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PAY-AS-BID PRICING IN COMBINED POOL / BILATERAL AND RESERVE ELECTRICITY MARKETS

Fabio STACKE

Department of Electrical Engineering
University of Brasilia (Brazil)

Pablo CUERVO

Department of Electrical Engineering
University of Brasilia (Brazil)

Abstract

This paper presents a pricing model considering the simultaneous interaction of pool, bilateral and reserve markets in a power system. The model is adapted to work through a ‘pay as bid’ (PAB) pricing approach that is currently being considered as an option for pricing in some actual systems. The combined market is settled through an AC Optimal Power Flow (OPF) that accounts for power generation (pool and bilateral contracts) and availability of reserve services. As a result, prices of energy and reserve services incorporate the influences of the transmission network such as topology, voltage levels, losses, generation and transmission capacity limits. Results show that with this model agents can better plan their portfolios based on prices that reflect the costs of resources considering several operation scenarios and bid strategies.

1. NOMENCLATURE

Functions:

$C_{g\,i}(p_{g\,i})$	generator i energy bid (\$/h)
$C^{RU}_{g\,i}(ru_{g\,i})$	Generator i regulation up bid (\$/h)
$C^{RD}_{g\,i}(rd_{g\,i})$	Generator i regulation down bid (\$/h)
$C^{SR}_{g\,i}(sr_{g\,i})$	Generator i spinning reserve bid (\$/h)
$C^{NS}_{g\,i}(ns_{g\,i})$	Generator i non spinning reserve bid (\$/h)
$C^{RC}_{g\,i}(rc_{g\,i})$	Generator i complementary reserve bid (\$/h)

Variables:

$p_{g\,i}$	total production of Generator i (MW)
$p^{p}_{g\,i}$	Pool Generation awarded level (MW)
$ru_{g\,i}$	generator i awarded level of regulation up reserve (MW)
$rd_{g\,i}$	generator i awarded level of regulation down reserve (MW)
$sr_{g\,i}$	generator i awarded level of spinning reserve (MW)
$ns_{g\,i}$	generator i awarded level of non spinning reserve (MW)
$rc_{g\,i}$	generator i awarded level of complementary reserve (MW)
$q_{g\,i}$	generator i reactive power generation (MVar)
$v_i\ ,\ \delta_i$	Bus i voltage phasor module and angle

Constant Parameters:

$p_{d\,j}$	Active power demand level at bus j (MW)
R^{RU}	Amount of regulation up reserve required by the system (MW)
R^{RD}	Amount of regulation down reserve required by the system (MW)
R^{SR}	Amount of spinning reserve required by the system (MW)
R^{NS}	Amount of non spinning reserve required by the system (MW)
R^{RC}	Amount of complementary reserve required by the system (MW)
N	Number of integration steps

$RP^{RU}_{g\,i}$	10 min. ramp rate for providing $ru_{g\,i}$ in MW/minute
$RP^{SNS}_{g\,i}$	10 min. ramp rate for providing $sr_{g\,i}$ and $ns_{g\,i}$ in MW/minute

Lagrange Multipliers:

λ^{p}_{i}	Active power nodal Price at bus i ($/MWh)
λ^{q}_{i}	Reactive power nodal price at bus i ($/MVarh)
λ^{RU}	L. M. of regulation up requirement ($/MWh)
λ^{RD}	L. M. of regulation down requirement ($/MWh)
λ^{SR}	L. M. of spinning reserve requirement ($/MWh)
λ^{NS}	L. M. of non spinning reserve requirement ($/MWh)
λ^{RC}	L. M. of complementary reserve requirement ($/MWh)

2. INTRODUCTION

In recent years, electricity markets have developed important economic and operational tools looking for efficiency in terms of determining prices that represent the costs of production and transmission of energy. This effort has been oriented to obtain corresponding payments and revenues that truly reflect the use of services and provide economic signals for future investments in infrastructure. From the point of view of pricing electricity services two approaches are mainly followed : One of them is the classical marginal pricing (MP) where nodal prices represent the cost of the last MW to be supplied and the other is “pay as bid” pricing (PAB) which is the way forward bilateral contracts are negotiated. Whether one or the other should be followed has been object of controversy and it is not the focus of this paper to discuss this issue. Recently, PAB pricing has showed an increasing interest because some markets like in Wales and England are essentially based on bilateral agreements that are traded following a PAB approach. Additionally, from the theoretical point of view, new studies have shown some advantages of PAB over MP. In [5] it is demonstrated that in the general case when the load is not exactly predicted, the expected profits and load payments are the same under MP and PAB but the risk of not meeting these values are greater under MP.

