

# Competitive Electricity Market for Spinning Reserve Evaluating the System Dynamic Behavior

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**Abstract** - The electric sector trend from vertically integrated structures to competitive structures outlines the need of exhaustive studies of Ancillary Services (AS) not only from the operative point of view but also from the economic one. In this paper the Spinning Reserve (SR) is the AS analyzed.

This paper proposes a methodology to determine the optimal level of SR required by the system and its optimal allocation in competitive electricity markets. This methodology carries out a joint economic dispatch of energy and SR, determining with this, the corresponding prices of each service for each generating unit. To achieve these objectives, the proposed methodology not only considers the economic aspect but also uses weighted factors as the speed of dynamic response and the geographical-electric location of each generating unit to improve the system dynamic response against different outages.

*Keywords:* Ancillary Services (AS), Dynamic Behavior, Spinning Reserve (SR), Competitive Electricity Market, Interruption Costs.

## 1 INTRODUCTION

AS are duties or activities performed by equipment or human being to support the basic services of electric energy generation and transmission to guarantee the system security and efficiency.

There are a diversity of AS identified in the bibliography, but our study is based on Spinning Reserve (SR). This service is necessary for the system security because it is responsible of maintaining the system frequency inside a predefined limit under disturbances. In geographically extensive systems, such as the Latin American networks that are weakly meshed and with load nodes located far from generation centers, the required level and the allocation of SR are particularly very important.

Generally, maintaining a SR level equal to the power of the greatest unit in operation in the system is the most used criterion. However, this SR amount is not a guarantee that during the first 30 seconds, the system could withstand an outage without Automatic Load Shedding (ALS) caused by low frequency.

The main problem of this method is that the system's dynamic behavior (capacity response and geographical location of the generating units) and the economic

evaluation of the expected value of energy not supplied (ENS) are disregarded [1], [2]. The optimal level of SR required by the system depends on the magnitude of the demand, the current dispatch and the amount and location of the ALS devices.

This paper proposes a methodology for the Joint Economic Dispatch (JED) of energy and the SR, which determines the optimal level of SR required by the system, by evaluating the system's dynamic behavior and the expected cost of ENS under different outages.

This methodology is implemented in a market-based cost where every generating unit uses its costs for energy and SR like a bids. As a result of the optimisation process the system marginal cost of energy and SR are given.

In order to evaluate the system's dynamic behavior, it is necessary to consider the individual response of each generating unit and their location within the transmission network. Each generating unit's dynamic response is modeled through the Capacity Response Factor ( $F_{CRi}$ ). The electric geographical location of each unit is evaluated by the Node Factor ( $FN_i$ ).

Many authors have studied these problems. For example, a method to determine the optimal levels of SR by considering the system's dynamic aspect without an economic evaluation of ENS was proposed in [3] and [4]. The proposed methodology could be of a great interest for people working in systems operation area as an independent system operator (ISO) or power producers.

The paper is structured as follows. In section 2 the JED formulation of energy and SR is shown. The method is applied to a test system of 44 nodes, as described in section 3, and conclusions are given in section 4.

## 2 JOINT ECONOMIC DISPATCH OF ENERGY AND SR

Current methodologies for the joint optimisation of energy and the SR services in [5] and [6] do not determine an optimal level of SR for the system, and their allocation is carried out only from the economic point of view. The proposed methodology (PM) determines the optimal level of SR required by the system for each analyzed demand level through an

economical evaluation of the system's dynamic behavior. Besides, it allocates this SR among the units in order to minimize the system's total costs (operative plus ENS).

The PM presented in this paper is general but its main application is in electric power systems where the outage of some generating units represent more than 2% of the system total demands causing considerable frequency deviations. Typical examples are the systems of Australia, New Zealand, and the most Latin American countries.

### 2.1 Non-Linear Mathematical Formulation

The mathematical formulation of JED is as follows:

$$FO = \text{Min} \sum_{i=1}^{N_g} C_i(P_{gi}) + \sum_{i=1}^{N_g} C_{Ri}(R_i) + E(C(ENS)) \quad (1)$$

where:

- $C_i(P_{gi})$  Generation production costs
- $C_i(R_i)$  SR costs
- $E(C(ENS))$  Expected value of interruption cost

Subjected to the following constraints:

Power balance

$$\Theta_P : \sum_{i=1}^N D_i + \sum_{l=1}^{Nl} L_l - \sum_{i=1}^{N_g} P_{gi} = 0 \quad (2)$$

- $D_i$  Demand in node.
- $L_l$  Losses in transmission network
- $P_{gi}$  Generated power by unit i.

