Multi-Area Decentralized Optimal Hydro-Thermal Coordination by the Dantzig-Wolfe Decomposition Method

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Abstract: This paper presents a new application of the Dantzig-Wolfe decomposition method for decoupling the multi-area hydro-thermal coordination problem. The aim of the model is to provide coordinated mechanisms to carry out medium-term operation planning studies maximizing autonomy and confidentiality for each area and assuring global economy to the whole system. The original multi-area multi-stage problem is broken into subproblems (one for each area) and a master problem (the coordinator). The coordination scheme is based on energy prices at border buses, which vary along the study period. Some algorithmic implementations may reduce the number of iterations. Numerical results for the interconnected hydro-thermal system of Central-America are presented.

Keywords: Decoupling of systems, Energy transaction optimal pricing, Interconnected power systems, Power system planning.

I. INTRODUCTION

Recently, the Central American countries: Guatemala, El Salvador, Honduras, Nicaragua, Costa Rica, and Panama have agreed a common energy act [1]. The new rules and the restructuring of regional institutions are the foundations for creating a regional energy market and they will allow to coordinate planning and operation of their electric energy systems. Initially, the countries would like to preserve autonomy in the operation planning of their hydro reservoir management and in local market, structures and regulation. Confidentiality between systems planning operators is also recommended. However, traditional software tools, like [2], [3] and [4], are being widely used assuming perfect shared information (marginal generation costs, types and sizes of thermal plants, technical data of hydro reservoirs and turbines, etc.) and central dispatch criteria [5]. This paper contributes with a new application of the Dantzig-Wolfe (DW) decomposition method [6] for decoupling the multi-area Hydro-Thermal Coordination (HTC) problem. The aim of the model is to provide coordinated mechanisms to carry out medium-term operation planning studies of interconnected hydro-thermal systems maximizing autonomy and confidentiality for each system and assuring global economy to the whole system. A regional coordinator having functions such as: to ensure technical feasibility of individual power flows through interconnections, and to induce all the systems to get global economy would be required. A small amount of information between the involved systems operators and the coordinator would be sufficient to reach the global optimum in a finite number of interactions. Fig. 1 shows the approach.

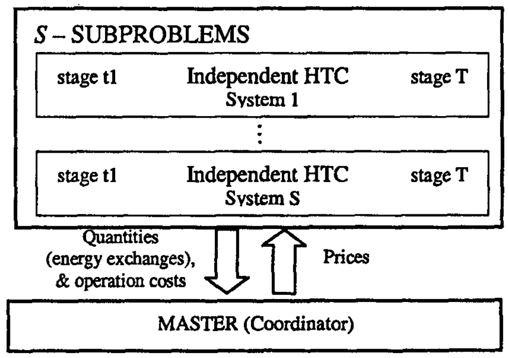

Fig. 1. Muti-Area HTC decentralization by Dantzig-Wolfe Decomposition.

The coordinator (master) proposes energy prices at boundaries, which vary along the study period. Systems operators (subproblems) decide how much energy they want to sell (export) or buy (import) at those prices and the incurred individual gross variable operating costs overall the study period (in net present value, if a discount rate is used).

DW concepts have already been applied to the economic dispatch (ED) [8-12] and unit commitment (UC) [13] problems. Similarly, the Lagrangian Relaxation (LR) decomposition [7] has been applied to the ED [14] and the UC [15] problems. Likewise, the Augmented Lagrangian (AL) decomposition [7] has been applied to the ED [16]. DW, LR and AL are analogous decomposition methods; their main differences are in the price updating procedure (master formulation). In general, LR and AL can be seen as extensions of DW to nonlinear or nonconvex cases. Two other methods have been applied to the ED decoupling, one based on LR combined with micro-economics principles [17], and the other one on a decomposition of the set of optimal conditions for a nonlinear programming problem [18]. The decomposition of the ED in unit [8, 9, 10] or area [11, 12, 14, 16, 17, 18] subproblems is limited to the single-stage case. These algorithms might be useful in the multi-stage case if temporal constraints are excluded (e.g., for a given hydro production). [13] extended unit decomposition to the multi-stage case in order to solve the daily dynamic generation scheduling. However, unit decomposition is excessive for multi-system (multi-country or multi-utility) purposes. [15] proposed another framework to solve a DC multi-area UC, which formulates the area subproblem as the

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aggregation of multiple unit subproblems. Other LR approaches for the short-term multi-area UC and HTC problems include [19, 20, 21]. Two coordinated subproblems, one thermal and one hydraulic, were proposed by [19, 20]. [21] changed the thermal subproblem into an electrical subproblem (hydro production is optimized in both the hydraulic and the electrical subproblems). [15, 19, 20, 21] lose sight of the desired role of a system (self-control of demand, generation and exchanges, confidentiality, etc.). Therefore, the multi-area HTC problem has not been fully decoupled in multiple areas using DW or other decomposition techniques.

