

A Novel Technique for Joint Energy and Reserve Dispatch Considering Lost Opportunity Cost

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Abstract: This paper presents a novel solution method for joint energy and Spinning Reserve (SR) dispatch problem. In systems in which the Lost Opportunity Cost (LOC) should be paid to generators, if the LOC is not considered in the dispatch problem, the results may differ from the truly optimum solution. Since the LOC is a non-differentiable function, including it in the formulation makes the problem solving process to be time-consuming and improper for real time applications. Here, the joint energy and SR dispatch problem considering the LOC in the objective function is reformulated as a Linear Programming (LP) problem which its solving process is computationally efficient. Also, with reliance on the performance of LP problem solving process, an iterative algorithm is proposed to overcome the self-referential difficulty arising from dependence of the LOC on the final solution. The IEEE 30-bus test system is used to examine the proposed method.

Keywords: Energy Market, Joint Dispatch, Linear Programming, Lost Opportunity Cost, Reserve Market.

1 Introduction

In the electricity industry, ancillary services are complementary services that facilitate technical and commercial electricity transactions [1]. Since they are defined with respect to the requirements and characteristics of each system, the various types of ancillary services and their precise definitions may vary from one system to another [2]. In the many restructured power systems provision of the ancillary services is a task of the Independent System Operator (ISO) [3]. A common commodity of ancillary services is the operating reserve which is defined in most systems so that to ensure their generation reliability. The operating reserve also may be divided and defined in the several types such as the Spinning Reserve (SR), Non Spinning Reserve (NSR) and Replacement Reserve (RR). These divisions and definitions may vary across the different restructured systems.

In the competitive environment of power industry in which there are several models and ways to procure system's reserve requirements, ISO can do this task

either on a pool basis or through long or short term bilateral contracts, which one shortcoming of the latter is lack of competitiveness [4, 5]. Since a perfect competition could lead to efficiency, price transparency and supply and demand side satisfaction, procuring of reserves through competitive markets has many advocates [6].

In this paper it is assumed that ISO runs energy and reserve markets on a pool basis. Also, as the most important and common type in the system's reliability, the operating reserve is referred to SR only. In the system assumed in this paper, ISO runs a real time market following a day-ahead market. Here, the focus is on the dispatch function of the real time market in which the energy and SR allocation will be co-optimized. Based on the submitted bids, ISO would optimally allocate the energy and SR requirements to the market participants and then determine the energy and reserve prices based on the marginal cost. Since the transmission constraints have been included in the dispatch problem, the energy price would be determined based on the nodal marginal price.

In the real time market, dispatch function optimizes the clearing of bids for various electricity products (energy and SR here) and updates economic generation assignments each 5 minutes for the immediately following 5 minutes to 1 hour horizon [7]. Recently, there have been a couple of studies focused on the formulation and solution algorithms of the dispatch optimization problem. The formulation of the dispatch

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problem is strongly related to the model, design and regulation of the energy and reserve markets. It is evident that solving method of the dispatch optimization problem should be selected considering the mathematical properties of the problem formulation and some computational criteria such as efficiency and convergence time. With respect to the formulation of different economic dispatch problems, several tools and methods such as Genetic Algorithm [4, 8-11], Differential Evolution Algorithm [12], Artificial Immune System [13], Honey Bee Mating Algorithm [14], Lagrangian Relaxation [15], Hybrid Direct Search Method [16], Particle Swarm Optimization Algorithm [17, 18], and Harmony Search Algorithm [19] have been used to solve the related optimization problems. If the dispatch problem could be formulated as a Linear Programming (LP) problem, it would be more efficient for the real time applications [20]. In fact, due to existing efficient simplex-based and interior-point methods and their sufficient improvements and developments as LP solvers, formulating a problem as a LP one, if possible, would be preferred and desired.