SR balance

$$\Theta_R : Refec_{Sis} - \sum_{i=1}^{N_g} Refec_i \leq 0 \quad (3)$$

- $Refec_{Sis}$  Effective SR required in the system
- $Refec_i$  Effective SR available in each generating unit

Technical limits of generation and SR

$$\begin{aligned} \Omega_{T_i} : P_{gi} + R_i &\leq P_{gi,max} \\ \Omega_{P_i} : P_{gi} &\geq 0 \\ \Omega_{r_i} : 0 &\leq r_i \leq r_{i,max} \end{aligned} \quad (4)$$

- $R_i$  SR in MW allocated in unit i
- $r_i$  SR percentage level in unit i
- $P_{gi,max}$  Maximum power generation

The minimum power constraint is not presented in the equation (4) because it produces a discontinuity in the problem solution. Because of this, the problem can not be directly resolve using a linear programming

algorithm. The problem of minimum power constraint is resolve through a iterative procedure based on heuristic. The heuristic is used to define the convex domain of the objective function to implement the linear programming algorithm [8].

The SR balance constraint (3) is used to obtain through the respective Lagrange multiplier ( $\delta$ ), the marginal cost of supplying an additional unit of  $Refec$ . Thus, this multiplier determines the market price of  $Refec$  in the system.

$Refec_{Sis}$  is a decision variable of the problem and it represents the effective optimal value of SR required by the system to achieve minimum total cost.  $Refec_i$  is the effective reserve available by each generating unit. It reflects the effective contribution of SR from a certain unit, at the site where it is required [7]. This term is modeled as:

$$\begin{aligned} Refec_i &= R_i FN_i F_{CRi} \\ R_i &= r_i P_{gi} \end{aligned}$$

- $F_{CRi}$  Capacity Response Factor
- $FN_i$  Node Factor

Some constraints as ramping, minimum up and down times of the units are not presented in the formulation because the economic dispatch was made for one hour and not integrated in the time. These additional constraints could significantly affect the dispatch of energy and SR. A dispatch considering these aspects can be seen in [8].

### 2.2 Dynamic Response of Generating Units

Each generating unit responds in a particular way to a system outage. To account for this aspect within the formulation, the factor  $F_{CRi}$  is used, reflecting the effective power contribution delivered by a generating unit with respect of a certain amount of allocated SR. This factor is calculated through dynamic behavior studies on each generating unit under various disturbances [7].

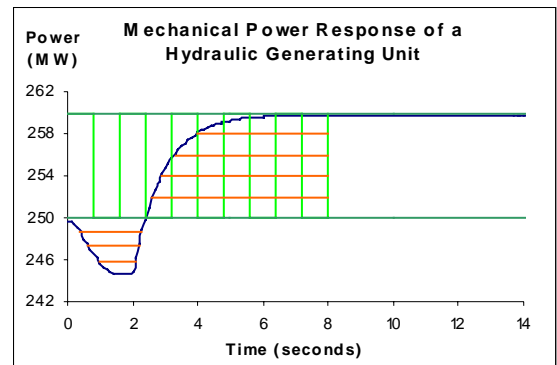


Figure 1: Mechanical Power Response of a Hydraulic Unit.

The behavior of mechanical power supplied by a hydraulic generating units deserves a special analysis, because during the first seconds after the outage, it contributes to a frequency decrease (Figure 1).

The figure 1 has been obtained from computer simulations. The hydraulic unit has a capacity of 300 MW and a generating unit outage of 246 MW is simulated. The dynamic characteristics of the system are typical parameter corresponding to the type and size of the units [10,11].

The formulation of  $F_{CRi}$  factor is as follow:

$$F_{CRi} = \frac{\int_0^t Emece \, dt}{\int_0^t Emeca \, dt}$$

$Emece$  Mechanical power effectively supplied

$Emeca$  Mechanical power that ideally must be supplied

The  $FN_i$  allows to evaluate the geographical-electric location of each generating unit. During the process of SR allocation, the  $FN_i$  evaluates the electric distance of the available SR from load center, so as to favor the SR allocation in each unit according to their proximity to this center [7,9].

