlier approaches and computational resources.

Although, this recent developments can be very important to solve the stated problems (P1) and (P2), serving as strong base of knowledge to face the problems of scheduling hydroelectric units in the very short-term (up to 24 hours) and modify the program in the intra-day energy markets under a competitive environment, and the determination of the lower and upper limits for the offers of the regulation complementary service.

These problems have not received great attention and not much has been published on this subjects, largely due to its complexity, resulting from the accuracy (the result must be a realistic value of power for each unit and not the water discharge of plant) and the real-time needed in the problem solution. The published work concerning the dispatch of hydro generating units considering head dependence sub--problem can be found in [20], [21].

Thus, the cascaded hydro systems exploitation imposes the optimal solution of the Dispatch of Head Dependent Hydro Units.

The paper is structured as follows: Section III provides the mathematical formulation of the Dispatch of Head Dependent Hydro Units problem and proposes a solution method based on optimization techniques using Lagrangean relaxation. In Section IV the proposed method is applied on a realistic hydro power plant with six units, illustrating the numerical results. Finally, concluding remarks are given in Section V.

III. Problem Formulation and Solution Method

The hydro generation model is either unit- or plant-based. For a more accurate approach, each individual unit in a plant is treated separately, which yields a hydro unit commitment problem. In this paper we adopt an aggregated plant concept, where units in a hydro plant are aggregated as one equivalent plant, but the unit commitment in the power plant can change, according to the head and the water flow to achieve optimal solution. The electric power generated is computed as a function of water flow, depending on hydro unit input/output (I/O) characteristic associated with the corresponding head. The dispatch of head dependent hydro units (set of characteristic curves, each one for a constant value of electric power generated, for each hydro power plant) incorporates water flow unit limits, unit power generated limits and the head dependency effect. In particularly, this problem assumes a great complexity when the units in a power plant are different from each other, mainly because some of them saw its capacity increased, and because the objective function is non-linear and non convex. For these reasons the problem solution imposes an optimization out of conventional non-linear programming (increasing the execution time). The advantage of using the aggregated plant concept is that it can be done offline reducing significantly the time required in the optimization process in hourly hydro resource scheduling for energy and reserve.

A. Mathematical Formulation

Given the imposed constraints, those required for each unit and those connected with all units, a proper unit commitment decision must be chosen and must be optimal from the economic benefit point of view. This problem involves, by one way, the statement of all possible decisions and the value associated with each of them, and by another way, the strategy analysis used to achieve the optimal solution. Thus, the problem formulation brings another problem, of mathematical programming, non-linear, described as follows.

Consider a hydro power plant with J units. Each unit is characterized by three variables: power, water flow and head. If one of these variables is kept constant – let be the head – each unit j is characterized by a set of curves. The number of curves I is as big as bigger are the discretization levels, assumed for the head.

Each curve i, of unit j, can be represented as a function of the generated power and the net head:

$$q_{ji} = f(p_{ji}, h_i) \tag{1}$$

with

$$i = 1, \ldots, I \quad \text{and} \quad j = 1, \ldots, J$$

The goodness of different possible decisions is made based on an established scale that characterizes each solution. This measurement scale is obtained from a function – objective function. The objective function that better fits the problem under analysis is the water flow through the turbines within the powerhouse (the water flow represents the operating cost).

Thus, expression (1) is a cost operation function, and the main problem to determinate the dispatch of head dependent hydro units (power plant characteristic curves) is related to the optimal unit commitment problem, and can be presented as follows.