Other important aspect in pricing is from the point of view of the two existing forms of markets auctions for trading energy and services [1]. One is based on private markets and the other is based on a strong coordination. In the first one, the provision of services is left to secondary markets after the main energy auction is defined. In this structure there is an unbundling of providing energy and services. Because of the free participation of traders in each market of each service is voluntary, opportunity for arbitrage motivates traders to move from one market to another. The possible advantage of this auction structure is that the voluntary participation of traders in markets could provide efficiency, like in a pool, avoiding using complex optimization tools. In the second kind of market auctions, market products are procured simultaneously through central auctions. The purpose of this type of auction is that optimization is necessary to minimize costs of generation, transmission and reserves to meet demand and ensure reliability. The advantage of this integrated market is that the resulting pricing better reflects the cost of resources. Several systems operate with this structure like in New York, New England and PJM. Also, several models have been suggested following this trend.

This paper analyzes the characteristics of a new pricing model designed for working with MP or PAB approaches in a combined integrated market structure with the presence of forward bilateral contracts. In the simultaneous auction, energy and reserve ancillary services are procured and the focus is obtaining pricing mechanisms for these services considering the coexistence with the forward bilateral contract market [4]. A detailed mathematical formulation of the problem is presented showing how prices of energy and ancillary services can be obtained from Lagrangean multipliers.

The model considers the ancillary service market composed of several reserve services [1,2,6]. The characterization of these services is previously defined by the regulator and is based on the quality of their response. The possibility of substitution among reserve services based on agent bids avoiding price reversal between them is considered like in [1,6].

The PAB version of this model is implemented through an integration process based on the Auman-Shapley [3,4] technique that takes into consideration the non-linear characteristic existing in the transmission network due to transmission losses and voltage behaviors using an AC OPF. These features are not present in simpler PAB schemes such as pro-rata. The integration process allows also to unbundling the use and prices of several services including transmission bilateral contracts losses, pool dispatch, and availability of reserve services.

One of the main advantages of this approach is the fact that market agents can better plan their portfolios of products to increase revenues (generators) or minimize payments (loads) because of the possibility of considering different operation scenarios with a less risky pricing approach such as PAB. From the ISO point of view, it is possible to estimate the impact of different levels of total bilateral trades, generation and transmission capacity on reserve and energy prices.

The paper is organized as follows. Section 3 presents the formulation used to represent the integrated market and bilateral contracts. Also in this section, the pricing mechanism is described. Section 4 presents numerical examples and Section 5 presents the conclusions.

3. FORMULATION

First of all, the suggested model considers that a Unit Commitment (UC) problem has been solved previously and the set of scheduled units are known for solving an AC OPF in the auction process. The focus here is to solve the pricing problem through a PAB approach operating in an integrated market. In order to simplify the presentation we consider that load has no participation in the ancillary service market but this extension can be easily incorporated. Also, we consider a one hour pricing model with no inter-temporal constrains.

3.1. Pool Market Model

Pool market determines awarded energy and reserve bids for a period of one hour with the presence of long term bilateral contracts. In this market is minimized a function composed by energy and reserve services bids characterized by the following objective function.

$$
\begin{aligned}
&Minimize \left\{ \sum_i C_i(p_{g\,i}) \ + \right. && \rightarrow \text{(Energy)}\\
&+ \sum_i C_i^{RU}(ru_{g\,i}) \ + && \rightarrow \text{(Regulation Up Reserve)}\\
&+ \sum_i C_i^{SR}(sr_{g\,i}) \ + && \rightarrow \text{(Spinning Reserve)}\\
&+ \sum_i C_i^{NS}(ns_{g\,i}) \ + && \rightarrow \text{(non-Spinning Reserve)}\\
&+ \sum_i C_i^{RC}(rc_{g\,i}) \ + && \rightarrow \text{(Complementary Reserve)}\\
&\left. + \sum_i C_i^{RD}(rd_{g\,i}) \right\} && \rightarrow \text{(Regulation Down Reserve)}
\end{aligned}
\tag{1}
$$

Bid functions can be used as quadratic functions approximations or linear functions related to bid blocks.

