Regional Ancillary Services Procurement in Simultaneous Energy/Reserve Markets

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***Abstract*— Ancillary Services are essential to the reliability and security of power system operation in any competitive electricity market environment. Procurement of ancillary services must take into account effective use of the capacity under emergency conditions, delivery time, transmission limitations, and local area requirements. Regional procurement of ancillary services is an approach that results in effective distribution of reserves and ensures continuous reliability in the event of a contingency occurring anywhere in the system. However, most ISOs procure and price ancillary services based on the least-cost service with little regard to zonal dispersion. In general, such an approach is not sufficient to ensure continuous reliability and security of the power system This paper presents a new methodology and numerical examples for procuring and pricing ancillary services on a regional basis, with an explicit representation of imports in a simultaneous energy/reserve market environment.**

***Index Terms*— Ancillary service region, ancillary service imports, optimal power flow, power system economics, transmission congestion.**

I. Introduction

ANCILLARY services (A/S) is an essential element in any electricity market design. The Independent System Operator (ISO) relies on A/S to ensure system security and reliability. A/S usually include regulation up (Reg-Up), regulation down (Reg-Down), spinning reserve (Spin), non-spinning reserve (Non-Spin), voltage support, and black start. Operating reserves, i.e., regulation, spin and non-spin, are usually procured through competitive markets. Voltage support and black start services are usually procured by resource specific agreements between the ISO and the suppliers. A generator must meet certain performance criteria in order to be eligible for providing a specific A/S. For example, a generator must be equipped with AGC devices in order to provide regulation services. Furthermore, the amount of capacity that a unit can provide is limited by the unit's operating characteristics, such as ramping capability. The minimum performance requirements for each ancillary service are usually specified by national reliability organizations such as NERC (North America Reliability Council.)

Proper product definition and design of A/S are the primary determinants of efficiency and liquidity in these markets. This in turn influences system reliability. Based on practical experience from various ISOs, it can be concluded that the A/S markets over the years have suffered from various flaws, such as low demand elasticity, price reversals, exercise of market power, and sequential market clearing. These flaws have hindered the smooth operation of A/S markets in several occasions. As a result, various ISOs have embarked in various reform efforts that have taken different form in each jurisdiction depending on specific circumstances.

A potential problem that has emerged as a result of the Northeast Blackout on August 14th, 2003, is the unbalanced distribution of A/S throughout the control area. According to reliability standards such as those from NERC and WECC, the A/S must be distributed throughout the control area in such a way that when the reserved capacity is needed to meet the load, the energy can be delivered to the location where it is needed. This goal requires the integration of the A/S procurement and congestion management. However, there are two major challenges in achieving this objective.

- First, it is unknown, at the time of the A/S procurement process, where the energy that is dispatched from the A/S capacity will be needed in real-time.
- Second, the laws of Ohm and Kirchoff, which govern the physical flows of power, do not apply to reserved capacity before it is converted to energy.

An approach to solving this problem is simulating various contingency scenarios and predicting where and how the reserves will be dispatched to keep the power balance while satisfying various system and network constraints. Based on these simulation studies the minimum and maximum reserve requirements for selected sets of generators can be determined. The zones that contain these groups of generators are defined as A/S regions. Obviously, this approach has limitations and in the general case there is no unique solution for defining A/S regional requirements. Only a few ISOs, including the California ISO (CAISO) in its new proposed market design and the New York ISO, have developed provisions for procuring and pricing ancillary services on a regional basis. However, the methodological underpinnings of these approaches have not been forthcoming in the literature. This paper presents the mathematical formulation and a sound methodology for solving the problem of procuring and pricing A/S on a regional basis.

A number of papers exist in the literature regarding ancillary services market design. The sequential market clearing auction approach in which the ancillary services are

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procured service by service in a sequential order after the closure of the forward energy market is described in [1]. The problem with this approach is that a lower quality service (e.g., Non-Spin) may end up being more expensive than a higher quality service (e.g., Spin). This phenomenon of price reversals poses serious incentive compatibility problems and creates perverse incentives for generators that may lead to misrepresentation of capability and bids. To address this problem, a Rational Buyer (RB) approach is presented in [2], in which substitution of ancillary services are allowed to minimize the payment for A/S. The RB auction is designed to minimize procurement costs and it sacrifices some efficiency to achieve this objective. Furthermore, the RB auction is still susceptible to price reversals when capacity constraints exist, as described in [3]. A comparison of the pool-based and the contract-based approaches and an analysis of their properties are presented in [4]. A summary of the various design options of the A/S markets is given in [5].