For a set of units within a hydro power plant, minimize the operating cost, according to:

- power demand – constraint connected with all units
- minimum and maximum generating capacity of each unit depending on head – constraint on individual curve
- minimum and maximum generating capacity of each unit independently on head – constraint on individual unit

So, the hydro unit commitment problem $(\mathscr{P})$, for each curve i, can be written as:

$$(\mathscr{P}) \qquad \min_{u} \left(\sum_{j=1}^{N} q_{ji}(p_{ji}, h_i, u_j) \right) \tag{2}$$

subject to:

$$\sum_{j=1}^{n} p_{ji} = P \tag{3}$$

$$p_{ji}^{\min}(h_i) < p_{ji} < p_{ji}^{\max}(h_i) \ \cap \ p_j^{\min} < p_j < p_j^{\max} \tag{4}$$

where:

$$u_j \in \mathrm{U}_j \qquad j = 1, \ldots, J \tag{5}$$

Expression (2) represents the total value of water flow and indicates that for a specific value of generated power P, with head h_i, the water flow depends on the unit's dispatch for the considered unit commitment. Expression (3) represents the power generated by the plant, for the considered unit commitment. Expression (4) is the result of considering the minimum and maximum generating capacity of unit j in curve i, together with the minimum and maximum generating capacity of unit j whatever the curve is. The expression (5) represents the resource feasibility set.

B. Proposed Solution Method

The objective function is non-linear and non convex. For these reasons problem $(\mathscr{P})$ is very difficult to solve, being necessary the optimization out of conventional non-linear programming. The non-linear programming algorithms optimization makes use of interpolation techniques that convert to convex the previously non-convex function. In this paper, the adopted method is based on optimization techniques using Lagrangean relaxation [12-16].

Lagrangean relaxation allows to relax the load constraint (3) that connects all units, as the same demanding load is satisfied by all operating units, being the load constraint possible to be violated. However, the relaxed constraint is not completely considered to be negligible. In fact, the weakness of problem $(\mathscr{P})$ is linearly penalized in Lagrange function, by mean of Lagrange multiplier λ, in order to avoid the constraint violation. That function (represented by $\mathscr{L}$) appears from the consideration of constraint (3) in the objective function of problem $(\mathscr{P})$. In such a way, the Lagrange function, resulting from problem $(\mathscr{P})$, as stated in (2), through constraint relaxation (3), can be written by:

$$\mathscr{L}(p_{ji}, h_i, u_j, \lambda) = \sum_{j=1}^{N} q_{ji}(p_{ji}, h_i, u_j) + \lambda \left(P - \sum_{j=1}^{N} p_{ji} \right) \tag{6}$$

For the characteristic curves evaluation the Lagrange function must be minimized and subjected to local constraints. The minimization problem is formulated as in $(\mathscr{Q})$:

$$(\mathscr{Q}) \qquad \min_{u} \mathscr{L}(p_{ji}, h_i, u_j, \lambda) \tag{7}$$

subject to:

$$p_{ji}^{\min} < p_{ji} < p_{ji}^{\max} \ \cap \ p_j^{\min} < p_j < p_j^{\max} \tag{8}$$

where:

$$u_j \in \mathrm{U}_j \qquad j = 1, \ldots, J \tag{9}$$

Assuming that quadratic costs representation is a good approximation, one can adopt the following expression as a cost curve for each unit

$$q_{ji} = f(p_{ji}, h_i = c^{te}) = \alpha_{ji} + \beta_{ji} p_{ji} + \frac{\gamma_{ji}}{2} p_{ji}^2, \tag{10}$$

which consequently gives that the objective function is a convex function. So, for each admissible decision u_j, it is possible to find a solution of problem $(\mathscr{Q})$, taking the partial derivative of the Lagrangean function in order to each independent variable and making them equal to zero.

Once the problem $(\mathcal{Q})$ solution is obtained, for each head value and according to the decision variable u_j, the plant characteristic curves are obtained too – the hydro unit optimal combination and the hydro units optimal level of power considering head dependency and the head loss effect is achieved. These curves allow knowing the power delivered by the plant and the available unit commitment, with minimum water flow. In such a way, the plant, as well as all his units, becomes characterized by one combination of three variables: power, water flow and head. This combination is non-linear and presents critical points, corresponding to discontinuities (generate/not generate points).