According to [21], four different designs may be exercised in short term reserve markets based on receiving availability and Lost Opportunity Cost (LOC) payments which are as follows:

- a. Generators receive only availability payments- called *model (A)*
- b. Generators receive only LOC payments- called *model (L)*
- c. Generators receive both availability and LOC payments- called *model (A+L)*
- d. Generators receive either availability or LOC payments- called *model (A|L)*

The LOC is declined energy profit of a generator as a result of providing reserve capacity [22]. In this effort, it is assumed that the SR market follows *model (A+L)* and the generators receive the availability and the LOC payments. In [23], an optimization-based framework was proposed to solve the energy and ancillary dispatch problem for ISO New England in which based on the market rules, the LOC must be explicitly evaluated and paid to the generators. Authors of [23] tried a series of LP solutions to solve the multi-commodity electricity market dispatch problem; however, the LOC functions were not included in the objective function of the optimization problem. Here, it is desired to solve the joint energy and SR dispatch optimization problem when the LOC function is explicitly included in the objective function. In [24], considering the LOC in the objective function of unit commitment problem, the energy and reserve market co-optimization model was developed using mixed integer programming formulations. Also in [21], the LOC was included in the objective function of the optimization problem and, because of being non-differentiable, the energy and reserve dispatch problem was reformulated as a 0-1 mixed integer programming problem. In [21], the

standard branch-and-bound method [25] was recommended to solve the 0-1 mixed integer programming problem. The standard branch-and-bound method may not meet needs of the real time application when the problem is of high dimension.

In this work, the energy and SR dispatch co-optimization, with the LOC considered in the objective function, is reformulated as a LP problem which can be suitable for the real time dispatch application. When the LOC is explicitly included in the objective function of the optimization problem, the marginal costs of energy and SR obtained from the Lagrange multipliers may reflect the true marginal values. The original energy and SR dispatch co-optimization under *model (A+L)* is self-referential because the LOC depends on the nodal energy prices which would not be known until the final solution is obtained [21, 24]. A simple method suggested in [21] and [24] to avoid this difficulty, is using a constant price in the calculation of the LOC. In this study, it is desired to improve this method so that to obtain the true marginal costs of energy and SR from the Lagrange multipliers. Therefore, with reliance on the performance of LP problem solving process, an iterative algorithm is proposed to improve the constant price method. The proposed solution algorithm is applied to the IEEE 30-bus test system and the nodal energy prices and the marginal cost of SR is calculated by the Lagrange multiplier approach. The accuracy of the novel solution method is demonstrated by comparing with alternative solutions.

2 Formulation of Energy and SR Dispatch Problem

2.1 Problem Description

As described in the previous section, in the considered system, ISO runs the real time energy and reserve markets and determines the co-optimized energy and SR allocation through the dispatch function. The transmission constraints are included in the dispatch problem and the energy price is determined based on the nodal marginal price. It is assumed the SR market follows *model (A+L)* and merited generators receive the availability and the LOC payments. Without loss of generality, maximum one generator is supposed at each node and zonal reserve requirements are not considered.

The Energy-only Dispatch (EOD) can be formulated as Eqs. (1a)-(1d). Equation (1a) states the objective function, and Eqs. (1b)-(1d) present the constraints of the optimization problem. In Eq. (1d), \hat{P} and D^P denote vectors related to \hat{P}_i and D_i^P , respectively. Other symbols are defined in the nomenclature presented in Appendix.

$$\text{Min} \sum_i C e_i \hat{P}_i \quad (1a)$$

$$\sum_i (\hat{P}_i - D_i^P) = 0 \quad (1b)$$

$$P_i^{\min} \leq \hat{P}_i \leq P_i^{\max} \quad (1c)$$

$$-\bar{F} \leq T(\hat{P} - D^P) \leq \bar{F} \quad (1d)$$

Formulation of the energy and SR dispatch co-optimization problem under *model (A+L)* can be stated as Eqs. (2a)-(2g). Equation (2a) presents the objective function, and Eqs. (2b)-(2g) state the constraints of the optimization problem. In Eq. (2g), P and D^P denote the nodal generation and demand vector, respectively. Other symbols are defined in the nomenclature provided in Appendix.