Later designs adopted in PJM, NYISO, NE ISO and recently at the ISO, preserve the central unit commitment aspect of the vertically integrated utilities by means of a multipart auction. Some inherent difficulties arising from central unit commitment in a competitive environment is presented in [6]. An incentive compatible multipart electricity auction based on the Vickery-Clarke-Groves mechanism is proposed in [7]. Unfortunately, as noted by the authors, this approach has limited practical value due to revenue deficiency problems. An incentive compatible design for the special case of a single reserve type is proposed in [8].

Till recently, an explicit formal and rigorous treatment of the regional aspects of the A/S procurement has not been forthcoming. A formulation of a simultaneous energy and A/S optimization in which substitution of A/S is allowed in meeting the regional A/S requirements has been recently proposed in [9]. However, the overlapping of regional A/S requirements is not considered in [9]. An early work in [10] describes the energy and reserve dispatch in a multi-zone electricity market; however, it did not consider substitution of A/S and overlapping zonal requirements. Another early work in [11] also provides a simultaneous energy and reserves optimization formulation; however it considers only one system-wide A/S requirement.

This paper proposes a methodology for procuring and pricing A/S on a regional basis with an explicit consideration of A/S imports. The paper is organized as follows. Section II presents the concept of regional A/S requirements. Section III provides an approach to modeling A/S imports on radially connected inter-ties. Section IV presents the formulation of the problem and the definition of the prices. Section V presents case studies to illustrate the proposed methodology by numerical examples. Section VI concludes the paper.

II. Regional Ancillary service requirements

A. Terminology

We provide the following definitions to clarify the presentation of the proposed methodology: a) A/S region, b) A/S requirement, c) A/S procurement, d) A/S provision, and e) A/S obligation.

- An *Ancillary Service Region*, is a set of network nodes where resources are capable of providing A/S services. For simplicity, all A/S types should have the same A/S regions.
- The *A/S requirement*, defined for each A/S type in each A/S region, specifies the amounts of capacity that the ISO must procure to meet reliability criteria. In general, the A/S requirements are specified as minimum and/or maximum capacity quantities.
- The *A/S procurement*, for each A/S type in each A/S region, refers to the amount of capacity that the ISO actually procures to meet the A/S requirements.
- The *A/S provision (or award)* is the quantity of a type of A/S capacity awarded to a resource, which may be used to meet the requirements of more than one A/S regions if the regional requirements overlap.
- The *A/S obligation*, for each A/S type and *market participant* (MP), is that MP's billing determinant for allocating the cost of A/S procurement.

B. Current Standards and Practice

The determination of A/S requirements involves two aspects: 1) the *quantity* of operating reserve including regulation (i.e., Reg-Up and Reg-Down) and contingency reserve (i.e., the combination of Spin and Non-Spin) is determined according to applicable reliability standards, such as the MORC (Minimum Operating Reliability Criteria) of the WECC (Western Electricity Coordinating Council), which is a member of the NERC, and 2) the *locational requirements* of operating reserves which are not explicitly specified in the reliability standards, such as in WECC. However, the MORC of the WECC requires that "prudent operating judgment shall be exercised in distributing operating reserve, taking into account effective use of capacity in an emergency, time required to be effective, transmission limitations, and local area requirements. Spinning reserve should be distributed to maximize the effectiveness of governor action."

C. Distribution of Contingency Reserves

The purpose of contingency reserves is to ensure that load can be served after a contingency. The development of the proposed methodology for distributing the contingency reserves is illustrated in the paper using a 4-node example shown in Figure 1.