The  $F_{CRi}$  is determined for the outage of the largest generating unit in the system. It was assumed that all units have the same percentage reduction or increment in their dynamic response against outages of smaller or larger magnitude than the largest unit. This is a valid assumption since the experimental tests showed that the error was not significant.

In this paper the Combined Cycle Gas Turbine (CCGT) units have not been considered. However the dynamic response of these units is faster than a conventional steam turbine and they must be used to supply this service [2]. Because the time horizon evaluated, some loads are also used to provide SR through automatic load shedding. Other type of interruptible load was not implemented.

### 2.3 Expected Value of Interruption Cost

The term  $E(C(ENS))$  of the objective function (1) evaluates –with a close approximation– the ALS under different SR allocations for each generating unit. The expected cost of ENS curves are pre-calculated for different demand levels and stored in a database. The calculation of these curves considers a pre-dispatch with an equal percentage of SR allocation in each generating [10]. The formulation of these curves is:

$$E(C(ENS)) = E(Pdes)(Vens T\bar{m} + VPdes)$$

$$E(C(ENS)) = m_B Refec_{Sis}$$

$E(Pdes)$  Expected value of disconnected power

$Vens$  Non-supplied energy cost

$T\bar{m}$  Average time of disconnection power

$VPdes$  Cost of disconnected power

$m_B$  Slope of linear segments

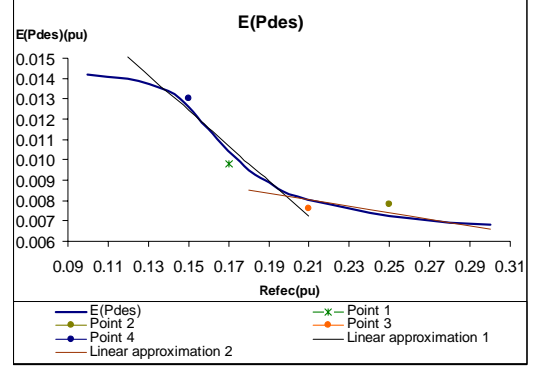


Figure 2: Expected Value of Disconnected Power Curve

The Figure 2 was calculated for a demand level of 2038 MW. The x-axis corresponds to the SR level allocated in the units (from 0% to 5%).  $E(Pdes)$  is approximated by two linear segments allowing their use in the optimisation process. The other points shown in the graphics corresponds to simulations for the same demand level but different allocation and different level of SR in the units. The point (Point 1) is the  $E(Pdes)$  calculated for the dispatch of the Table 2.

### 2.4 Mathematical Solution

The Lagrange multiplier method is used to solve the outlined problem. The minimization of the objective function subjected to the above-presented constraints is the same as to minimize the Lagrangian L.

$$L = C + \lambda \Theta_p + \delta \Theta_R + \langle \mu, \Phi \rangle + \langle \xi, \Omega_{Ti} \rangle + \langle \alpha, \Omega_{ri} \rangle \quad (6)$$

The constraints are presented in the Lagrangian by means of the Lagrange multipliers  $\lambda$ ,  $\delta$ ,  $\mu$ ,  $\xi$ ,  $\alpha$ .

By stating  $\frac{\partial L}{\partial P_{gi}} = 0$ , it is obtained:

$$\frac{\partial L}{\partial P_{gi}} = \frac{\partial C_i(P_{gi})}{\partial P_{gi}} + \frac{\partial C_{Ri}(R_i)}{\partial P_{gi}} + \frac{\partial E(C(ENS))}{\partial P_{gi}} - \lambda \left( 1 - \frac{\partial L}{\partial P_{gi}} \right) - \delta \left( \frac{\partial Refec_i}{\partial P_{gi}} \right) + \langle \mu, \nabla F_i \rangle + \langle \xi, \nabla (P_{gi} + R_i) \rangle = 0 \quad (7)$$

Likewise by  $\frac{\partial L}{\partial r_i} = 0$ , it is obtained:

$$\frac{\partial L}{\partial r_i} = \frac{\partial C_i(P_{gi})}{\partial r_i} + \frac{\partial C_{Ri}(R_i)}{\partial r_i} + \frac{\partial E(C(ENS))}{\partial r_i} - \delta \left( \frac{\partial Refec_i}{\partial r_i} \right) + \langle \xi, \nabla' R_i \rangle + \langle \alpha, \nabla' r_i \rangle = 0 \quad (8)$$