$$\underset{P_i, R_i}{\text{Min}} \sum_i (C e_i P_i + C r_i R_i + \text{LOC}_i) \quad (2a)$$

$$\sum_i (P_i - D_i^P) = 0 \quad (2b)$$

$$\sum_i R_i = D^R \quad (2c)$$

$$P_i^{\min} \leq P_i \quad (2d)$$

$$P_i + R_i \leq P_i^{\max} \quad (2e)$$

$$0 \leq R_i \leq R_i^{\max} \quad (2f)$$

$$-\bar{F} \leq T(P - D^P) \leq \bar{F} \quad (2g)$$

In the market with uniform settlement rule, the Lost Opportunity Price (LOP) and the LOC of the generator at node i can be defined as in Eqs. (3) and (4), respectively [21].

$$\text{LOP}_i = \begin{cases} \gamma_i - C e_i, & \gamma_i > C e_i \\ 0, & \gamma_i \leq C e_i \end{cases} \quad (3)$$

$$\text{LOC}_i = \max\{0, \text{LOP}_i(\hat{P}_i - P_i)\} \quad (4)$$

There are two main challenges in solving the real time dispatch problem in Eqs. (2a)-(2g):

First- In this form of formulation, the dispatch problem can not be treated as a LP problem, since the LOC included in the objective function (2a) is a non-differentiable function. In [21], such problem was reformulated as a 0-1 mixed integer programming problem and the standard branch-and-bound method was recommended to solve this 0-1 problem. However, the standard branch-and-bound method may not meet needs of the real time application in a large scale system.

Second- Since the LOC is dependant to the nodal energy prices (γ_i), which are not known until the final solution is obtained, the optimization problem in Eqs. (2a)-(2g) is self-referential. In [21] and [24], using a constant price in the LOC formula was proposed as a simple and approximate method. In this simple method, the constant price which must be used in the LOC calculation is the nodal energy price obtained from the EOD which is formulated as Eqs. (1a)-(1d). On the other hand, the LOC payments to the generators must be evaluated based on the final nodal energy prices. Therefore, the final prices which are calculated based on the Lagrange multipliers of the optimization problem may not exactly reflect the true marginal values because of difference between the LOC used in the objective function and the LOC paid to the generators.

2.2 Handling of the First Challenge Using a Mathematical Trick

Here, using a mathematical trick, the co-optimization problem in Eqs. (2a)-(2g) is reformulated as a LP problem which could be more efficient in solution.

Define a new variable, x_i , as follow:

$$x_i = \hat{P}_i - P_i \quad (5)$$

This new variable can be positive or negative according to the problem conditions. Then, Eq. (4) can be rewritten as follow:

$$\text{LOC}_i = \frac{\text{LOP}_i}{2} (|x_i| + x_i) \quad (6)$$

Variable x_i can be expressed as difference of two positive variables, y_i and z_i , as follow:

$$x_i = y_i - z_i \quad (7)$$

Then, the following Eq. (8) can be resulted by Eqs. (5) and (7):

$$P_i = \hat{P}_i - y_i + z_i \quad (8)$$

And Eq. (6) can be reformed as follow:

$$\text{LOC}_i = \frac{\text{LOP}_i}{2} (|y_i - z_i| + y_i - z_i) \quad (9)$$

Hence, with attention to Eqs. (8) and (9) and with an additional condition which implies y_i and z_i are positive variables, the optimization problem in Eqs. (2a)-(2g) can be rewritten as Eqs. (10a)-(10h):

$$\begin{aligned} \text{Min}_{y_i, z_i, R_i} \sum_i (C e_i (\hat{P}_i - (y_i - z_i)) + C r_i R_i \\ + \frac{LOP_i}{2} (|y_i - z_i| + y_i - z_i)) \end{aligned} \quad (10a)$$