3.2. Transmission Network Model

From ISO the point of view, awarded bids should attend operation constraints imposed by the transmission system; therefore, feasible solutions should belong to the set S described in equations (2)-(7). Equations (2) and (3) represent the load flow equations. Equation (4) represents transmission line active flow limits, equations (5)-(7) represent capacity limits and voltage limits. Vector v represents bus voltage modules and vector δ represents phase angle bus voltages. Both vectors have dimension equal to the number of buses *n*.

$$p_i = p_{g\,i} - p_{d\,i} = p_i(\mathrm{v},\delta),\, i = 1,\ldots,n \quad \rightarrow \lambda_i^p \tag{2}$$

$$q_i = q_{g\,i} - q_{d\,i} = q_i(\mathrm{v},\delta)\,,\, i = 1,\ldots,n \quad \rightarrow \lambda_i^q \tag{3}$$

$$-p_{i\,j}^{\max} \le p_{i\,j} \le p_{i\,j}^{\max}, \qquad i, j = 1,\ldots,n \tag{4}$$

$$p_{g\,i}^{\min} \le p_{g\,i} \le p_{g\,i}^{\max}, \qquad i = 1,\ldots,n \tag{5}$$

$$q_{g\,i}^{\min} \le q_{g\,i} \le q_{g\,i}^{\max}, \qquad i = 1,\ldots,n \tag{6}$$

$$v_i^{\min} \le v_i \le v_i^{\max}, \qquad i = 1,\ldots,n \tag{7}$$

Lambda variables represent dual variables associated to each constraint. In the case of equations (2) and (3), they also represent nodal prices.

3.3. Reserve Market characteristics

Generators agents can bid in five kinds of reserve services: Regulation up, Regulation Down, Spinning, Non-Spinning, and Replacement. The speed of response defines the quality of each service. Faster regulations services such as regulation up and down and spinning reserve are considered of higher quality. In order to open possibilities of reducing costs, it is also allowed the possibility of substitution among reserve services. The substitution consists in allowing that services with better quality and lower cost can substitute services with lower quality [1,6]. A feasible bid selection in the reserve market auction should belong to the set E described by equations (8)-(14).

$$R^{RU} \leq \sum_{i=1}^{n} ru_{g\,i} \qquad \rightarrow \lambda^{RU} \qquad (8)$$

$$R^{RU} + R^{SR} \leq \sum_{i=1}^{n} ru_{g\,i} + \sum_{i=1}^{n} sr_{g\,i} \qquad \rightarrow \lambda^{SR} \qquad (9)$$

$$\begin{aligned} & R^{RU} + R^{SR} + R^{NS} \leq \\ & \qquad \sum_{i=1}^{n} ru_{g\,i} + \sum_{i=1}^{n} sr_{g\,i} + \sum_{i=1}^{n} ns_{g\,i} \qquad \rightarrow \lambda^{NS} \end{aligned} \qquad (10)$$

$$R^{RC} \leq \sum_{i=1}^{n} rc_{g\,i} \qquad \rightarrow \lambda^{RC} \qquad (11)$$

$$R^{RD} \leq \sum_{i=1}^{n} rd_{g\,i} \qquad \rightarrow \lambda^{RD} \qquad (12)$$

$$ru_{g\,i} \geq 0, sr_{g\,i} \geq 0, ns_{g\,i} \geq 0, rc_{g\,i} \geq 0, rd_{g\,i} \geq 0 \qquad (13)$$

$$\begin{aligned} & ru_{g\,i} \leq ru_i^{\max}, sr_{g\,i} \leq sr_i^{\max}, ns_{g\,i} \leq ns_i^{\max}, \\ & rc_{g\,i} \leq rc_i^{\max}, rd_{g\,i} \leq rd_i^{\max} \end{aligned} \qquad (14)$$

Where, lambda variables are dual variables associated to each constraint, and R^{RU} , R^{SR} , R^{NS} e R^{RC} e R^{RD} (in MW) are the required system amounts of each service during one hour. These quantities are considered known fixed parameters in the market auction. Upper limits (14) represent physical limits such as ramp rates, which are part of the reserve bids.