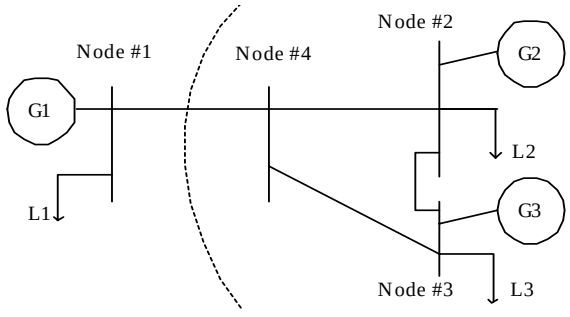

Figure 1. A 4-node DC network with four branches

The particulars of the example are as follows:

- The network has a loop inside the control area and one radial tie line. Node 1 is outside the control area. Nodes 2, 3, and 4 are inside the control area. All the branches in the loop are identical and rated at 50 MW in both directions. The tie line from Node 1 to Node 4 is rated at 40 MW in both directions.
- The generators G1, G2 and G3 can operate between 0 MW and their maximum capacity with infinite ramp rate. All units bid their full capacity in an integrated energy and Spin market. G3 represents aggregated generation and is selected as the refence bus.
- The loads L1 (export), L2, and L3 have fixed schedules of 20 MW, 30 MW, and 100 MW, respectively.
- The control area Spin requirement is 100 MW.

Table I shows the energy and Spin bids, and the optimal dispatch (ignoring the Spin requirement) under the base case and three contingencies.

TABLE I
BIDS AND OPTIMAL DISPATCH

Resources:	G1	G2	G3
Energy Bid Price ($/MWh)	10	30	45
Spin Bid Price ($/MW)	5	15	35
Total Bid Capacity (MW)	100	200	300
Energy Schedule (MWh) – Base Case	60	85	5
Energy Schedule (MWh) – G1 outage	0	115	35
Energy Schedule (MWh) – G2 outage	60	0	90
Energy Schedule (MWh) – Line 1–4 outage	0	105	25

Based on these results, we analyze the regional Spin requirements as follows:

- It is assumed that all the three generators are on-line.
- The system-wide Spin requirement of 100 MW is met by G1, G2 and G3.
- Assume a reliability constraint that Spin import may not exceed 50% of the total Spin requirement; therefore, G1 may not provide more than 50 MW of Spin.
- G3 must provide 90 MWh under G2 outage. Since in the base case G3 provides 5 MWh, G3 needs to provide at least 85 MW of Spin.
- No additional Spin constraints are needed since 90 MW of Spin from G3 can meet the load under all contingencies shown in Table II.

Let R_1, R_2, R_3 represent Spin provision from generators G1, G2, and G3, respectively. Based on the above contingency analysis, there are three A/S Regions as follows:

Region 1 (contains Node 1): $R_1 \le 50$

Region 2 (contains Nodes 1, 2, and 3): $100 \le R_1 + R_2 + R_3$

Region 3 (contains Node 3): $85 \le R_3$

III. MODELING ANCILLARY SERVICE IMPORTS

In a simultaneous energy/reserve market, the ISO optimizes the use of the transmission network by both energy and A/S capacity. Usually, congestion management for A/S is performed implicitly through the provision of regional A/S requirements. Consequently, A/S bids from resources inside the control area do not compete with energy bids for the use of transmission network. Energy and A/S bids compete only for the use of inter-ties in the import direction. However, A/S imports may not provide counter-flow transmission capacity for energy exports and vice versa.

In the example of Figure 1, the energy export from Node 4 to Node 1 must be less than the 40 MW limit :

$$-40 \le (G_1 - L_1) \tag{1}$$

where G_1 represents the output of G1 and L_1 represents the quantity of L1. In the import direction, the transmission constraint on the inter-tie is as follows:

$$\max(0, G_1 - L_1) + R_1 \le 40 \Rightarrow \begin{cases} R_1 \le 40 \\ G_1 - L_1 + R_1 \le 40 \end{cases} \tag{2}$$

Only one of the constraints may be binding at any time period.