$$\sum_i (\hat{P}_i - (y_i - z_i) - D_i^P) = 0 \quad (10b)$$

$$\sum_i R_i = D^R \quad (10c)$$

$$P_i^{\min} \leq \hat{P}_i - (y_i - z_i) \quad (10d)$$

$$\hat{P}_i - (y_i - z_i) + R_i \leq P_i^{\max} \quad (10e)$$

$$0 \leq R_i \leq R_i^{\max} \quad (10f)$$

$$-\bar{F} \leq T(\hat{P} - (y - z) - D^P) \leq \bar{F} \quad (10g)$$

$$y_i, z_i \geq 0 \quad (10h)$$

In Eq. (10g), \hat{P} , y , z and D^P are vectors related to \hat{P}_i , y_i , z_i and D_i^P , respectively. Since $\sum_i \hat{P}_i = \sum_i D_i^P$, Eq. (10b) can be expressed as a simple form of Eq. (11).

$$\sum_i (y_i - z_i) = 0 \quad (11)$$

Suppose the main optimization problem formulated as Eqs. (2a)-(2g) has an optimal solution, P_i^* and R_i^* . Now, it can be claimed that solving of the optimization problem in Eqs. (10a)-(10h) results in the same optimal solution, P_i^* and R_i^* , under the following condition:

$$y_i z_i = 0 \quad \forall i \quad (12)$$

Suppose y_i^* and z_i^* are the optimal values of the optimization problem in Eqs. (10a)-(10h), then the optimum value, x_i^* , can be derived from Eq. (7). By the condition of Eq. (12), x_i^* will be represented by pairs ($y_i^* \geq 0, z_i^* = 0$) or ($y_i^* = 0, z_i^* \geq 0$) depending on its positive or negative value, respectively. Then, the condition expressed in Eq. (12) implies the condition of Eq. (13):

$$|y_i - z_i| = y_i + z_i \quad \forall i \quad (13)$$

Hence, by applying the condition of Eq. (13) and with attention to Eq. (11), the optimization problem in Eqs. (10a)-(10h) can be reformulated as follows:

$$\text{Min}_{y_i, z_i, R_i} \sum_i (C e_i (\hat{P}_i - (y_i - z_i)) + C r_i R_i + LOP_i \cdot y_i) \quad (14a)$$

$$\sum_i (y_i - z_i) = 0 \quad (14b)$$

$$\sum_i R_i = D^R \quad (14c)$$

$$P_i^{\min} \leq \hat{P}_i - (y_i - z_i) \quad (14d)$$

$$\hat{P}_i - (y_i - z_i) + R_i \leq P_i^{\max} \quad (14e)$$

$$0 \leq R_i \leq R_i^{\max} \quad (14f)$$

$$-\bar{F} \leq T(\hat{P} - (y - z) - D^P) \leq \bar{F} \quad (14g)$$

$$y_i, z_i \geq 0 \quad (14h)$$

Equation (14a) presents the objective function and Eqs. (14b)-(14h) show the constraints of the reformed dispatch problem. Note that P_i^* can be calculated based on Eq. (8). The energy and SR dispatch can be performed applying the LP solution algorithms on the co-optimization problem formulated as in Eqs. (14a)-(14h), instead of using other solution algorithms on the main formulation in Eqs. (2a)-(2g). This will be more efficient to meet the real time application requirements. The final nodal energy prices could be calculated based on the Lagrange multipliers related to the constraints in Eqs. (14b) and (14g), and the SR marginal cost could be obtained from the Lagrange multiplier related to the constraint in Eq. (14c) [26]. The nodal energy prices are given by the marginal cost vector, γ , as follow:

$$\gamma = -\lambda e - T^T \hat{\mu} + T^T \tilde{\mu} \quad (15)$$

In Eq. (15), λ denotes the Lagrangian multiplier of the constraint in Eq. (14b), e is the unit vector (every elements of e is unity), and $\hat{\mu}$ and $\tilde{\mu}$ denote the Lagrangian multipliers related to the upper and lower limitations of the constraint in Eq. (14g), respectively.