3.4. Bilateral Market Model

Private Bilateral contracts are considered as firm contracts to be implemented by ISO who should take into consideration the transmission network. In a compact form, bilateral contracts can be grouped in a GD matrix where each coefficient $GD_{i\,j}$ represents the MW traded between generator at bus i and load at bus j. Therefore, the total amount of contracts supplied by generator *i* is,

$$p_{g\,i}^{b} = \sum_{i=1}^{n} GD_{i\,j} \qquad (15)$$

In addition, the total amount of contracts supplying the demand at bus *j* is,

$$p_{d\,i}^{b} = \sum_{j=1}^{n} GD_{i\,j} \qquad (16)$$

In this model is supposed that long-term bilateral contracts have priority in relation to the pool dispatch. Because of this, the availability of generators participating in the pool market is constrained due to their already committed capacity with bilateral contracts as shown in. Equation (17).

$$p_{g\,i} \geq p_{g\,i}^{b} \qquad (17)$$

3.5. Generator and Load Participations

In the integrated market, besides attending bilateral and pool loads, each generator *i* participates bidding the availability of several reserve services in the reserve market. The awarded reserve bids should respect the operational capacity limits of each generator as described in equations (18) and (19).

$$p_{g\,i} + ru_{g\,i} + sr_{g\,i} + ns_{g\,i} \leq p_{g\,i}^{\max} \qquad (18)$$

$$rd_{g\,i} - p_{g\,i} \geq p_{g\,i}^{b} \qquad (19)$$

In addition, an important consideration is the capacity of response due to the technology employed by each generator *i* characterized by the corresponding ramp rate in MW/min. In the same way as in [1], equation (20) shows how to consider this constraint in a time basis of 10 minutes through a linear relationship.

$$\frac{ru_{g\,i}}{RP_{g\,i}^{RU}} + \frac{rs_{g\,i} + ns_{g\,i}}{RP_{g\,i}^{SNS}} - 10 \leq 0 \qquad (20)$$

3.6. Pricing of Reserve Services

The Lagrangean function of the optimization problem described before in equations (1) to (20) allows to obtain expressions for the market clearing prices of services based on the dual variables as shown in equations (21)-(25).

$$\frac{\partial L}{\partial R^{RU}} = \lambda^{RU} + \lambda^{SR} + \lambda^{NS} = MCP_{RU} \qquad (21)$$

$$\frac{\partial L}{\partial R^{SR}} = \lambda^{SR} + \lambda^{NS} = MCP_{SR} \qquad (22)$$

$$\frac{\partial L}{\partial R^{NS}} = \lambda^{NS} = MCP_{NS} \qquad (23)$$

$$\frac{\partial L}{\partial R^{RC}} = \lambda^{RC} = MCP_{RC} \qquad (24)$$

$$\frac{\partial L}{\partial R^{RD}} = \lambda^{RD} = MCP_{RD} \qquad (25)$$

Since Lagrange, multipliers are positive; this formulation ensures not reversal prices among services. In other words, $MCP_{RU} \geq MCP_{SR} \geq MCP_{NS}$ [1,6].

3.5. *Pay as Bid* pricing model

The pay as bid version of this model is implemented through an integration process based on the Auman-Shapley [1] technique that takes into consideration the non-linear characteristic existing in the transmission network due to transmission losses and voltage behaviors. These features are not present in simpler pay as bid schemes such as pro-rata. The integration process allows also to unbundling the use and prices of several services including pool dispatch, reserve availability and bilateral contracts. One-step of the process is described as follows.

Bilateral Contracts: Losses attributed to bilateral contracts due to the use of the transmission network are compensated in the Pool market. Initially, bilateral load is incremented by $dGD_{i\,j}$ while holding fixed the pool load and reserve requirements whose value at the very beginning are nil. In this step, the optimization problem minimizes costs of loss compensation due bilateral contracts. The incremental problem to be solved is the following,

$$\begin{aligned} &\underset{P_{g\,i}}{Min} \sum_{i=1}^{n} C_i(P_{g\,i}) \quad s.t. \quad \{\, dGD \in S \cup E \\ &and \quad (P_d^p, R^{RU}, R^{RG}, R^{NG}, R^{RC}, R^{RD})\ fixed\} \end{aligned} \qquad (26)$$

If the solution of this problem is $dp^*_{g\,i}$ then the contract incremental losses are obtained through equation (27).