IV. Illustration Results

As an illustration of problem $(\mathcal{Q})$ solution, a small hydro power plant with six units, G1-G4 (identical units), G5 and G6, was considered. Each unit is characterized by eight curves, $I = 8$, and the relation between heads is given by $h_{i+1} > h_i$ with $i = 1,\cdots 8$. Fig. 1, Fig. 2 and Fig. 3 show the curves of each unit, where each curve corresponds to the function $q_{ji} = f(p_{ji}, h_i)$, and their quadratic approximation, which are given by the function

$$q_{ji} = \alpha_{ji} + \beta_{ji} p_{ji} + \frac{\gamma_{ji}}{2} p_{ji}^2 ,$$

with $h_i = c^{te}$, $j = 1,\cdots 6$ and $i = 1,\cdots 8$.

In these figures, the following values of power are also marked (these values correspond to the local restrictions of power, as indicated in the expression (4)): minimum and maximum values that the unit can generate in the curve i; minimum and maximum values that the unit can generate whatever the curve i is.

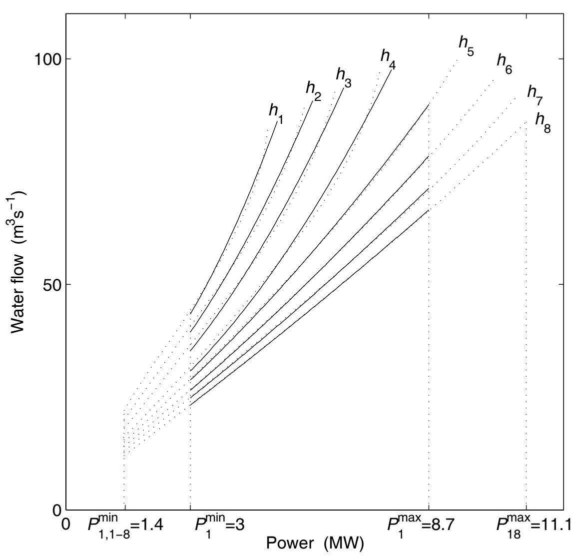

Fig. 1 Characteristic curves of unit 1 of the hydro power plant – dotted line – and their quadratic approximation – solid line.

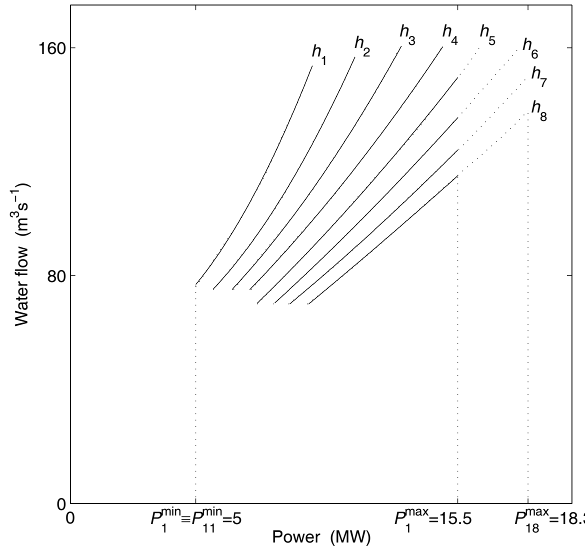

Fig. 2 Characteristic curves of unit 2 of the hydro power plant – dotted line – and their quadratic approximation – solid line.