The reserve price is also set to the marginal cost, φ , which is equal to the negative of Lagrange multiplier related to the constraint in Eq. (14c).

2.3 Constant Price Method Improvement

To avoid the self-referential difficulty, in [21] and [24], the nodal energy price obtained from the EOD problem in Eqs. (1a)-(1d), $\hat{\gamma}_i$, was used in the LOP (or LOC) calculation, which here is called the constant price method. Note that there are a few problem solving algorithms such as Genetic Algorithm which does not

face the self-referential difficulty, but it may not meet the real time requirements. Here, with reliance on the performance of LP problem solving, an iterative algorithm is presented to improve the use of constant price in the LOP calculation. The flowchart of the proposed algorithm is shown in Fig. 1.

In each iteration of the proposed algorithm, the joint dispatch optimization problem will be solved. In the first iteration, the nodal energy price obtained from the EOD will be used in the LOP calculation. In the next iterations, the constant price to be used in the LOP calculation will be updated with the final nodal energy price resulted in the past iteration. If sum square of differences between the nodal energy prices used in the LOP calculation, γ_i , and the nodal energy prices resulted from LP solution, γ_i^* , is less than a small value, ε , the algorithm is stopped. This stop criterion for the algorithm can be stated as follow:

$$Error = \sum_i (\gamma_i - \gamma_i^*)^2 < \varepsilon \quad (16)$$

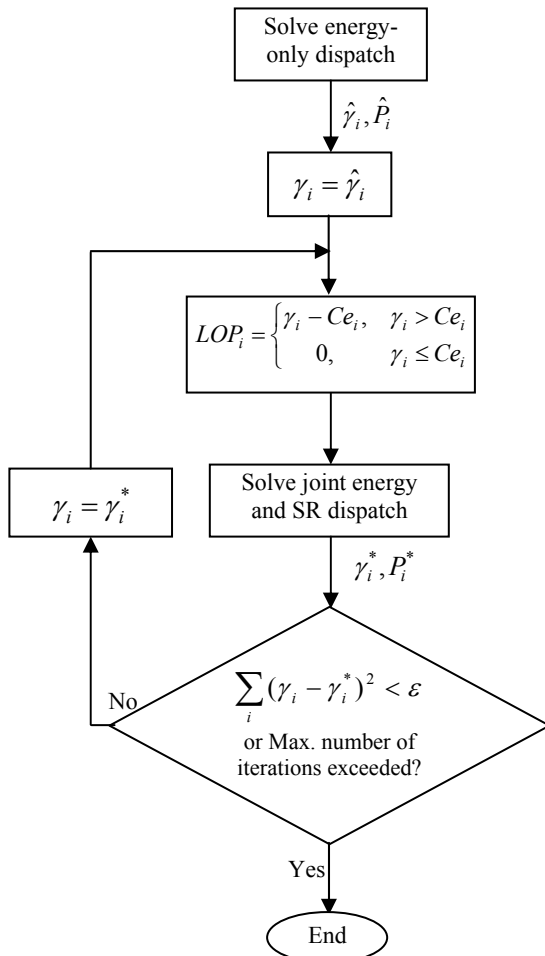


Fig. 1 Flowchart of the iterative algorithm for the constant price method improvement.

Selecting very small value for ε may cause numerical oscillations. Therefore, another stop criterion based on the maximum number of iterations is considered in the algorithm. The initial constant price obtained from the EOD is a suitable starting point, and if the algorithm converges, it would be at the first iterations. This algorithm may not lead to better results occasionally, but in many cases the results will be more appropriate. If the algorithm converges, then the resulted nodal energy prices and reserve marginal cost will reflect the true marginal values with more accuracy.