$$dp^b_{g\,i} = dp^*_{g\,i} - \sum_{j=1}^{n} dGD_{i\,j} \qquad (27)$$

Pool Market: In this step, the pool load is incremented by vector dp_d^p and reserve requirements are incremented sequentially by $dR^{RU}, dR^{SR}, dR^{NS}, dR^{RC}, dR^{RD}$ while holding fixed bilateral contracts load. The problem to be solved in this case is the following,

$$\begin{aligned} \underset{P_{g\,i}, ru_i, sr_i, ns_i, rc_i, rd_i}{Min} \quad & \sum_{i=1}^{n} [C_{g\,i}(p_{g\,i}) + C^{RU}_{g\,i}(ru_{g\,i}) + \\ & + C^{SR}_{g\,i}(sr_{g\,i}) + C^{NS}_{g\,i}(ns_{g\,i}) + \\ & + C^{RC}_{g\,i}(rc_{g\,i}) + C^{RD}_{g\,i}(rd_{g\,i})] \end{aligned} \qquad (28)$$

$$\begin{aligned} s.t. \quad & \{(GD\ fixed), dP_d^p, dR^{RU}, dR^{SR}, \\ & dR^{NS}, dR^{RC}, dR^{RD}\} \in S \cup E \end{aligned}$$

3.6. Integration Process

The integration process consists in solving alternatively problems (26) and (28) for small load increments following a uniform integration path from zero to the final value of the load, according to the "*t*" parameter such that $0 \leq t \leq 1$, as shown in equation (29).

$$X = \int_{t=0}^{1} dx(t) \qquad (29)$$

Vector X is composed of variables $dp_{g\,i}$, $dp^b_{g\,i}$, $dru_{g\,i}$, $dsr_{g\,i}$, $dns_{g\,i}$, $drd_{g\,i}$ and $drc_{g\,i}$. In particular, the integration process of each load and required service follows the adjustment of parameters indicated in equations (30)-(32). Others reserve services follow the same procedure.

$$GD(t^b) = t^b \cdot GD, \quad 0 \leq t^b \leq 1 \qquad (30)$$

$$P_d^p(t^p) = t^p \cdot P_d^p, \quad 0 \leq t^p \leq 1 \qquad (31)$$

$$R^{RR}(t^{RU}) = t^{RU} \cdot R^{RU}, \quad 0 \leq t^{RU} \leq 1 \qquad (32)$$

Considering the set of vectors $t = [t^b; t^p, t^{RU}, t^{SR}, t^{NS}, t^{RD}]^T$ of size[1] n x 1 with $t^{(0)} = [0, 0, 0, 0, 0]^T$ and a constant increment step dt = t/N, the initial step of the integration process increases parameters sequentially as showed in equations (33)-(35).

$$t^{(1)} = [dt^b, 0, 0, 0, 0, 0]^T \qquad (33)$$

$$t^{(1)} = [dt^b, dt^p, 0, 0, 0, 0]^T \qquad (34)$$

$$t^{(1)} = [dt^b, dt^p, dt^{RU}, 0, 0, 0]^T \qquad (35)$$

In the following integration steps, additional dt increments are added in the same order.

3.7 Revenues and Payments

This section presents how revenues and payments are obtained for generators and

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[1] vectors t^{RU}, t^{SR}, t^{NS} and t^{RD} are built by using a unit elementary vectors of the type $e=[0,\ldots,1,0,\ldots0]^T$ with size n x 1

loads participating in the integrated market. These economic indexes are presented in incremental terms since they are calculated inside the integration process.

Bilateral Contracts

Because bilateral contracts are negotiated in private, their prices are not available. Nevertheless, we adopt as a price for these contracts the corresponding incremental costs of generators.

Revenues: The generator *i* revenue due to bilateral contracts and loss compensation is,

$$dR_i^b = IC_i^b \cdot \sum_{j=1}^{n} dGD_{ij} \qquad (36)$$

$$dR_i^{bL} = \lambda_i \cdot dp_{gi}^b \qquad (37)$$

Payments: Load *j* pays bilateral contracts and half of the loss compensation according with equations (38) and (39),

$$d\pi_{dj}^b = \sum_{i=1}^{n} IC_i^b \cdot dGD_{ij} \qquad (38)$$

$$d\pi_{dj}^{bL} = (1/2)\sum_{i=1}^{n}(\lambda_i - \lambda_j)\cdot dGD_{ij} \qquad (39)$$

In addition, Generator *i* pays half of the loss compensation,

$$d\pi_{gi}^{bL} = (1/2)\sum_{i=1}^{n}(\lambda_j - \lambda_i)\cdot dGD_{ij} \qquad (40)$$

Pool and Reserve

Revenues: Generator *i* has a revenue portfolio due to its awarded bids in energy and reserve market given by equations (41)-(43).

$$dR_{gi} = \lambda_i \cdot dp_{gi} \qquad (41)$$

$$dR_{gi}^{RU} = MCP_{RU} \cdot dru_{gi} \qquad (42)$$

$$dR_{gi}^{SR} = MCP_{SR} \cdot dsr_{gi} \qquad (43)$$

Incremental revenues of other services follow similar calculations.