IV. ANCILLARY SERVICE PROCUREMENT AND PRICING

A. Integrated Market for Energy and Ancillary Services

In an integrated energy and A/S market with unit commitment, the ISO optimizes A/S and energy procurement simultaneously. The objective of the optimization is to minimize the start-up cost, minimum load cost, incremental energy cost, and A/S bid cost subject to network and resource constraints over the entire time horizon. The formulation allows substitution of a high quality A/S for a lower quality one. Both social efficiency and rational procurement behavior dictate that such substitution should be allowed and should lead to lower overall procurement costs. Specifically, Reg-Up can also meet Spin and Non-Spin requirements; and Spin can also meet Non-Spin requirements. Resources are committed at least cost to meet the demand and the ancillary service requirements. Locational Marginal Prices (LMPs) for energy and Ancillary Services Marginal Prices (ASMPs) are obtained for each time period from the optimal commitment and scheduling results.

The general characteristics of the LMPs and ASMPs are analyzed from a theoretical viewpoint using an OPF formulation in [9]. In this paper, the 4-Node network shown in Figure 1 is used to study the effect of having overlapping regional A/S requirements and A/S imports on the ASMPs. A DC-OPF formulation is used to illustrate the proposed methodology and offer insights to the regional A/S problem without the complexity found in nonlinear and discrete systems. Let G_1, G_2, and G_3 represent the output of generators G1, G2, and G3. Let L_1, L_2, and L_3 represent the loads of L1, L2, and L3, respectively. The DC-OPF problem is formulated as follows:

Minimize:

$$f_1 G_1 + f_2 G_2 + f_3 G_3 + c_1 R_1 + c_2 R_2 + c_3 R_3 \tag{3}$$

where f_i is the energy bid and c_i the Spin bid from Gi.

Subject to the following constraints:

Power Balance:

$$G_1 + G_2 + G_3 = L_1 + L_2 + L_3 \tag{4}$$

Spin Requirements:

$$R_1 \le 50 \quad \text{(Region 1)} \tag{5}$$

$$100 \le R_1 + R_2 + R_3 \quad \text{(Region 2)} \tag{6}$$

$$85 \le R_3 \quad \text{(Region 3)} \tag{7}$$

Power Flow (#4→#2):

$$-50 \le (1/3)\,(G_1 - L_1) - (1/3)\,(G_2 - L_2) \le 50 \tag{8}$$

Power Flow (#4→#3):

$$-50 \le (2/3)\,(G_1 - L_1) + (1/3)\,(G_2 - L_2) \le 50 \tag{9}$$

Power Flow (#2→#3):

$$-50 \le (1/3)\,(G_1 - L_1) + (2/3)\,(G_2 - L_2) \le 50 \tag{10}$$

Power Flow (#4→#1):

$$-40 \le (G_1 - L_1) \tag{11}$$

Power Flow and Spin (#1→#4):

$$R_1 \le 40 \tag{12}$$

$$G_1 - L_1 + R_1 \le 40 \tag{13}$$

Capacity limits:

$$G_i + R_i \le P_i^{max}, \text{ for } i = 1, 2, 3. \tag{14}$$

Lower Bounds:

$$0 \le G_i \text{ and } 0 \le R_i, \text{ for } i = 1, 2, 3. \tag{15}$$

B. Market Clearing Price Definition and Properties

The ASMPs are derived from the Lagrange multipliers of the regional Spin requirements. The Lagrange function of the optimization problem is as follows:

$$\begin{aligned} L = {} & f_1 G_1 + f_2 G_2 + f_3 G_3 + c_1 R_1 + c_2 R_2 + c_3 R_3 \\ & - \lambda_3 (G_1 + G_2 + G_3 - L_1 - L_2 - L_3) \\ & + \lambda_1^{SP} (R_1 - 50) \\ & - \lambda_2^{SP} (R_1 + R_2 + R_3 - 100) \\ & - \lambda_3^{SP} (R_3 - 85) \\ & - \mu_{4,2}^{min} [(1/3)\,(G_1 - L_1) - (1/3)\,(G_2 - L_2) + 50] \\ & + \mu_{4,2}^{max} [(1/3)\,(G_1 - L_1) - (1/3)\,(G_2 - L_2) - 50] \\ & - \mu_{4,3}^{min} [(2/3)\,(G_1 - L_1) + (1/3)\,(G_2 - L_2) + 50] \\ & + \mu_{4,3}^{max} [(2/3)\,(G_1 - L_1) + (1/3)\,(G_2 - L_2) - 50] \\ & - \mu_{2,3}^{min} [(1/3)\,(G_1 - L_1) + (2/3)\,(G_2 - L_2) + 50] \\ & + \mu_{2,3}^{max} [(1/3)\,(G_1 - L_1) + (2/3)\,(G_2 - L_2) - 50] \\ & - \mu_{1,4}^{min} (G_1 - L_1 + 40) \\ & + \mu_{1,4}^{max} (G_1 - L_1 + R_1 - 40) \\ & + \mu_{1,4}^{SP} (R_1 - 40) \\ & - \pi_1^{min} G_1 - \beta_1^{min} R_1 + \pi_1^{max} (G_1 + R_1 - P_1^{max}) - \pi_2^{min} G_2 \\ & - \beta_2^{min} R_2 + \pi_2^{max} (G_2 + R_2 - P_2^{max}) - \pi_3^{min} G_3 - \beta_3^{min} R_3 \\ & + \pi_3^{max} (G_3 + R_3 - P_3^{max}) \end{aligned} \tag{16}$$