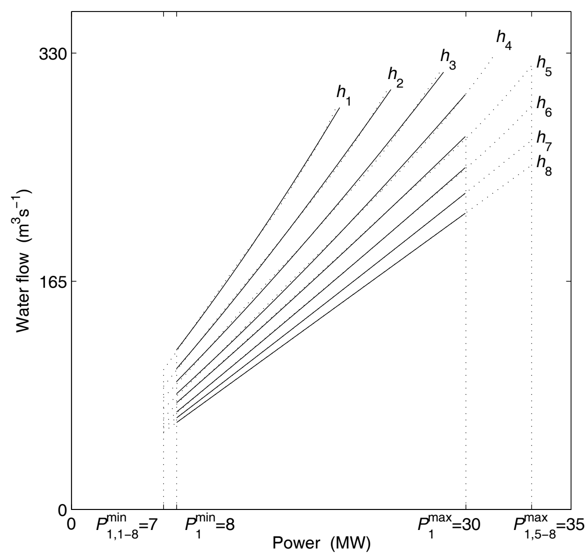

Fig. 3 Characteristic curves of unit 3 of the hydro power plant – dotted line – and their quadratic approximation – solid line.

Each unit has a non-linear and non-convex relationship between the quantities involved: power, water flow and head. The quadratic approximation of each curve guarantees that the objective function is convex, which gives a good approximation of characteristic curve in unit 1 (Fig. 1) and an excellent approximation of the characteristic curves in unit 2 and unit 3 (Fig. 2 and Fig. 3, respectively).

A. Without Considering the Elevation of the Downstream Head–Afterbay Elevation

In this example, the problem $(\mathcal{Q})$ solution allows to obtain eight characteristic curves for the central – the same number of curves that characterizes each unit, without considering the elevation of the downstream head with the water flow through power house.

Fig. 4 and Fig. 5 show the characteristic curves of the hydro power plant, for constant values of head and for constant values of power, respectively.

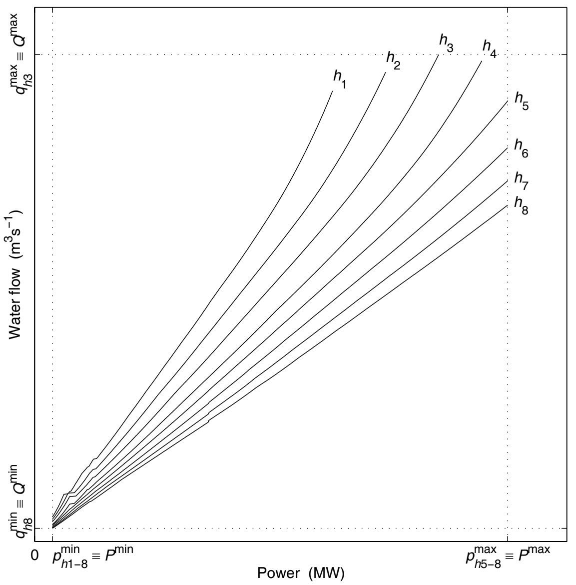

Fig. 4 Set of characteristic curves of the hydro power plant for constant head values.

For any value of power P generated by the hydro power plant, and for the considered values of head h_i the water flow Q is minimum, defining the unit commitment (Q is the total water flow through the committed units). In the case of unit commitment involving a combination of units, the level of power generation is different for each one of them – Fig. 4 shows the total values of power and water flows. Note that a discontinuity exists, near low power area, caused by the transitions between different unit commitments. This fact results from both the different characteristics of each unit and the generating capacity limits. Except for the critical area, the curves have a smooth and continuous evolution**.**