3 Numerical Studies

The IEEE 30-bus test system is one of the commonly used benchmark systems in similar studies [27-29]. In this section, the proposed solution algorithm is applied to the IEEE 30-bus test system, and the results are compared with some alternative solutions. The network configuration of the IEEE 30-bus test system is presented in Fig. 2 [29]. The branch parameters are available in [30-32]. Table 1 presents the system load data and the submitted specifications and bid data of the generators. The coordinated dispatch of energy and SR is performed in two cases as follows: In Case I, there is no transmission congestion in the network, and in Case II, the line flow limitations and the network congestion effects are considered.

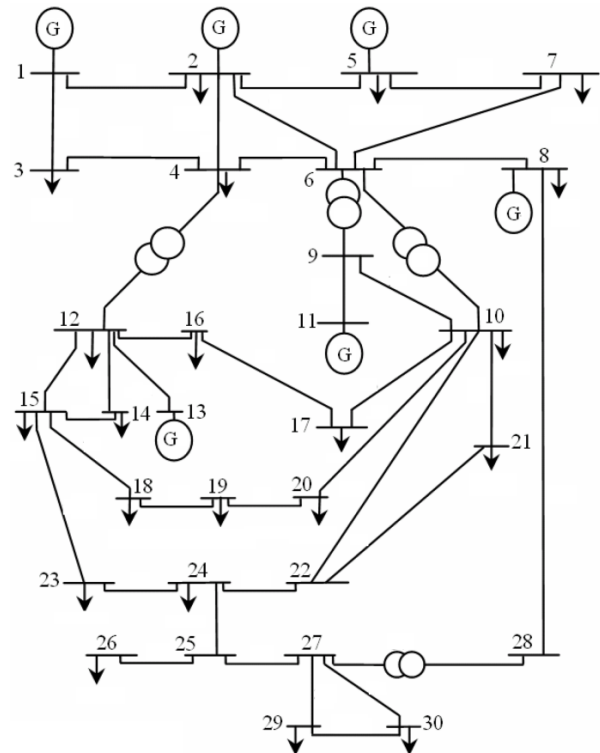


Fig. 2 The configuration of the IEEE 30-bus test system [29].

Table 1 The system load data and the submitted specifications and bid data of the generators.

| Bus No. | P^{max} (MW) | P^{min} (MW) | R^{max} (MW) | Energy bid price (\$/MWh) | SR bid price (\$/MWh) | Load (MW) |
|---------|----------------|----------------|----------------|---------------------------|-----------------------|-----------|
| 1 | 120 | 30 | 30 | 35 | 25 | - |
| 2 | 100 | 30 | 40 | 13 | 10 | 21.7 |
| 3 | - | - | - | - | - | 2.4 |
| 4 | - | - | - | - | - | 7.6 |
| 5 | 80 | 20 | 40 | 19 | 11 | 94.2 |
| 6 | - | - | - | - | - | - |
| 7 | - | - | - | - | - | 22.8 |
| 8 | 80 | 20 | 50 | 15 | 18 | 30 |
| 9 | - | - | - | - | - | - |
| 10 | - | - | - | - | - | 5.8 |
| 11 | 65 | 10 | 40 | 25 | 15 | - |
| 12 | - | - | - | - | - | 11.2 |
| 13 | 50 | 5 | 45 | 17 | 16 | - |
| 14 | - | - | - | - | - | 6.2 |
| 15 | - | - | - | - | - | 8.2 |
| 16 | - | - | - | - | - | 3.5 |
| 17 | - | - | - | - | - | 9 |
| 18 | - | - | - | - | - | 3.2 |
| 19 | - | - | - | - | - | 9.5 |
| 20 | - | - | - | - | - | 2.2 |
| 21 | - | - | - | - | - | 17.5 |
| 22 | - | - | - | - | - | - |
| 23 | - | - | - | - | - | 3.2 |
| 24 | - | - | - | - | - | 8.7 |
| 25 | - | - | - | - | - | - |
| 26 | - | - | - | - | - | 3.5 |
| 27 | - | - | - | - | - | - |
| 28 | - | - | - | - | - | - |
| 29 | - | - | - | - | - | 2.4 |
| 30 | - | - | - | - | - | 10.6 |

It is worth noting that in the main co-optimization problem of (2), the index i varies from 1 to the total number of buses, and the dimension of the vectors such as P and D^P is equal to the total number of buses; hence, in addition to obtain the energy and SR dispatch results, the line flow limitations can be considered and the nodal energy prices can be calculated. It can be comprehended that for the 30-bus test system, the index i varies from 1 to 30, and the dimension of the vectors such as P and D^P is of 30. It is evident that the obtained values of P_i and R_i for the buses that do not include directly connected generation units will be zero.