The next section gives basic terminology and notation to facilitate reading of this paper. The original HTC problem is formulated in Section III. Section IV shows the decentralized model. Section V presents numerical results. Section VI provides conclusions.

II. BASIC TERMINOLOGY AND NOTATION

A. Terminology

System or area: it is an individual system (country or utility),
Whole or global system: set of systems,
Border bus: it is a fictitious bus or system located between two interconnected systems. It has no generation or load.

B. Sets

- s, S index and set of real systems,
- t, T index and set of stages,
- j, J index and set of primal vertices (answers) of the feasible region of the subproblems, index j means current iteration of the DW algorithm, $j = 1,\ldots,k$,
- k auxiliary index for iteration counter (accumulated number of vertices), j and k are super-index/sub-index in parameters/variables associated to vertices,
- K maximum number of iterations, $K \ll J$, J is unknown.

C. Primal Variables

- g_{st} thermal generation in system s, stage t, in MW,
- q_{st} hydro turbine outflow in system s, stage t, in m^3/s,
- vi_{st}, vf_{st} volumes of stored water in the reservoir at the beginning and ending of current stage, in hm^3,
- w_{st} spillage or waste outflow of hydro reservoir, in hm^3,
- f_{st} power flow that system s injects/extracts to/from the border bus (see Fig. 2), in MW,
- d_{st}, e_{st} power deficit and power excess, the former means non-supplied power and acts as a dummy generator, the latter acts as a dummy load, d_{12t} & e_{12t} are analogous artificial variables at the border bus indicated in Fig. 2,
- λ_{js} unit weight associated to the answer (or vertice) j of system s.

D. Dual Variables

- p_{st} marginal energy price or Lagrange multiplier or spot price, in US\$/MWh, p_{12t} is the price at border bus,
- α_s net cost of system s estimated by the master, it is equal to gross cost (c_s) plus incomes from exports ($f_{st}<0$) minus payments for imports ($f_{st}>0$), it is computed overall stages, in US\$, $\alpha_s = c_s + \sum_t p_{st} f_{st}$.

E. Functions

- c_s gross cost of system s estimated by subproblem s for all the study period, in US\$; $c_s = \sum_t c_{st}$,
- c_{st} sum of the variable thermal generation costs plus penalty costs associated to power deficit or excess, $c_{st} = cvg_s\, g_{st} + cd\, d_{st} + ce\, e_{st}$.

F. Constants or Parameters

- ρ_s energy coefficient of the hydro turbine, in $MW/m^3/s$,
- τ conversion factor to change m^3/s to hm^3,
- cvg_s thermal variable operating unit cost, in US\$/MWh,
- cd, ce strong penalty for artificial variables, US\$ 1000/MWh,
- c_s^j gross cost of system s, iteration j, in US\$,
- f_{st}^j power flow of system s, stage t, iteration j, in MW,
- I_{st} hydro inflows, in hm^3,
- D_{st} demand, in MW,
- F_s maximum power flow through interconnection, in MW,
- G_s maximum thermal generation, in MW,
- Q_s maximum hydro turbine outflow, in m^3/s,
- V_s', V_s'' minimum & maximum storage in reservoir, in hm^3.

III. CENTRAL PROBLEM FORMULATION

For the sake of simplicity it will be assumed, without loss of generality, that the global system consists of just two areas and each area has only one thermal plant and one hydro with reservoir as shown in Fig. 2. A fictitious border bus is defined in order to facilitate spatial decomposition.

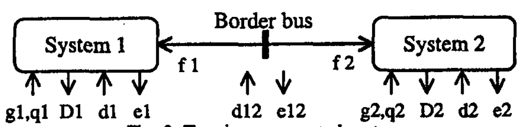

Fig. 2. Two interconnected systems.