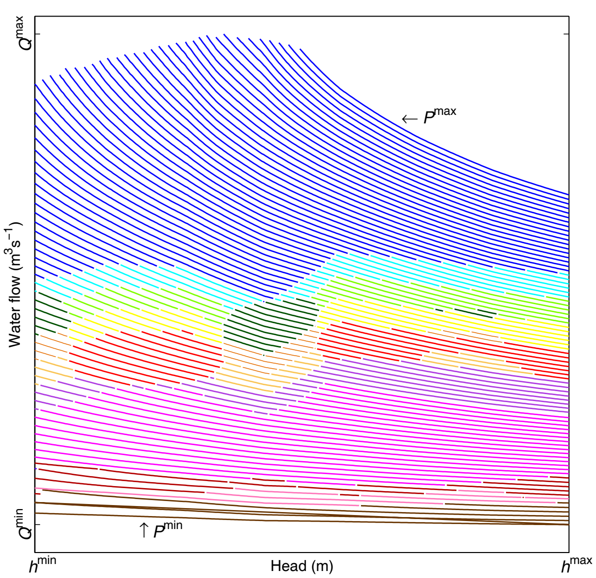

Fig. 5 Set of characteristic curves of the hydro power plant for constant power generated values and the corresponding unit commitment according to the color map.

Fig. 5 shows the characteristic curves of the hydro power plant for a constant value of generated power. This figure shows the increase in water flow needed to generate the same value of power with the decrease in head. Also, it can be seen that for some values of power, the unit commitment changes, according to the head and the water flow to achieve optimal solution. The critical area referred above can also be seen near low power values.

Also, Fig. 5 shows the obtained different unit commitments with different colors. Each color represents a different combination of units. Note that is possible to obtain up to nine different commitments for the same generated power, up to five different commitments for the same water flow and up to ten different commitments for the same head.

B. Considering the Elevation of the Downstream Head–Afterbay Elevation

In Subsection *A* the numerical results were obtained without considering the elevation of the downstream–the head loss effect was neglected.

Here the dispatch of head dependent hydro units problem is solved considering the head loss effect. Although in cascaded reservoirs the assumption made in *A* is valid (since the downstream is a reservoir and the net head is the difference between the level of the upstream reservoir and the level of the downstream reservoir), in a hydro power plant without downstream reservoir the loss head effect is of major concern (since the afterbay elevation tends to reduce the head).

The set of characteristics curves of the hydro power plant are obtained considering the head loss effect — here assumed as $h_i^{'}$ and are shown in Fig. 6 with solid lines. The set of curves obtained for this case is smaller, since the power generated is constrained for a minimum value of the head.

Fig. 6 analysis allows concluding that the head loss effect tends to reduce the power plant efficiency. This effect is a major factor on the central exploitation optimization and must be taken into account. For small hydro power plant and for the presented illustration problem, the head loss effect reduces the power plant efficiency in about 20 per cent. Also, if the head loss effect is neglected the obtained solution leads to results that are unrealistic or even infeasible.

The obtained results are a database for the problems of (1) obtain the optimal operation schedule for every power plant in each Operational Area, in order to satisfy the contracted scheduled as sent from the Market Operator, as a result of yesterday's "day-ahead bidding". The optimal operation schedule obtained should be physically feasible and optimal in terms of resource allocation. Feasibility comprises observing all constraints regarding the resource limits and resource dynamics and (2) obtain the optimal upper limit and the optimal lower limit for the intra-day bidding for the ancillary services. It is a bidding process to the System Management and Operation (SMO), so that the operation will be feasible in real time. With this bidding process, the SMO will build the so-called Provisional Viability Program, from which he will get the real-time feasibility.

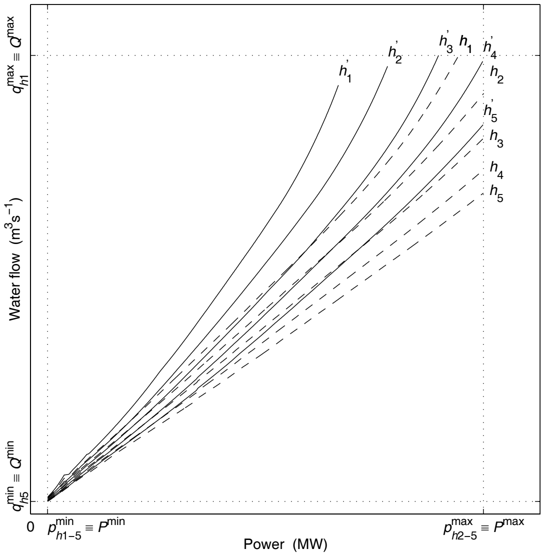

Fig. 6. Set of characteristic curves of the hydro power plant for constant head values, considering the head loss effect.