3.1 Case I

Since the transmission congestion is not considered here, energy prices will be same at all nodes of the network. At first, the joint dispatch is done without including the LOC in the objective function while it should be paid to the generators (similar to *model A*). Afterward, the joint dispatch optimization problem is solved while the LOC is explicitly considered in the objective function (*model (A+L)*). The joint dispatch

under *model (A+L)* is done in two ways: a) using the constant price obtained from the EOD in the LOC calculation, b) applying the iterative algorithm presented in Fig. 1. Table 2 shows the results of the energy and SR dispatch performed in the different forms as described above.

As presented in Table 2, the results of the energy and SR dispatch, with and without including the LOC in the objective function of optimization problem, are different. Also, the results of the dispatch including the LOC in the objective function, based on the constant price method and the proposed iterative algorithm, are the same; however, the calculated reserve marginal prices are different. The marginal prices calculated by the Lagrange multiplier approach in the dispatch under *model (A+L)* applying the proposed iterative algorithm reflect the true marginal values, since the energy price used in the LOC calculation is approximately the same as the final resulted price. It is worthy to note that the proposed iterative algorithm, with $\epsilon=0.1$, has converged in the second iteration.

Table 2 The energy and SR dispatch results for Case I.

| Bus No. | Similar to Model (A) | | Model (A+L) | | Model (A+L) (Proposed Iterative Algorithm) | |
|------------------------|----------------------|----------|-------------|----------|--|----------|
| | P (MW) | R (MW) | P (MW) | R (MW) | P (MW) | R (MW) |
| 1 | 30 | 0 | 30 | 0 | 30 | 0 |
| 2 | 80 | 20 | 100 | 0 | 100 | 0 |
| 5 | 33.4 | 40 | 33.4 | 40 | 33.4 | 40 |
| 8 | 80 | 0 | 80 | 0 | 80 | 0 |
| 11 | 10 | 40 | 10 | 40 | 10 | 40 |
| 13 | 50 | 0 | 30 | 20 | 30 | 20 |
| Marginal Cost (\$/MWh) | 19 | 16 | 19 | 18 | 19 | 20 |

Table 3 The energy and SR dispatch results for Case II.

| Bus No. | Similar to Model (A) | | Model (A+L) | | Model (A+L) (Proposed Iterative Algorithm) | |
|------------------------|----------------------|----------|-------------|----------|--|----------|
| | P (MW) | R (MW) | P (MW) | R (MW) | P (MW) | R (MW) |
| 1 | 30 | 0 | 30 | 0 | 30 | 0 |
| 2 | 60.4 | 39.6 | 100 | 0 | 100 | 0 |
| 5 | 53.4 | 26.6 | 42.3 | 37.7 | 42.3 | 37.7 |
| 8 | 80 | 0 | 55.6 | 17.8 | 55.6 | 17.8 |
| 11 | 10 | 33.8 | 10 | 40 | 10 | 40 |
| 13 | 49.6 | 0 | 45.5 | 4.5 | 45.5 | 4.5 |
| Marginal Cost (\$/MWh) | - | 15 | - | 18 | - | 18 |