For math clarity, stair index (load stairs per stage), transport losses and discount rate are not shown and duration of stages is assumed as one hour. The central HTC problem can be formulated as the following deterministic linear and convex programming model:

$$Z = \underset{g,d,e,q,w}{\text{Minimize}} \quad \sum_t (c_{1t} + c_{2t} + c_{12t}) \qquad (1)$$

subject to: *dual variable*

$$-f_{1t} - f_{2t} + d_{12t} - e_{12t} = 0 \qquad : p_{12t} \qquad \forall t \quad (2)$$

$$g_{st} + \rho_s q_{st} + f_{st} + d_{st} - e_{st} = D_{st} \qquad : p_{st} \qquad \forall s\ \forall t \quad (3)$$

$$vf_{st} + \tau q_{st} + w_{st} = vi_{st} + I_{st} \qquad \forall s\ \forall t \quad (4)$$

$$0 \le g_{st} \le G_s \qquad \forall s\ \forall t \quad (5)$$

$$0 \le q_{st} \le Q_s \qquad \forall s\ \forall t \quad (6)$$

$$V_s' \le vi_{st},\ vf_{st} \le V_s'' \qquad \forall s\ \forall t \quad (7)$$

$$-F_s \le f_{st} \le F_s \qquad \forall s\ \forall t \quad (8)$$

$$w_{st} \ge 0 \qquad \forall s\ \forall t \quad (9)$$

$$d_{st},\ e_{st} \ge 0 \qquad s = 1, 2, 12,\ \forall t, \quad (10)$$

where c_{12t} is the border artificial cost, $c_{12t} = cd\, d_{12t} + ce\, e_{12t}$. Decision variables are: g_{st}, d_{st}, e_{st}, q_{st} and w_{st} (q_{st} & w_{st} have zero unit cost). The global objective function Z consists of gross costs for each system and border bus (1). Equations (2, 3) are the energy balances at equivalent buses. Water balances is modeled by (4). The other constraints fix bounds to the primal variables (5-10).

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IV. DECENTRALIZED MODEL

DW decomposition is suitable for problems with an angular-structure matrix (matrix with complicating constraints). The angular structure of (2-4) at any stage t is shown in Fig. 3.

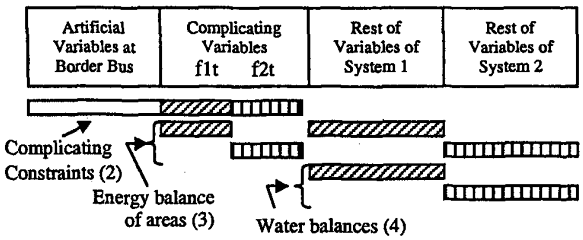

Fig. 3. Matrix structure of the HTC problem at any stage

Looking at Fig. 3, it is easy to conclude that (2) is complicating the problem because its variables are presented in different equations. The DW decomposition idea is to relax (2) in order to transform the angular structure of the original matrix into a diagonal structure. The master would be in charge of the complicating constraint (2), spatial links between systems. The subproblems would be in charge of their corresponding blocks of constraints, they will be free to self-control all their own resources including exchanges with neighboring systems.

A. Subproblems

The independent HTC subproblem for system s is defined as:

$$Z_s(p_{12t}) = \underset{g,d,e,q,w,f}{\text{Minimize}} \quad \sum_t (c_{st} + p_{12t}\, f_{st}) \qquad (11)$$

subject to:

$$g_{st} + \rho_s q_{st} + f_{st} + d_{st} - e_{st} = D_{st} \quad \forall t \qquad (12)$$

$$v_{fst} + \tau q_{st} + w_{st} = v_{ist} + I_{st} \quad \forall t \qquad (13)$$

$$0 \le g_{st} \le G_s \quad \forall t \qquad (14)$$

$$0 \le q_{st} \le Q_s \quad \forall t \qquad (15)$$

$$V_s' \le v_{ist},\ v_{fst} \le V_s'' \quad \forall t \qquad (16)$$

$$-F_s \le f_{st} \le F_s \quad \forall t \qquad (17)$$

$$w_{st},\ d_{st},\ e_{st} \ge 0 \quad \forall t, \qquad (18)$$

where $Z_s(p_{12t})$ is the individual net costs of subproblem s conditioned to the last border prices proposal. Note that border prices are fixed parameters and exchanges have become decision variables. Repeating (11-18) for s=1,...,S, all subproblems can be defined and solved in a decentralized fashion (in parallel). At each iteration, the structure of the subproblems is invariant, changing only the border prices.