Payments: Load *j* pays pool demand and reserve services according to equations (44)-(46). In the case of reserve services, load *j* pays in a pro-rate manner.

$$d\pi_{dj} = \lambda_j \cdot dp_{di} \qquad (44)$$

$$d\pi_{dj}^{RU} = MCP_{RU} \cdot \Big(\sum_{i=1}^{n} dru_{gi}\Big)\cdot(p_{dj} / p_{d\,Total}) \qquad (45)$$

$$d\pi_{dj}^{SR} = MCP_{SR} \cdot \Big(\sum_{i=1}^{n} dsr_{gi}\Big)\cdot(p_{dj} / p_{d\,Total}) \qquad (46)$$

Incremental payments related to the other services are obtained in similar way. As can be seen, this model allows generators and loads to estimate the impact of several scenarios like for instance, total load level of bilateral contracts, power transfer capacity, and reserve level requirements on their portfolios.

4. NUMERICAL RESULTS

This section analyzes results of a 5-Bus and a modified version of the IEEE 30-Bus networks when the pricing model is applied.

5 Bus System

Table 1 shows the data used in the 5-Bus system. Per unit values are in the base of 100 MVA and 200 kV. Table 2. describes capacity limits of generators and the submitted bids in the energy market are characterized by the C_{gi} continuous functions. The estimated total system requirement of reserve is 5% of total load. In order to simplify the amount of data, the generators bid functions for each reserve service are considered with the same parameters of the energy bids in Table 2 with exception of regulation up bid of generator 1 that is half of the energy bid ($a_{g1}^{RU} = 10$ \$/MWh and $b_{g1}^{RU} = 0.02$ \$/MW^{2}h). In addition, in order to simplify the observation of results, the cases presented do not produce transmission congestion.

TABLE 1 Network data of 5-Bus system

From	To	r (pu)	x (pu)	b (pu)	p_{flow}^{max} (pu)
1	2	0,0147	0,168	0,138	3,00
1	4	0,0108	0,126	0,102	3,55
2	3	0,0185	0,210	0,185	3,00
3	4	0,0294	0,336	0,296	3,00
3	5	0,0221	0,252	0,213	3,00
4	5	0,0108	0,126	0,104	4,50
2	4	0,0105	0,130	0,100	3,60

TABLE 2 Generators Bids and Capacity

$$C_{gi}(p_{gi}) = c_{0i} + a_i \cdot p_{gi} + 0.5 \cdot b_i \cdot p_{gi}^2 \quad (\$/h)$$

Bus	p_g^{min} (MW)	p_g^{max} (MW)	c_0 (\$/h)	a (\$/MWh)	b (\$/MW^{2}h)
1	0	500	0	20	0.040
2	0	500	0	21	0.030
3	0	500	0	25	0.045
4	0	500	0	56	0.040
5	0	500	0	57	0.040

Table 3. shows bilateral contracts matrix GD whose coefficients are in MW. When the full amounts in GD matrix are implemented, the pool load required in each bus is $p_d^p = [2,\ 5,\ 7,\ 19,\ 31]^T$. Total system load is 1088 MW distributed in each bus according with the following vector: $p_d = [34,\ 85,\ 119,\ 323,\ 527]^T$.

TABLE 3 Bilateral Contracts

		Loads (MW)					
	Bus	1	2	3	4	5	Total
Generators (MW)	1	32	48	32	144	160	416
	2	0	32	32	112	240	416
	3	0	0	48	48	96	192
	4	0	0	0	0	0	0
	5	0	0	0	0	0	0
	Total	32	80	112	304	496	

Tables 4 to 9 show results for a base case considering that 47% of load is supplied by the bilateral contract market, substitution among reserve services is allowed and two reserve services are available in the reserve market that requires a total reserve margin of 5% of total load (with RU= 14.4 MW and SR= 40 MW).