The Regional A/S Marginal Prices (RASMPs) for Regions 1, 2, and 3 are defined as follows:

$$RASMP_1 = -\partial L/\partial(R_1 - 50) = -\lambda_1^{SP} \tag{17}$$

$$RASMP_2 = -\partial L/\partial(R_1 + R_2 + R_3 - 100) = \lambda_2^{SP} \tag{18}$$

$$RASMP_3 = -\partial L/\partial(R_3 - 85) = \lambda_3^{SP} \tag{19}$$

Generators that provide the same Spin capacity to meet the Spin requirement of more than one region are paid by the RASMPs of all relevant A/S regions. Specifically, the A/S Marginal Price (ASMP) for each generator is as follows:

$$ASMP_1 = RASMP_1 + RASMP_2 \tag{20}$$

$$ASMP_2 = RASMP_2 \tag{21}$$

$$ASMP_3 = RASMP_2 + RASMP_3 \tag{22}$$

In general, if we define for an A/S incidence matrix **A** whose (i, j) element is 1 if generator j participates in A/S region i, and 0 otherwise, the ASMP for that A/S for generator j is calculated as follows:

$$ASMP_j = \sum_i A(i, j) \cdot RASMP_i \tag{23}$$

To study the impact of inter-tie congestion on the $ASMP_1$, let us apply the Karush-Kuhn-Tucker (KKT) conditions to the Lagrange function as follows:

$$\begin{aligned} \partial L/\partial R_1 = {} & c_1 + \lambda_1^{SP} - \lambda_2^{SP} - \beta_1^{min} + \pi_1^{max} + \mu_{1,4}^{max} \\ & + \mu_{1,4}^{SP} = 0 \end{aligned} \tag{24}$$

$$\begin{aligned} \Rightarrow \quad ASMP_1 = {} & -\lambda_1^{SP} + \lambda_2^{SP} = c_1 - \beta_1^{min} + \pi_1^{max} + \mu_{1,4}^{max} \\ & + \mu_{1,4}^{SP} \end{aligned} \tag{25}$$

This equation shows that the $ASMP_1$ includes the congestion price $(\mu_{1,4}^{max} + \mu_{1,4}^{SP})$ for the inter-tie. The congestion price $\mu_{1,4}^{max}$ is the difference between the marginal energy prices across the radial inter-tie when net energy imports and A/S imports are constrained by the inter-tie capacity. The congestion price $\mu_{1,4}^{SP}$ is the shadow price on the inter-tie when A/S imports alone are constrained by the inter-tie capacity (the case of net energy exports). Since inter-tie capacity is reserved in the import direction for A/S imports, the importer of an A/S over a congested inter-tie should be charged the shadow price of the inter-tie in the import direction for the amount of the A/S import. In other words, the A/S importer should receive effectively the ASMP minus the shadow price of the inter-tie in the import direction.