Now, the interconnection is as a new agent, which competes with local generators. At each stage, it can be seen as an offer (one for each border bus connected to the system) whose quantity is the line transfer capability, and price is given by the master. Since prices may come from outside (other system) or inside local system, the offers induce a more efficient use of the thermal and hydro resources. Under an isolated HTC, hydro is dispatched trying to substitute the most expensive local thermal generation and/or avoid non-supplied energy. Under this coordinated scheme, hydro will try to take advantage about opportunity costs propagated across interconnections. The water value will tend to adapt progressively to the global competition induced by the border prices.

The subproblems are optimized at the end of the current iteration (j=k), but their answers are sent to the master as if they were generated at the beginning of the next one (j=k+1). The answers are: i) power exchanges at each stage (at each border bus connected to the system), f_{st}^{k+1}; and ii) gross operating cost aggregated overall the study period, c_s^{k+1}. Since subproblems are decoupled, the individual power flows may differ in any border bus at any stage. The master must eliminate those infeasibilities.

B. Master

Applying DW Theory [6], using k accumulated vertices of the subproblems and taking boundaries (complicating constraints) into account, at iteration k, the master is defined as:

$$\underset{\lambda,d,e}{\text{Minimize}} \sum_{j=1}^{j=k} (c_1^j \lambda_{j1} + c_2^j \lambda_{j2}) + \sum_t (c_d\, d_{12t} + c_e\, e_{12t}) \qquad (19)$$

subject to: *dual variable*

$$-\sum_{j=1}^{j=k}(f_{1t}^j \lambda_{j1} + f_{2t}^j \lambda_{j2}) + d_{12t} - e_{12t} = 0 \quad : p_{12t} \quad \forall t \qquad (20)$$

$$\sum_{j=1}^{j=k} \lambda_{js} = 1 \quad : \alpha_s \quad \forall s \qquad (21)$$

$$\lambda_{js} \ge 0 \quad \forall j, \forall s \qquad (22)$$

$$d_{12t},\ e_{12t} \ge 0 \quad \forall t. \qquad (23)$$

Decision variables are λ_{js}, d_{12t} and e_{12t}. Answers of Subproblems are considered as fixed parameters, but adjustable according to their weights (19-20). The function (19) consists of the estimation of the individual gross costs plus the penalties at the border bus. Equation (20) ensures global (spatial) feasibility of the individual power flows at boundaries. Equation (21) is called convexity or unified equation (one for each system), because it ensures global (temporal and spatial) feasibility to the individual sets of k vertices in the master. Formulation (19-23) is called multi-column, since adds as many columns as systems, at each iteration. Other structure called mono-column (one global weight per iteration) has been analyzed too, see Section V. The master estimates the individual attributes as convex linear combinations of the j=1,...,k vertices:

$$c_s = \sum_j c_s^j \lambda_{js} \quad \forall s \qquad (24)$$

$$f_{st} = \sum_j f_{st}^j \lambda_{js} \quad \forall s, \forall t. \qquad (25)$$

The master combines the accumulated answers in the best way to compute new prices that improve the global economy. In order to start the master, the subproblems can be solved fixing power flows to zero (isolated HTC), to compute separately the first S vertices. Those vertices will give a real reference to estimate the coordinated operation savings achieved after each iteration. If the number of vertices is reduced, then the linear combinations may be no well-balanced (in some stages). In that case, the dummy generator or load will get involved in the solution to guarantee optimality. The more vertices the more possibilities to ensure global feasibility reducing the need for artificial variables.

Dual variable of (20) is the border marginal price, p_{12t}. Dual of (21) is the estimation of individual net costs, α_s.

After solving the master with a standard solver [22], both variables are obtained automatically. The master sends only prices to the subproblems. New vertices are identified and the process is repeated until satisfying the optimality condition.