TABLE 4 Awarded Energy Dispatch (47% of load traded as B.C.)

Bus	Dispatch (MW)		Incremental Cost	nodal Price
	Bilateral	Pool	($/MW)	($/MW*h)
1	208.0	174.6	35.3	35.3
2	208.0	275.8	35.5	35.5
3	96.0	168.4	36.9	36.9
4	0.0	0.0	56.0	37.8
5	0.0	0.0	57.0	40.6
Total = 1130.86 Losses = 42.86				

TABLE 5 Awarded Reserve and Price

Bus	Regulation up reserve		Spinning reserve	
	($/MW*h)	(MW)	($/MW*h)	(MW)
1	11.09	54.4	11.09	0.0
2 to 5	11.09	0.0	11.09	0.0
Total	54.4		0.0	

TABLE 6 Generators Revenue Portfolio

Bus	Economic indexes ($/h)		
	Energy	Reserve	Total
1	10581.40	573.58	11154.90
2	13670.70	0.0	13670.70
3	8183.17	0.0	8183.17
4 and 5	0.0	0.0	0.0
Total	32435.27	573.58	33008.85

TABLE 7 Loads Payment Portfolio

Bus	Energy Payment	Reserve Payment	Total
	($/h)	($/h)	($/h)
1	1013.6	17.92	1031.52
2	2534.0	44.81	2578.81
3	3547.6	62.74	3610.34
4	9629.2	170.28	9799.48
5	15710.8	277.83	15988.63
Total	32435.27	573.58	33008.85

Table 4 shows that the incremental cost of generators in operation are almost the same. Ninety seven percent of the capacity of the cheap generator 2 is allocated to the energy market that also considers low cost transmission loss compensation. Since generator 1 has the lowest regulation up bid, its entire reserve bid for regulation up is awarded for attending both services (as shown in Table 5) and reducing the price in reserve market to 11 $/MWh. Tables 6 and 7 show the generators and loads portfolios. Because of the PAB principle, no Merchandising Surplus (MS) is produced as can be observed when comparing total revenues and total payments in these tables. If the same generator bids are used in a marginal pricing approach, total cost of operation is increased by 31% because of the MS paid by loads.

As a second example, we increase bilateral contracts level from 47% to 94% while holding fixed total load (pool load is decreased). Table 8 shows that generators 1 and 2 are heavy committed with bilateral contracts. Only generator 2 participates in the three markets. The low bid of generator 1 for regulation up is awarded and part of its capacity is allocated for the reserve market rather than in the pool energy market, as shown in Table 9. Reserve price is higher than in the previous case. Again, no merchandising surplus is produced because of the PAB principle as can be seen comparing Tables 10 and 11. Total payments increases 565.8 ($/h).

TABLE 8 Awarded Energy Dispatch (94% of load traded as Bilateral Contracts)

Bus	Dispatch (MW)		Incremental Cost	nodal Price
	Bilateral	Pool	($/MW)	($/MW*h)
1	416.0	0.0	36.6	34.5
2	416.0	47.8	34.9	34.9
3	192.0	59.8	36.3	36.3
4	0.0	0.0	56.0	37.1
5	0.0	0.0	57.0	39.9
Total=1131.63 Losses= 43.63				

TABLE 9 Awarded Reserve and Price

Bus	Regulation up reserve		Spinning reserve	
	($/MW*h)	(MW)	($/MW*h)	(MW)
1	21.5	37.6	21.5	0.0
2	21.5	16.8	21.5	0.0
3,4,5	21.5	0.0	21.5	0.0
Total	54.4		0.0	

TABLE 10 Generators Revenue Portfolio

Bus	Economic indexes ($/h)		
	Energy	Reserve	Total
1	11781.1	752.0	12533.1
2	12967.9	352.8	13320.7
3	7721.4	0.0	7721.4
4 and 5	0.0	0.0	0.0
Total	32470.3	1104.8	33575.1

TABLE 11 Loads Payment Portfolio

Bus	Payment for Energy	Payment for Reserve	Total
	($/h)	($/h)	($/h)
1	1014.70	34.53	1049.23
2	2536.74	86.31	2623.05
3	3551.44	120.34	3671.78
4	9639.63	327.99	9967.62
5	15727.82	535.14	16262.96
Total	32470.30	1104.31	33574.64

30 Bus System

A modified version of the IEEE 30-Bus system is used according with the following conditions: Total load is 283.4 MW, there is a bilateral contract of 50 MW between generator at bus 2 and load at bus 4, and two reserve services are required. The total reserve requirement is 5% of total load (with 2.5% needed for RU and 2.5% needed for SR). Reserve ancillary services bids are 10% of energy bids. Each generator submits equal RU and SR bids.