Where:

$$\nabla = \frac{\partial}{\partial P_{gi}}, \quad \nabla' = \frac{\partial}{\partial r_i}, \quad \eta_i = -\langle \mu, \nabla F_i \rangle$$

$\langle \cdot, \cdot \rangle$  Scalar product

By mathematically solving (7) and (8), the spot prices for energy and SR are obtained as shown in (9), (10) and (11):

$$\lambda \left( 1 - \frac{\partial L}{\partial P_{gi}} \right) + \eta_i = \frac{\partial C_i(P_{gi})}{\partial P_{gi}} - \frac{1}{P_{gi}} \alpha_i r_i + \xi_i \quad (9)$$

$$\delta m_i FN_i = FN_i m_i \left( \frac{\partial E(C(ENS))}{\partial R_{efec_i}} \right) + \frac{\partial C_{Ri}(R_i)}{\partial R_i} + \xi_i + \frac{1}{P_{gi}} \alpha_i \quad (10)$$

$$\lambda \left( 1 - \frac{\partial L}{\partial P_{gi}} \right) + \eta_i = \rho_{Ei} \quad \delta m_i FN_i = \rho_{Ri} \quad (11)$$

Where  $\rho_{Ei}$  and  $\rho_{Ri}$  are the spot prices of energy and SR at node  $i$  respectively.

This problem is non-linear not only for considering the transmission network losses but also for the actual formulation of SR ( $r_i P_{gi}$ ).

### 2.5 Linear Formulation

A thermal economic dispatch model that takes into account the transmission network capacity and losses was developed in [8]. This model has been used as the base for developing the present work. In addition, an algorithm based on Iterative Linear Programming (ILP) is used to solve model described in the PM. The ILP solves a non-linear problem as a linear problem in each iteration. Results from one iteration are used to give the appropriate signals to the next iteration until achieve the desired convergence. Details of this Linear formulation was presented in [12].

## 3 TEST CASE

To implement the proposed algorithm, an electric power system with 44 nodes, 57 transmission lines and 40 generating units (13 hydraulic and 27 thermal units) is used. The technical data of available generators that take part in the test system of figure 3 are presented in Table 1.

In this case all units offer a price based-costs for energy and SR and the detail of these bids are presented in the Table 5.

The production costs for hydro unit are assumed as the water value. This water value has been determined through an optimal operation scheduling. We have assumed that the hydro dispatch is predefined, the proposed methodology only move this operating point

down or up depending on the water value and the interruption costs.