C. Optimality Condition

According to linear programming theory [23], the optimality of a primal is assured by its corresponding dual constraints. The dual of (19-23) is:

$$\underset{\alpha,\, p12t}{\text{Maximize}} \ \sum_{s=1}^{s=2} \alpha_s \tag{26}$$

subject to: *dual variable*

$$\alpha_s - \sum_t f_{st}^{j}\, p12_t \le c_s^{j} \qquad : \lambda_{js} \qquad \forall j\ \forall s \tag{27}$$

$$- c_e \le p12_t \le c_d \qquad \forall t. \tag{28}$$

Decision variables are α_s and $p12_t$. Equation (27) defines the main DW cuts. Note that dual variables of (27) are the DW primal weights. Other cuts (28) impose bounds to the price fluctuations according to the unit penalty costs of the artificial variables. Fig. 4 depicts the geometry of the dual.

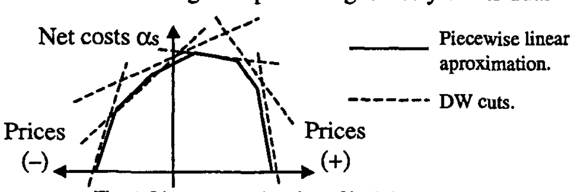

Fig. 4. Linear approximation of individual net costs

Fig. 4 states that optimal individual net cost function (unknown because of the decentralization) can be constructed gradually adding more cuts to the dual or columns to the primal. DW cuts ensures individual net costs are under the feasible region drawn in Fig. 4. Thus, each estimated net cost, α_s, is an upper bound of the real optimum net costs.

Obviously, master's dual solution (prices and net costs) always satisfies (27) for all known k vertices. To assure general optimality, (27) must be satisfied for other unknown vertices (e.g., next vertices j=k+1):

$$\alpha_s \le \left(c_s^{k+1} + \sum_t f_{st}^{k+1}\, p12_t \right) \qquad \forall s. \tag{29}$$

If the optimality sufficient conditions (29) are satisfied individually, they should also be verified globally. Adding (29) together for s=1,...,S, and reorganizing terms, we get the global optimality necessary condition:

$$\sum_s \left(c_s^{k+1} + \sum_t f_{st}^{k+1}\, p12_t - \alpha_s \right) \ge 0, \tag{30}$$

which is called the global reduced costs for all the coupling constraints for the last vertices k+1. An equivalent condition can be implemented applying bounds to the net costs. The upper and lower bounds, at iteration k, are defined as:

$$\overline{Z}^k = \sum_{s=1}^{S} \alpha_s \tag{31}$$

$$\underline{Z}^k = Max\{ \underline{Z}^{k-1}, \sum_{s=1}^{S} Z_s \}, \tag{32}$$

where Z_s is defined by (11) considering last prices proposal. Lower bound is updated in such a way that it shows a monotonous increase between two consecutive iterations (if k=1, then $\underline{Z}^0 = -\infty$). That gives a better reference for reducing the net costs of the master. Now, (30) can be redefined as:

$$\left| \overline{Z}^k - \underline{Z}^k \right| / \overline{Z}^k \le \varepsilon, \tag{33}$$

where ε is a given relative tolerance between bounds, in per unit. It should be noted that the master has enough information to estimate both bounds and determine global optimality. If the last vertices satisfy (33) or (30), then the process stops. The optimal solution for subproblems (and the whole system) is guaranteed and should be constructed by a linear combination of the k vertices. Otherwise, the new vertices go to the master, and the process continues.

D. Pre-process

If ε is equal to zero, then (33) is fully equivalent to (30). Exact optimal solution can be achieved for small-scale problems. Real large-scale systems are more complex and may require a less precise tolerance, e.g., 0.01 per unit, in order to have acceptable solutions in less number of iterations. Another idea to accelerate convergence is implementing a pre-process. A pre-process would need some historical series of prices (compatible with the expected hydro inflows, demand, fuel prices, etc.) to compute vertices before starting the master up. Master will estimate better prices because of the set of initial vertices. Subproblems will rapidly find rational answers. Both things induce bounds closer to the optimal solution.

E. Post-process

The last vertice of each subproblem is only used for assuring optimal convergence. It is not the individual optimum. The optimum can be constructed following an efficient post-process: (i) the master computes optimal exchanges using (25), f_{st}^*, and send them together with the optimum prices, $p12_t^*$, to the subproblems; and (ii) each subproblem is optimized once more fixing exchanges to f_{st}^*, to compute its final feasible and optimal solution.