TABLE 12 Awarded Energy Dispatch

Bus	Dispatch (MW)		Incremental Cost	Local Price
	Bilateral	Pool	($/MW)	($/MWh)
1	0.0	100.0	11.2	18.1
2	50.0	0.7	18.4	18.4
5	0.0	50.0	13.8	18.7
8	0.0	50.0	13.8	19.0
11	0.0	0.0	37.9	17.8
13	0.0	0.6	19.3	18.5
15	0.0	36.5	18.5	18.5
24	0.0	0.0	39.9	19.6
30	0.0	0.0	49.3	21.0
Total	287.83		Losses	4.43

Table 12 and 13 show the awarded bids for energy, reserve and prices as well as bilateral contract including losses. Generators at buses 1, 5, and 8 are dispatching energy at maximum capacity. Because of this, they do not participate in the less profitable reserve market. Table 14 shows generators revenue portfolio. Results show that if compared with the solution obtained with a marginal pricing approach using the same generator bids, the PAB version gives an economy of 32% in total cost because merchandising surplus is not produced.

TABLE 13 Awarded Reserve and Price

Bus	Regulation reserve		Spinning reserve	
	($/MWh)	(MW)	($/MWh)	(MW)
2	1.82	7.1	1.82	0.0
13	1.82	2.0	1.82	0.0
15	1.82	5.1	1.82	0.0
others	1.82	0.0	1.82	0.0
Total	14.2		0.0	

TABLE 14 Generators Revenue Portfolio

Bus	Economic indexes ($/h)		Bus	Economic indexes ($/h)	
	Energy	Reser.		Energy	Reser.
1	1092.40	0.0	13	11.1	2.66
2	926.20	12.81	15	628.69	9.28
5	677.23	0.0	24	0.00	0.0
8	678.78	0.0	30	0.00	0.0
11	0.00	0.0			
Total: Energy = 4014.88 Reserve = 25.84					

5. CONCLUSION

In this paper a new pricing model is presented with the following characteristics: i) integration of bilateral, pool, and reserve markets; ii) integration allows to know the impact of markets interactions on the operation and consequently on prices; iii) Allows the possibility of assessment of pay as bid pricing against the uniform pricing counterpart; iv) Allows to produce detailed portfolios for agents in terms of revenues and payments for each awarded bid in each market; v) Allows possibility of testing several operation scenarios with price strategies in order to evaluate the impact on agents portfolios.

The model considers the transmission system operation in detail including generation and transmission capacities, transmission losses, voltage limits and reactive limits. Bilateral contracts are treated as physical firm contracts loading transmission lines and therefore producing transmission losses. Several reserve services are considered according with the quality of speed response. The possibility of substitution among these services is allowed for cost reduction without creating the undesirable price reversal.

The characteristics of this model make it attractive for analyzing the impact of several operation scenarios and bid strategies on the agent's portfolios. Further research is in progress for considering large power systems.

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M.Sc. Fabio STACKE

Was born in 1975 in Rio de Janeiro, Brazil. He received the M.Sc. degree in electrical engineering from Department of Electrical Engineering, University of Brasilia.

Mailing address:
Fabio Stacke, CCSW 5, lote 3, bloco B, apt 201, Setor Sudoeste, Brasília, DF
BRAZIL,
Phone: (+55) (61) 2192-8846,
Fax: (+55) (61) 2192-8745.
e-mail: fabiostacke@hotmail.com

Prof. Pablo CUERVO

received his M.S. and D.S. degrees from University of Campinas - UNICAMP, Brazil. He developed post-doctoral research activities at McGill University, Canada.

Mailing address:
Pablo Cuervo, Universidade de Brasilia - UnB, Dep. Engenharia Elétrica - ENE, Asa Norte, 70910-900 Brasilia - DF
Phone: (+55)-61-32735977 Ext.:216,
Fax: (+55)-61-32746651
e-mail: pablo@ene.unb.br