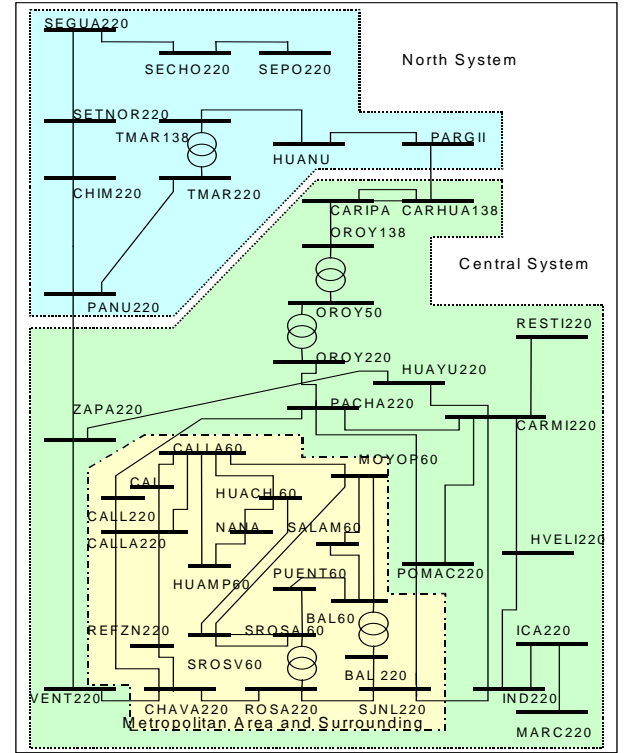


Figure 3: Test System

Gener. Units	Node	Outage Prob [10 <sup>-3</sup> ]	Type	Pgmax [MW]	rmax [%]
TGN4	SEPO220	1.40	T	95.36	5.00
TGN3	SEPO220	1.40	T	16.50	5.00
TG33V	VENT220	1.40	T	154.00	5.00
TG1A	TMAR220	1.20	T	80.00	5.00
TG 2A	TMAR220	1.50	T	80.00	5.00
Carhua	SECHO220	0.70	H	93.00	8.00
Cadpa	CHIM220	0.85	H	182.00	0.00
Cahua	PANU220	0.60	H	41.50	0.00
Huinc 1	ROSA220	0.80	H	125.00	8.00
Huinc2	ROSA220	0.80	H	125.00	8.00
Huamp	HUAMP60	0.78	H	30.00	8.00
Manta1	CARMI220	0.90	H	300.00	8.00
Manta2	CARMI220	0.90	H	300.00	8.00
Resti	RESTI220	0.80	H	200.00	8.00
Oromal	OROY138	0.90	H	65.00	8.00
Moyop	MOYOP60	0.88	H	60.00	8.00
Calla	CALLA60	0.50	H	71.00	8.00
Matuc	CALLA220	0.87	H	127.00	8.00
Yaupi	CARHUA138	0.65	H	100.00	8.00
Galli	SEGUA220	0.68	H	36.00	0.00

Table 1: Test System Data

Comparing the results obtained with the PM we have applied another two methodologies to allocate the SR in the test system. These two additional methodologies consider:

- Methodology 1 (M1): All generating units are allocated with an equal level (%) of SR [7,9,13].
- Methodology 2 (M2): The energy and SR are joint optimized but the system dynamic behavior is not evaluated during the optimisation.

The results of the JED proposed in this paper for the period of maximum demand are shown in Table 2.

Generating Units	Power		SR Dispatched.	
	Dispatched [MW]	[MW]	[MW]	[%]
TGN4	61.10	3.05	5.00	
TG33V	50.00	2.50	5.00	
TG1A	72.84	3.64	5.00	
TG2A	76.19	3.81	5.00	
Carhua	88.57	4.43	5.00	
Cadpa	182.00	0.00	0.00	
Cahua	41.50	0.00	0.00	
Huinc 1	115.00	0.00	0.00	
Huinc2	115.00	0.00	0.00	
Huamp	26.17	1.31	5.00	
Manta1	291.57	8.43	3.00	
Manta2	291.57	8.43	3.00	
Resti	200.00	0.00	0.00	
Oromal	60.00	0.00	0.00	
Moyop	60.00	0.00	0.00	
Calla	67.62	3.38	5.00	
Matuc	127.00	0.00	0.00	
Yaupi	74.97	3.75	5.00	
Galli	36.00	0.00	0.00	
Total	2037.10	42.73	2.00	

Table 2: JED with Dynamic Evaluation

The Table 2 shows the power and the SR allocated to each generating unit. Each generating unit was allocated with a different percentage of SR and not all of them have allocated this AS, this can be observed in units Cadpa and Cahua, Huinc etc.

Results of the JED of energy and SR without evaluating the dynamic behavior of the system are shown in the Table 3. That means, the optimisation is realized only from the economic point of view. To do this we defined a SR level of 42.73 MW to be allocated in the system. This level is the same one that was obtained in the PM and presented in the Table 2.

Generating Units	Power		SR Dispatched	
	Dispatched [MW]	[MW]	[MW]	[%]
TGN4	60.93	3.00	5.00	
TG33V	50.00	2.50	5.00	
TG1A	73.07	3.71	5.00	
TG2A	76.19	3.81	5.00	
Carhua	88.57	4.43	5.00	
Cadpa	182.00	0.00	0.00	
Cahua	41.50	0.00	0.00	
Huinc 1	115.00	0.00	0.00	
Huinc2	115.00	0.00	0.00	
Huamp	26.38	1.31	5.00	
Manta1	300.00	0.00	0.00	
Manta2	300.00	0.00	0.00	
Resti	190.48	9.52	5.00	
Oromal	60.00	0.00	0.00	
Moyop	57.14	2.86	5.00	
Calla	67.62	3.38	5.00	
Matuc	122.54	4.46	4.00	
Yaupi	74.97	3.75	5.00	
Galli	36.00	0.00	0.00	
Total	2037.39	42.73	2.00	

Table 3: JED without Dynamic Evaluation

In the Table 3 the SR level allocated in some unit differ with the SR allocated in Table 2, examples of that are the unit Manta, Resti Moyop and Matuc. The difference is because in Table 3 the objective is minimize the operative system cost while in Table 2 the objective is minimize the total cost (operative and  $E(C(ENS))$ ) that means evaluating the dynamic behavior of the system.