To conclude the marginal price calculation, the LMPs for energy are defined as follows:

$$LMP_1 = f_1 - (\pi_1^{min} - \pi_1^{max}) \tag{26}$$

$$LMP_2 = f_2 - (\pi_2^{min} - \pi_2^{max}) \tag{27}$$

$$LMP_3 = \lambda_3 \tag{28}$$

$$LMP_4 = \lambda_1 + (\mu_{1,4}^{min} - \mu_{1,4}^{max} - \mu_{1,4}^{SP}) \tag{29}$$

V. Case Study

A. Case 1: Energy and Spin in the Same Direction

The energy and spin bids, final energy schedules and prices, and the Spin awards and prices are summarized in Table II. In this case, since G1 is a cheaper resource for both energy and Spin, the local load at Node 1 is provided by G1. In addition, the Spin bid and the energy bid compete for the use of the 40 MW capacity of Branch 1-4. Since provision of energy provides more savings, the line is used to transfer 40 MW of energy from Node 1 to Node 4.

By solving a simple LP problem, the values of the Lagrange multipliers are obtained as follows. The multipliers that are not shown below have zero values:

$\lambda_3 = 45$, $\lambda_2^{SP} = 15$, $\lambda_3^{SP} = 20$, $\mu_{14}^{max} = 27.5$, $\mu_{23}^{max} = 22.5$.

As can be seen from Table II, G1 is awarded 60 MWh of energy schedule and 0 MW of Spin to fully utilize the 40 MW capacity of Branch 1→4; G2 is awarded 85 MWh of energy schedule and 15 MW spin reserve, and G3 picks up the other 5 MWh of load and 85 MW of spin reserve requirement. The resulting LMPs at Node 1, Node 2 and Node 3 are \$10/MWh, \$30/MWh and \$45/MWh, respectively.

TABLE II
BIDS AND RESULTS IN CASE 1

Resources	G1	G2	G3	*Total*
Energy Bid Price (\$/MWh)	10	30	45	-
Spin Bid Price (\$/MW)	5	15	35	-
Total Capacity (MW)	100	200	300	600
Energy Schedule (MWh)	60	85	5	150
LMP (\$/MWh)	10	30	45	-
Spin Award (MW)	0	15	85	100
Spin $RASMP_1$ (\$/MW)	0	-	-	-
Spin $RASMP_2$ (\$/MW)	15	15	15	-
Spin $RASMP_3$ (\$/MW)	-	-	20	-
Spin ASMP (\$/MW)	15	15	35	-
Spin Congestion Price (\$/MW)	–27.5	-	-	-
Effective Spin Price (\$/MW)	–12.5	15	35	-

TABLE III
SUMMARY OF A/S REQUIREMENT, PROCUREMENT, PROVISION AND OBLIGATION IN CASE 1

Regional Requirement, Procurement and Price	A/S Region Num	1	2	3
	A/S Region Definition (by sets of generators)	{G1}	{G1, G2, G3}	{G3}
	Spin Requirement (MW)	≤ 50	≥ 100	≥ 85
	Procurement by A/S Region (MW)	0	100	85
	RASMP for each Region (\$/MW)	0	15	20
Unit Spin Provision & Price	Generator	G1	G2	G3
	Provision by Generator (MW)	0	15	85
	ASMP for each Gen (\$/MW)	15	15	35
Obligation and User Rate	Load	L1	L2	L3
	Spin Obligations by Load (MW)	13	20	67
	Spin Obligation User Rate (\$/MW)	32		

The RASMP for Spin for Region 1, i.e., $RASMP_1$, is zero because the regional requirement constraint for Region 1, i.e., (5), is not binding.

The RASMP for Spin for Region 2, i.e., $RASMP_2$, is set by the Spin bid from G2 at \$15/MW because the other two generators are constrained; specifically, R_1 is constrained by Branch 1→4 congestion, and R_3 is constrained by its minimum limit constraint, i.e., (7). From G1's viewpoint, the \$15/MW Spin price is not sufficient to cover its \$5/MW Spin bid because of the \$27.5/MW congestion cost. Therefore, G1 does not provide any Spin in this case.

The RASMP for Region 3, i.e., $RASMP_3$, is determined by λ_3^{SP} which is \$20/MW. It equals to the Spin bid of G3 minus the RASMP for Region 2. An interpretation for this is that G3 would be paid by \$35/MW for providing Spin in region 3 if it had not also provided Spin in Region 2; and to avoid double compensation, the payment must be reduced by \$15/MW. However, since G3 participates in both Region 2 and Region 3, it is paid by both $RASMP_2$ and $RASMP_3$. Therefore, the ASMP that G3 receives for providing Spin to meet both Region 2 and Region 3 requirements is \$15/MW + \$20/MW = \$35/MW. The regional requirements, procurements, provisions and obligations are given in Table III.