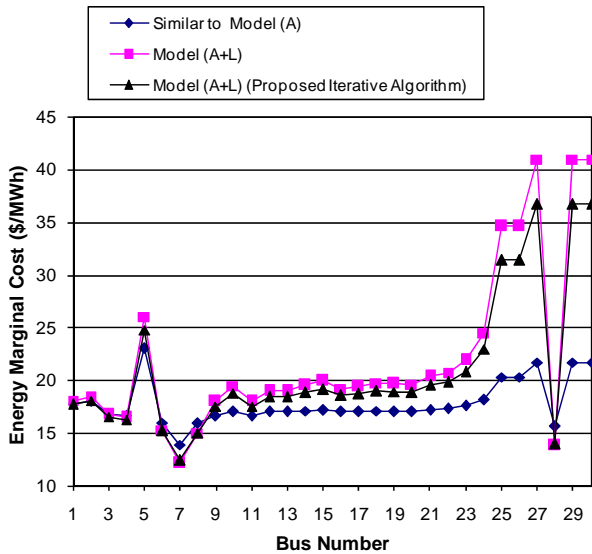


Fig. 3 The nodal energy prices calculated by the Lagrange multiplier approach in Case II.

3.2 Case II

In this case, the active power flow limitations are supposed to be 10MW on the line between buses 5 and 7, and 16 MW on the line between buses 27 and 28. The joint energy and SR dispatch is performed in the different forms as described in Case I. Table 3 presents the energy and SR dispatch results and the reserve marginal prices calculated using the Lagrange multipliers. Also, the nodal energy prices calculated using the Lagrange multiplier method are presented in Fig. 3.

As shown in Table 3, there are differences between the results of the dispatch problem with and without considering the LOC in the objective function. Also, the results of the dispatch under *model (A+L)*, using the constant price in the LOC calculation and through the proposed iterative algorithm, are the same; however, as presented in Fig. 3, the differences in the nodal energy prices are obvious. The nodal energy prices calculated in the dispatch using the proposed iterative algorithm are less in the most critical buses as compared to ones which are calculated in the dispatch using the constant price in the LOC. The marginal prices obtained from the proposed iterative algorithm reflect the true marginal values, since the nodal energy prices used in the LOC function are approximately the same as the final nodal energy prices. Note that the iterative algorithm under *model (A+L)*, with $\varepsilon=0.1$, has converged in the seventh iteration.

4 Conclusion

In this paper, using a mathematical trick, the energy and SR dispatch co-optimization problem considering the LOC in the objective function is reformulated as a LP problem which could meet the real time application requirements. Also, with reliance on the advantages of the LP solution algorithms, an iterative algorithm is

proposed to improve the constant price method used in the LOC calculation. The numerical results show that in the system in which the LOC should be evaluated and paid to the generators, if the LOC is not included in the objective function of the dispatch optimization problem, the obtained results may have deviations from the truly optimum solution. Furthermore, in such a case, the marginal costs calculated by the Lagrange multiplier method may not reflect the true marginal values. Using the novel form of formulation and applying the proposed algorithm on the case studies have resulted in better solutions in terms of optimality. In such cases, the nodal energy prices and the reserve marginal cost computed using the Lagrange multipliers would reflect the true marginal values more accurately.

Appendix

The nomenclature is provided as follows:

| | |
|------------------|--|
| C_{e_i} | offered price for energy from generator at node i |
| P_i | output power of generator at node i |
| \hat{P}_i | output power of generator at node i , obtained from energy-only dispatch |
| P_i^{\min} | minimum generation capacity of generator at node i |
| P_i^{\max} | maximum generation capacity of generator at node i |
| C_{r_i} | offered price for spinning reserve from generator at node i |
| R_i | spinning reserve capacity of generator at node i |
| R_i^{\max} | maximum spinning reserve capacity of generator at node i |
| D_i^P | load demand at node i |
| D^R | system spinning reserve requirement |
| LOP_i | lost opportunity price of generator at node i |
| LOC_i | lost opportunity cost of generator at node i |
| \bar{F} | transmission thermal limit vector |
| T | generation sensitivity factor matrix |
| γ_i | energy price at node i |
| $\hat{\gamma}_i$ | energy price at node i , obtained from energy-only dispatch |
| φ | spinning reserve clearing price |

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