V. Conclusion

The optimal dispatch of head dependent hydro units was obtained. The problem was formulated and solved based on optimization techniques using Lagrangean relaxation. The dispatch solutions are a set of characteristic curves of the hydro power plant for constant head values, with and without the consideration of the head loss effect. These are major curves for the optimization problem of central exploitation. The optimal dispatch allowed evaluating all possible generated power values, which units must be used, with which water flow and at what power level.

VI. References

[1] M. Shahidehpour, H. Yamin, Z. Li, *Market Operations in Electric Power Systems: Forecasting, Scheduling, and Risk Management*, John Wiley and Sons, New York, 2002.

[2] L.A.F.M. Ferreira, S.J.P.S. Mariano, V.M.F. Mendes, "Production Scheduling: Regulation or Deregulation? – Back to a Theoretical Basis", in *Proc. of the Int. Conference on Electric Utility Deregulation and Restructuring, and Power Technologies*, 2000, pp. 655-659.

[3] L.A.F.M. Ferreira, S.J.P.S. Mariano, V.M.F. Mendes, "Restructuring Models -- A Comparison Based on Numerical Simulation Results", in *Proc. IEEE PES 2000 Summer Meeting*, pp. 2189-2194.

[4] O. B. Fosso, A. Gjelsvik, A. Haugstad, B. Mo, and I. Wangensteen, "Generation scheduling in a deregulated system. The Norwegian case," *IEEE Trans. on Power Systems*, vol. 14, no. 1, pp. 75–80, Feb. 1999.

[5] L. Hongling, J. Chuanwen, and Z. Yan, "A review on risk-constrained hydropower scheduling in deregulated power market", *Renew. Sust. Energy Rev.*, vol. 12, no. 5, pp. 1465–1475, Jun. 2008.

[6] Mariano S, Catalão J, Mendes V, Ferreira L., "Power generation efficiency improvement in cascaded and head-dependent reservoirs", in *Proc. of the 15th PSCC*, Liège, Belgium, August 22-26, 2005.

[7] S.J.P.S. Mariano, J.P.S. Catalão, V.M.F. Mendes, L.A.F.M. Ferreira, "Profit-based short-term hydro scheduling considering head-dependent power generation", *in Proc. IEEE Lausanne Power Tech Conference*, Lausanne, Switzerland, pp. 1362-1367, July 1-5, 2007.

[8] S. J. P. S. Mariano, J. P. S. Catalão, V. M. F. Mendes, and L. A. F. M. Ferreira, "Optimising power generation efficiency for head-sensitive cascaded reservoirs in a competitive electricity market", *Int. J. of Elect. Power & Energy Systems*, vol. 30, no. 2, pp. 125–133, Feb. 2008.

[9] J.P.S. Catalão, S.J.P.S. Mariano, V.M.F. Mendes, L.A.F.M. Ferreira, "Scheduling of head-sensitive cascaded hydro systems: a nonlinear approach", *IEEE Trans. on Power Systems*, pp. 337-346, Feb. 2009.

[10] O. B. Fosso and M. M. Belsnes, "Short-term hydro scheduling in a liberalized power system", in *Proc. 2004 Int. Conf. Power System Technology*, pp. 1321–1326, Singapore, 2004.

[11] S. M. Amado and C. C. Ribeiro, "Short-term generation scheduling of hydraulic multi-reservoir multi-area interconnected systems", *IEEE Transactions on Power Systems*, vol. 2, no. 3, pp. 758–763, Aug. 1987.

[12] J. M. Pursimo, H. K. Antila, M. K. Vilkko, and P. A. Lautala, "A short--term scheduling for a hydropower plant chain", *Int. J. Elect. Power Energy Syst.*, vol. 20, no. 8, pp. 525–532, Nov. 1998.