The centralized and decentralized models have been formulated and developed in a more generic way to handle: load-duration curves approximated by monotonous stairs (e.g., peak and off-peak) at each stage, hydro networks, run-of-the-river plants, discount rate and linear transmission losses. The models were programmed in the GAMS language [22] and optimized with primal simplex of CPLEX 6.0 [22].

V. CASE STUDY

The proposed approach has been applied to the Central-American system. At first, detail results will be presented for a case of 3 systems, 2 border buses, 3 stages, 2 stairs/stage (peak stair is 17.8% of the stage duration), 1 large hydro with reservoir, and 2 thermal plants (one representing steam turbines and efficient Power Purchase Agreements (PPAs), and the other one, gas turbines and expensive PPAs). Then, results for the whole system (6 countries), 5 border buses, considering a study period of 1 year divided in 12 months, 2 stairs/month, 10 hydro plants with reservoir, 18 run-of-the-river plants, hydro networks, and 38 thermal plants will be given. Next tables present data only for the 3 systems case, which considers 200 MW as transfer capability between areas.

Table 1. Hydro plants data

Hydro Plant	Sys.	V^i Hm^3	V^* Hm^3	Q m^3/s – MW	ρ $MW/m^3/s$	Inflows, m^3/s t1	t2	t3
Chixoy	GU	128	451	69 – 275	3.974	55	36	95
Cerrón	ES	787	2180	293 – 135	0.461	292	163	312
Cajón	HO	2139	5653	239 – 300	1.257	115	95	225

Note: initial and final hydro reserves (vist1, vfsT) were assumed equal to 75% of V*.

Table 2. Thermal plants data

Thermal Plant	System	G MW	Unit Cost $US/MWh
BK	GU	150	35
DS		335	55
BK	ES	185	45
DS		210	65
BK	HO	160	60
DS		110	75

BK: Base-load plant firing heavy-fuel oil, DS: Peak-load plant firing diesel.

Table 3. Demand data (MW)

System	Stage t1		Stage t2		Stage t3	
	Peak	Off-Peak	Peak	Off-Peak	Peak	Off-Peak
GU	450	300	460	310	440	330
ES	375	250	385	210	365	240
HO	421	270	390	220	470	320

Both cases were solved in a centralized and decentralized fashion using a workstation Sun Ultra-1 Model 170. Centralized and decentralized models gave identical results. The former has been used to deduce and validate the latter.

Considering ε=0 for the 3-system case, multi-column DW converged in 26 iterations, with a CPU time of 940 ms. Mono-column DW took 73 iterations. Fig. 5 shows the convergence behavior of the upper and lower bounds.

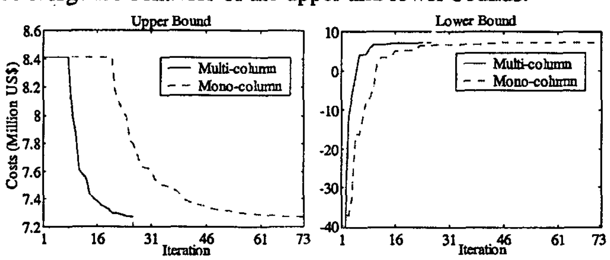

Fig. 5. Evolution of upper and lower bounds

As shown in Fig. 5, the multi-column master is faster than the mono-column one (individual approximations are more efficient that global ones). Note how the upper bound keeps at the isolated operation costs (first vertice: US$ 8.4×10^6) until the lower bound becomes positive. Upper bound decreases slowly. Lower bound increases rapidly, but later converges smoothly. Good convergence is possible before bounds are identical.

Table 4. Report of Costs, in 10^3US$, and Energy Balance (3-systems case)

Sys.	Gross Costs	Incomes (-) Payments (+)	Net Costs	Dem GWh	Therm GWh	Hydro GWh	Exchange GWh
GU	3646	-2344	1302	170	94	125	-49
ES	3599	-384	3215	130	80	60	-9
HO	27	2728	2755	150	0	92	58
Global	7272	0	7272	451	174	277	0

Energy balances of Table 4 indicate that GU and ES are net exporter because it is attractive to displace all expensive thermal generation in HO. Fig. 6 illustrates the typical evolution of prices and power flows during the process.