Table 4 shows results of economic dispatch considering an equal SR level allocated in each generating unit. In this case it can be observed that all units without exception have a SR level allocated of 2 %.

Generating Units	Power		SR. Disp.	
	Dispatched [MW]	[MW]	[MW]	[%]
TGN4	75.35	1.51	2.00	
TG33V	50.00	1.00	2.00	
TG1A	65.69	1.31	2.00	
TG2A	78.43	1.57	2.00	
Carhua	91.18	1.82	2.00	
Cadpa	178.43	3.57	2.00	
Cahua	40.69	0.81	2.00	
Huinc 1	112.75	2.26	2.00	
Huinc2	112.75	2.26	2.00	
Huamp	26.05	0.52	2.00	
Manta1	294.12	5.88	2.00	
Manta2	294.12	5.88	2.00	
Resti	196.08	3.92	2.00	
Oromal	58.82	1.18	2.00	
Moyop	58.82	1.18	2.00	
Calla	69.61	1.39	2.00	
Matuc	124.51	2.49	2.00	
Yaupi	74.97	1.50	2.00	
Galli	35.29	0.71	2.00	
Total	2037.66	40.75	2.00	

Table 4: JED with a equal SR level in each unit

Generating Units	Energy Bid	SR Bid	Energy Price	SR Price
	[\$/MWh]	[\$/MW]	[\$/MWh]	[\$/MW]
TGN4	23.74	2.37	23.74	8.94
TG33V	38.30	3.83	38.30	10.34
TG1A	17.06	1.71	17.06	9.12
TG2A	16.16	1.62	17.06	10.01
Carhua	18.36	1.84	23.30	8.92
Cadpa	12.00	1.20	22.96	9.43
Cahua	13.00	1.30	23.43	9.09
Huinc 1	17.77	1.78	29.34	10.52
Huinc2	17.77	1.78	29.34	10.52
Huamp	10.00	1.00	10.00	9.67
Manta1	16.22	1.62	26.90	12.32
Manta2	16.22	1.62	26.90	12.32
Resti	18.36	1.83	26.67	5.52
Oromal	15.82	1.58	30.54	15.05
Moyop	17.52	1.75	27.81	10.25
Calla	16.95	1.69	25.68	10.98
Matuc	17.29	1.73	28.17	6.29
Yaupi	24.36	2.44	24.36	5.12
Galli	10.00	1.00	23.48	6.96

Table 5: Spot prices of Energy and SR

Table 5 shows the resulting prices for energy and for SR after applying the PM. This table shows that the SR price compensates appropriately the gain lost that some

generating units have when they reduce their generation -foreseen to prepare it as SR-. This provides the appropriate economic signals to encourage the supply and to ease the creation of a spot market for this AS.

In the table 5 is shown that the marginal unit of SR is the unit Manta because for this unit the supplying of energy or SR is indifferent. The actual price of SR is exactly equivalent to the difference between the energy price and the energy price offered plus the SR availability price offered, that means:  $\$12.32/\text{MW} = (\$26.90/\text{MWh} - \$16.22/\text{MWh}) * 1\text{h} + 1.62\$/\text{MW}$ . The remaining units receive a SR price greater than their gain lost in reducing their power to prepare it as SR.

### 3.1 Analysis of the System Dynamic Behavior

In this section is presented the system dynamic behavior under generating units outages for different SR allocations in each generating units.

Each one of the different SR dispatches made with the above methodologies has a different performance under generating unit outages. This is because the SR has been allocated in different way. Results corresponding to the system dynamic behavior for each SR configuration are shown below not only numerically but also graphically.

From the point of view of ALS and system total cost, the system dynamic behavior of the economic dispatches shown in Table 2 and 4 present considerable differences which are shown in the next Table.