In this example, the Spin obligations for load are calculated as follows:

L1: $100 * L_1/(L_1 + L_2 + L_3) = 100*20/150 = 13.33$ (MW)
L2: $100 * L_2/(L_1 + L_2 + L_3) = 100*30/150 = 20$ (MW)
L3: $100 * L_3/(L_1 + L_2 + L_3) = 100*100/150 = 66.67$ (MW)

The total A/S procurement cost is the sum of the products of each generator's provision and the ASMP as follows:

0 * 15 + 15 * 15 + 85 * 35 = \$3200.

The total A/S procurement cost is allocated to the obligations using an A/S user rate per service regardless of the A/S regions. The user rate is calculated by dividing the total procurement cost by the total obligation, that is \$3200/100 MW = \$32/MW.

B. Case 2: Energy and Spin in Opposite Directions

In this case, we examine a rather infrequent condition where energy and A/S are constrained in opposite directions. This condition assumes that A/S imports would exceed the total capacity of an inter-tie. In this case, we make the following changes in the assumptions:

- The energy bid of G1 is increased to \$80/MW, and
- Branch 1–4 is derated to 10 MW in both directions.

The energy schedules/prices and the Spin awards/prices are summarized Table IV. In this situation, G1 is an expensive resource for energy but a cheap resource for Spin. The local energy demand at Node #1 is provided by 10 MW of export from Node 4, and only the remaining 10 MW demand is provided by G1. Since the capacity limit for Branch 1–4 is only 10 MW, the Spin import from Node 1 to Node 4 is 10 MW.

By solving a simple LP problem, the values of the Lagrange multipliers are obtained as follows. The multipliers that are not shown below have zero values:

$\lambda_3 = 45$, $\lambda_2^{SP} = 15$, $\lambda_3^{SP} = 20$, $\mu_{14}^{min} = 42.5$, $\mu_{23}^{max} = 22.5$,

$\mu_{1,4}^{SP} = 10$

Since similar explanations as given in Case 1 also apply to the results in Table IV, only the differences in Case 2 are explained here. In Case 2, from G1's viewpoint, the \$15/MW Spin price is sufficient to cover its \$5/MW Spin bid after

paying the $10/MW congestion charge. Therefore, G1 provide 10 MW of Spin to fully utilize the capacity on Branch 1–4.

TABLE IV
BIDS AND RESULTS IN CASE 2

Resources	G1	G2	G3	*Total*
Energy Bid Price ($/MWh)	80	30	45	-
Spin Bid Price ($/MW)	5	15	35	-
Total Capacity (MW)	100	200	300	600
Energy Schedule (MWh)	10	110	30	150
LMP ($/MWh)	80	30	45	-
Spin Award (MW)	10	5	85	100
Spin $RASMP_1$ ($/MW)	0	-	-	-
Spin $RASMP_2$ ($/MW)	15	15	15	-
Spin $RASMP_3$ ($/MW)	-	-	20	-
Spin ASMP ($/MW)	15	15	35	-
Spin Congestion Price ($/MW)	-10	-	-	-
Effective Spin Price ($/MW)	5	15	35	-

VI. CONCLUDING REMARKS

A/S are essential to the reliability and security of power system operation in any competitive electricity market environment. Procurement of A/S must take into account effective use of the capacity under emergency conditions, delivery time, transmission limitations, and local area requirements. Regional procurement of A/S is an approach that results in effective distribution of reserves and ensures continuous reliability in the event of a contingency occurring anywhere in the system. Procuring A/S in prescribed A/S regions is an approach towards such effective distribution of the reserves. This paper presents a new methodology for procuring and pricing A/S on a regional basis, with an explicit representation of imports in a simultaneous energy/reserve market environment. The proposed methodology is illustrated by numerical examples. To implement this approach, further work is required to develop standards and procedures in order to determine the regional ancillary service requirements.

DISCLAIMER

This paper does not necessarily reflect the position of the California ISO. Any errors and omissions are the sole responsibility of the authors.

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