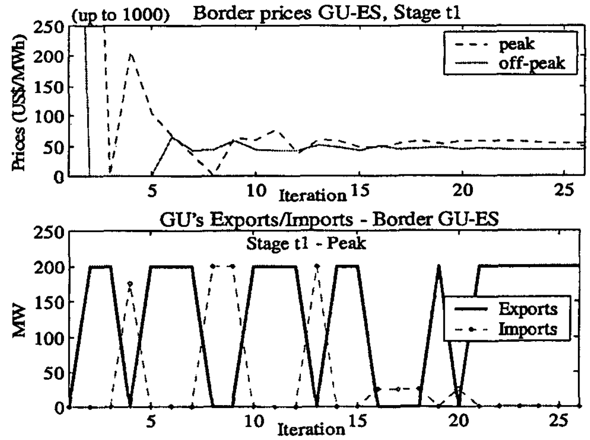

Fig. 6. Typical evolution of border prices and power flows.

At the beginning, prices are unstable and fictitious (inducing unstable power flows), then decrease and fluctuate softly around the optimal value. Power flows tend to stabilize when prices are close to convergence.

The 6-system case was solved with the multi-column DW algorithm, without and with a pre-process, considering year 2000 data and forecasts, and three different tolerances (ε=0.001, 0.005, 0.01 per unit) typical to the large family of relaxation methods. The pre-process used 60 series border prices to let the subproblems generate 60 initial vertices before starting the master up. Those prices were obtained with different DW simulations (without pre-process) for some specific operation conditions (the same network topology, average hydrology, expected evolution of fuel prices and demand, etc.). Those conditions are compatibles to the ones simulated in the case study. Table 5 presents the main numerical results (number of iterations, CPU time, and global costs) estimated for each tolerance.

Table 5. Numerical Results of the DW algorithm (6-systems case)

Tolerance %	¿Pre-process?	Number of Iterations	CPU Time (s)	Costs ZDW (10^6 US$)	$\frac{\lvert Z_{DW}-Z^*\rvert \cdot 100}{Z^*}$
0.1	No	309	284	413.061	0.008
	Yes	126	170	413.062	0.008
0.5	No	219	182	413.294	0.065
	Yes	25	62	413.280	0.061
1.0	No	184	147	413.525	0.120
	Yes	8	29	413.403	0.091

Z* = US$ 413.027 million (optimal solution - centralized model). Isolated operation cost was US$ 433.384 million, operation savings US$ 20.3 million. Column 6 shows relative difference between DW solution and centralized solution.

For the complex Central-American case, the general DW HTC (without pre-process) has shown a very poor convergence. Some reasons: high number of complicating constraints in the master (5 borders x 2 stairs/stage x 12 stages = 120), which is unusual in static cases (e.g., [14]), little changes in prices cause sudden fluctuations in transactions because of dynamic hydro reservoirs, hydro networks, run-of-the-river dispatch between load levels (stairs) of the same stage, etc.. However, the number of iterations and consuming time may be adequate for doing studies in an automatic, decentralized and remote way.

Besides, we must remember that medium-term operation models are used to be executed in an off-line mode. Whatever the application may be, for any tolerance, a simple pre-process may reduced the number of iterations drastically due to more stables coordinating signals (prices and quantities). In our case study, assuming 1% (or 0.5%) as relative tolerance between bounds, the pre-process makes the DW algorithm very attractive for practical applications (8 iterations and half a minute of CPU). Additional studies were conducted to analyze the robustness of the pre-process. The results not mentioned here motivate its generic use.

VI. CONCLUSIONS

This paper proposes a new multi-area HTC algorithm that maximizes autonomy and confidentiality of each system while achieving global economy to the whole system. Autonomy: each system keeps the operation planning control with absolutely loose coordinated mechanisms. Confidentiality: local information is not shared, declaring only some exports or imports, and the aggregated operation costs incurred in the local market. In addition, the algorithm allows the coexistence of different individual regulations, which is of special interest in an international environment.

The algorithm is based on the Dantzig-Wolfe decomposition procedure and has been applied to a realistic case study. Future developments include hydro uncertainty modeling, and design of necessary rules for real implementations.

VII. ACKNOWLEDGMENTS

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