	Economic Dispatch Table 4	Economic Dispatch Table 2
<b>Generating Units</b>	<b>Load Shedding [MW]</b>	<b>Load shedding [MW]</b>
Manta1	278.29	282.89
Manta2	278.29	282.89
Resti	189.50	176.21
Cadpa	102.89	106.4
Matuc	94.75	94.75
UICN	94.75	94.75
Carhua	16.55	24.7
<b>E(Pdes) [MW]=</b>	<b>0.896</b>	<b>0.902</b>
<b>Operative Cost [\$/h]=</b>	<b>35388.37</b>	<b>35277.90</b>
<b>Cost E(ENS) [\$/h]=</b>	<b>840.05</b>	<b>845.90</b>
<b>Total Cost [\$/h]=</b>	<b>36228.42</b>	<b>36123.80</b>

**Table 6:** Load shedding under different SR allocation

Table 6 shows the ALS for the economic dispatch that consider an equal level of SR allocated in each generating unit (M1, Table 4) and for the JED proposed in this paper (Table 2).

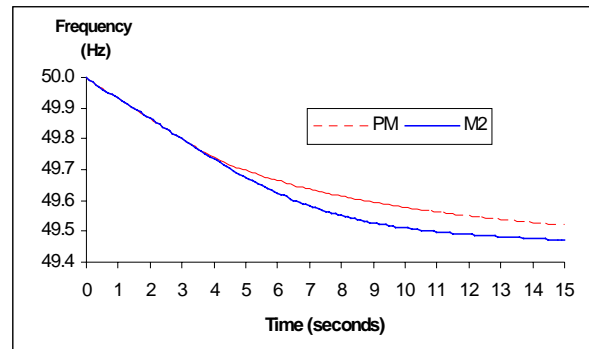
Clearly, we can observe that from the ALS point of view, the economic dispatch of table 4 gives the best results because the  $E(P(des))$  of 0.896 MW is lesser than 0.902 obtained with the economic dispatch of

Table 2. However the substantial difference resides in the system operative costs because for an equal SR Allocation in the units, the costs turn out to be \$35388, which are greater than those obtained with the PM.

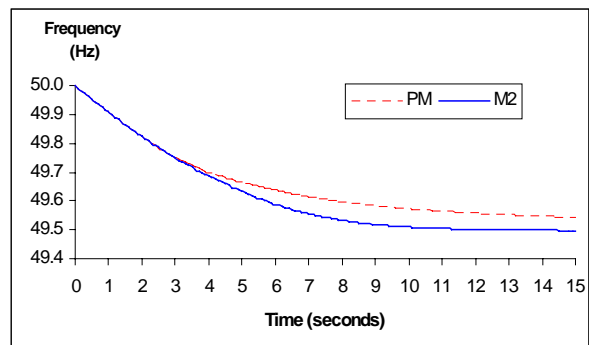
This fact produces that the system total costs (operative and  $E(C(ENS))$ ) with the PM turn out to be lesser than the system total costs obtained with M1( 0.3%).

The other comparison presented in this section is the PM with the methodology that realizes a JED without evaluating the system dynamic behavior in the optimisation (M2. Table 3). From the economic and ALS point of view there are not considerable differences between these two economic dispatches. The difference between these dispatches is presented in the mean frequency behavior of the system under generating unit outages.

The figures 4 and 5 show that under the outage of the unit Calla and Yaupi the PM provides a better dynamic response from the point of view of the maximum frequency deviation. This is because in the optimisation of the PM the SR is allocated in the fastest units to respond and those located the closest possible from the load center.



**Figure 4:** System Mean Frequency under the Outage of Calla



**Figure 5:** System Mean Frequency under Yaupi's Outage

In this way we are justifying the implementation of the  $F_{CRi}$  and the  $FN_i$  to weight the SR allocation among the best units to make it.

The dynamics responses of figure 4 and 5 have been obtained using linear models and typical parameters corresponding to the type and size of the generating unit, these can be obtained from [10,11].

The curves with the title PM correspond to the system dynamic response when the SR is allocated evaluating the system dynamic aspect. For the other hand, the curves with the title M2 correspond to the system dynamic response when the SR is allocated without evaluating the system dynamic aspects during the optimisation process.

In both figures (4 and 5) one can observe that the frequency deviation slope is reduced when the PM is implemented.

#### 4 CONCLUSIONS

In this paper a new methodology for the joint optimisation of the energy and SR services evaluating the system dynamic behavior has been presented.