[13] P. H. Chen and H.-C. Chang, "Genetic aided scheduling of hydraulically coupled plants in hydro-thermal coordination", *IEEE Trans. Power Syst.*, vol. 11, no. 2, pp. 975–981, May 1996

[14] R. Naresh and J. Sharma, "Hydro system scheduling using ANN approach", *IEEE T. Power Syst*, vol. 15, no. 1, pp. 388–395, Feb. 2000.

[15] P. E. C. Franco, M. F. Carvalho, and S. Soares, "A network flow model for short-term hydro-dominated hydrothermal scheduling problems", *IEEE Trans. Power Syst*., vol. 9, no. 2, pp. 1016–1022, May 1994.

[16] L.A.F.M. Ferreira, T. Andersson, C.F. Imparato, T.E. Miller, C.K. Pang, , and A.F. Vojdani, "Short-Term Resource Scheduling in Multi-Area Hydrothermal Power Systems", *International Journal of Electric Power and Energy Systems*, EPES-11, pp. 200-212, 1989.

[17] A. Borghetti, C. D'Ambrosio, A. Lodi, and S. Martello, "An MILP approach for short-term hydro scheduling and unit commitment with head-dependent reservoir", *IEEE Trans. Power Syst.*, vol. 23, no. 3, pp.1115–1124, Aug. 2008.

[18] J. García-González, E. Parrilla, and A. Mateo, "Risk-averse profit-based optimal scheduling of a hydro-chain in the day-ahead electricity market", *Eur. J. Oper. Res*., vol. 181, no. 3, pp. 1354–1369,Sep. 2007.

[19] E. Ni, X. Guan, and R. Li, "Scheduling hydrothermal power systems with cascaded and head-dependent reservoirs", *IEEE Trans. Power Syst.*, vol. 14, no. 3, pp. 1127–1132, Aug. 1999.

[20] Soares, S. Ohishi, T. Cicogna, M. Arce, A., "Dynamic dispatch of hydro generating units", *IEEE Power Tech Conference*, June 23-26, 2003, Bologna, Italy.

[21] S.J.P.S. Mariano, L.A.F. Marcelino Ferreira, "Métodos de optimização aplicados na determinação das curvas características de centrais Hídricas", in *Proc. V Congreso Métodos Numéricos en Ingenieria*, SEMNI, Madrid 3-6 June 2002 (*in Portuguese*).

VII. Biographies

S. J. P. S. Mariano received the M.Sc. degree from the IST, Lisbon, Portugal, in 1994 and the Ph.D. degree from the University of Beira Interior, Covilhã, Portugal, in 2002. He is currently an Assistant Professor at the University of Beira Interior. His research interests include hydrothermal scheduling, power industry restructuring, and optimal control. He is the author or coauthor of more than 60 scientific papers presented at international conferences or published in reviewed journals.

M. R. A. Calado received the electrical engineering degree from the Instituto Superior Técnico (IST), Lisbon, Portugal, in 1991, the MSc equivalent degree and the PhD degree from University of Beira Interior, Covilhã, Portugal, in 1996 and 2002, respectively. She is currently Professor at UBI, Department of Electromechanical Engineering (DEM). Her research interests include electrical machines and actuators and numerical methods. She has about 50 scientific publications.

L. A. F. M. Ferreira received the M.S.E.E. and Ph.D. degrees from the Georgia Institute of Technology, Atlanta, in 1983 and 1986, respectively. From 1986 to 1989, he was with the Pacific Gas and Electric Company, San Francisco, CA, where he was a major developer of the Hydro-Thermal Optimization program. He is currently a Full Professor at the IST, Lisbon, Portugal. His research interests include planning, management and operation of generation, transmission, and distribution systems. He is the author or coauthor of more than 150 scientific papers presented at international conferences or published in reviewed journals.