In the PM, the dynamic aspect is evaluated in such a way of guaranteeing a good response of the system under different generating units outages. This is achieved allocating the SR in the units with the fastest response and in the units closest to the system load center. This allocation is carried out by means of weight factors that indicate the speed of response of each unit through  $F_{CRi}$  and the distance or proximity of a unit far from the load center through  $FN_i$ .

The results of the PM have been contrasted with the results of two different methodologies of SR allocation among the generating units. One of them consists on allocate a equal SR level (%) in each generating unit and the other carries out a joint optimisation of energy and SR considering only the economic aspect without evaluating during the optimisation process the system dynamic aspect

From the total costs (operative and expected of interruption) point of view the PM provided better results than the methodology M1 reducing this cost in 0.3%. On the other hand, in comparison with the methodology M2, the PM does not improve the total system cost but it does in the system dynamic response, reducing the frequency decreasing slope under outages of a same power level (figure 4 and 5).

The system mean frequency behavior and the values of ALS have been obtained with a system dynamic behavior simulation software SiCoDiS [14].

The SR prices thus obtained compensate appropriately the gain lost by the generating units when restricting their generation aiming at preparing them as SR. With this, the necessary economic signals are given to encourage the supply and to create a competitive

market, because any generator will be available to maintain this AS if it were not appropriately compensated.

#### REFERENCES

- [1] M E Flynn, M P Walsh and M J O'Malley "Efficient use of generator in emerging electricity markets," *IEEE Transaction on Power Systems*, vol. 15, No. 1, pp 241-249, Feb. 2000.
- [2] W W Hung "Frequency Control Response/ Reserve Requirement of Embedded/Grid Connected Thermal/CCGT Plants," *IBC Technical Conference*, May 1995, London.
- [3] J W O'Sullivan, M J O'Malley "Economic Dispatch of a small Utility with a Frequency Based Reserve Policy" *IEEE Transaction on Power Systems*, Vol. 11, No.3, pp. 1648-1643, August 1996.
- [4] J W O'Sullivan, M J O'Malley "A New Methodology for the Provision of Reserve in an Isolated Power System" *IEEE Transaction on Power Systems*, vol. 14, No. 2, pp. 519-524, May 1999.
- [5] Trevor Alvey, Doug Goodwin, Xingwang Ma, Dan Streiffert and David Sun "A security Constrained Bid-Clearing System for the New Zealand Wholesale Electricity Market" *IEEE Transaction on Power Systems*, vol. 13, No. 2, pp 340-346, May 1998.
- [6] Xingwang Ma, David Sun "Energy and Ancillary Service Dispatch in a Competitive Pool" *IEEE Power engineering Review*, pp 54-56, January 1998.
- [7] R A Castillo, A Vargas "Economic Analysis For PFR Service in Competitive Electricity Markets considering the Dynamic Behavior of the System", *VII SEPOPE* 23-28 Mayo 2000 Curitiba, Brazil.
- [8] A. Hoese, V. Doña, A. Vargas "DESTER: Despacho Económico Térmico considerando la Red de Transporte" *IX ERLAC*, Foz do Iguazu, Mayo 2001.
- [9] R A Castillo, A Vargas "Despacho Económico Conjunto de Energía y Reserva. Determinación Óptima del requerimiento de Reserva de Segundos considerando el comportamiento dinámico del sistema", *IX ERLAC*, Foz do Iguazu, Mayo 2001, Brazil.
- [10] P M Anderson and A A Fouad "Power System Control and Stability" Iowa State University Press 1980.
- [11] P Kundur "Power System Stability and Control", McGraw-Hill, Inc. 1993, p.377.
- [12] R A Castillo, A Vargas "Joint Economic Dispatch, Energy and reserve. Optimal Second reserve Determination in Isolated System", *IEEE Porto Power Tech Conference*, September 2001 Porto, Portugal.
- [13] P Mercado, F Garcés "Optimal Generation Reserve Calculation", *Probabilistic Method Applied to Power System*, September 26-29, Rio de Janeiro, Brazil 1994.
- [14] A Gebhart "Zum Einfluß des Lastverhaltens auf die dynamischen Vorgänge nach Blockausfällen in elektrischen Energieversorgungssystemen" Fakultät für Elektrotechnik der Rheinisch-Westfälischen Technischen Hochschule Aachen 1984.