A Study on Congestion Effect on Locational Market Price for Profit Market Strategies

G. V. Rajasekhar and P. Surekha

Abstract This paper presents an analysis on the effect of congestion in determining the profit for generating companies. The locational market price (LMP) determined at each node/bus determines the profit for generating companies and benefit for the consumers. The transmission line loading capabilities will have effect on scheduling the generators. The congestion of transmission line influences the LMP at each node where the transmission line is connected. The difference in marginal cost of generator and LMP at the node connected will determine loss or profit to the generating company. In this paper, a three-bus, seven-bus, and nine-bus systems are simulated for different congestions, and effect on profit is studied. The congestion effect on price of generating companies is studied in this paper. A method to relieve congestion by some percentage on transmission line to benefit generating companies is the key study in this paper, and results are presented in detail.

Keywords Locational market price (LMP) · Congestion · Optimal power flow (OPF) · Bidding · Independent system operator (ISO)

1 Introduction

The price of electric power generated at power stations will be determined by the cost incurred in producing the unit power. Each generating station will have different price per unit. When the generating stations are connected in the network, price per unit will be same for all generating plants if losses are not considered. In the interconnected network, the generating companies will be using the existing network to transmit the power. The transmission lines will have a limit to load them. If the loading of a transmission line is exceeding the limits, then the line is said to be congested. If

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congestion occurs on a transmission network, the locational market price (LMP) will not be same at each node. The difference in LMP is due to congestion on the line.

The trading has to be done by taking into account LMPs and bids based on the congestion effect and other local conditions [1]. Due to congestion, each node takes on different locational price reflecting the effect of transmission congestion. All generators are required to submit supply bids to a system operator taking into consideration, their respective marginal costs. If there is no transmission congestion, then the nodal price calculated from optimal power flow solution at each node is used for bidding [2].

The participation of number of generating companies in the market will make the available lines more congested. There will be more pressure on the transmission network as they are loaded with their maximum loading capacity. The small increase in load demand may congest a few transmission lines. In such systems, providing a uniform pricing to the participants is difficult. The price component will have the congestion component included which will indirectly determine the profits and social welfare. The profit made by the generation companies depends on the percentage of congestion on the line on which it has to transmit its power. The more the congestion the less is the profit [3]. Rescheduling the real and reactive power will help the participants to reduce the loss [3]. The participants will submit the bids to the independent system operator (ISO) based on the LMP calculations at their respective generating and load points [4]. The price to be bid will be based on the system conditions like the amount of power to be transacted, the line congestion for a specific period of time. If the parameter of a network component is exceeding the limits, the network is said to be congested network [5]. In determining the market price, optimal power flow (OPF) is done on the network with constraints.

The congestion effect is then included in determining the OPF which will change the LMP at each bus. The congestion of the network will occur due to overloading of transmission line, tripping of a transformer, and generator outages or due to a combination of these factors. The congestion effect on the market price can be reduced with the help of FACT devices. A proper controlling of reactance of the line by using FACT devices may help reduce the effect of congestion on market price.

2 Literature Review

The annual report of Central Electricity Regulatory Commission (CERC) says that volume of electricity transacted through power exchanges is sometimes constrained due to transmission congestion [6]. The transacted power will have congestion cost which is levied on both consumer and generator. Congestion and consequent market splitting have been considered to calculate the congestion charges, which results in different market prices in different regions. In India, the congestion charges of both power exchanges (IEX and **PXIL**) during the year 2017–2018 were about 53 crore [6].

To increase the number of participants, Government of India focus on attaining “power for all” has accelerated capacity addition in the country. The power additions to existing grid increase the competitive intensity at both the market and supply sides [7]. In nodal pricing, there is the variation of the price according to the change in the geographical location; hence, it is also termed as the locational marginal pricing. The nodal pricing can be calculated by operating the system after 1 MW use and before 1 MW use and calculating the difference between the two costs of operation [8]. As soon as a bidder bids other than marginal costs, he tries to exploit the imperfections in the market setting. Such a behavior is called strategic bidding. The bidder can increase his/her profits by strategic bidding or by any other means except for lowering the costs [9]. The energy markets are now implementing locational marginal pricing. The LMP mechanism was first invented by [10] and introduced at Pennsylvania-New Jersey-Maryland (PJM) ISO. The basis to implement the LMP mechanism is the theory of spot pricing [11].

The congestion and its impact on LMP have gained importance as a less number of transmission corridors are available and a number of participants are increasing. Providing a transmission line for the participant and maintaining grid security is a major challenge.

2.1 LMP and Congestion

Locational marginal price (LMP) and congestion are related to each other. Congestion occurs in the system due to line outages, transformer outage, generator outage, etc. due to the congestion the LMP at each bus changes. The change in LMP changes the market-clearing price. The transmission system imposes some constraints on the power flow in the network; hence, marginal costs become localized [12]. To determine the LMP, optimal power flow is to be used. Further, to solve OPF, linear programming (LP) method is adopted, and without congestion on transmission lines, the OPF matches the economic dispatch, i.e., the LMP at each node becomes equal. In the deregulated power system environment, locational marginal pricing (LMP) method is used to determine the market price. The “*locational marginal price (LMP) at a bus signifies the cost of supplying the next increment of load at that bus. The LMP is the sum of supplying energy marginal cost, cost of losses due to the increase in the transmission congestion cost, if any, arising from the increment and congestion”*.

The LMP is used to determine the marginal price of energy. Congestion and LMP are related in such a way that the profits of generating companies will be effected.

The congestion and loss in the system make the LMP to be different at different nodes of the system. The LMP calculated at each node will help us to determine the energy price at that node.

The LMP method uses security-constrained dispatch to determine the price at each node. By definition, the LMP reflects the cost of supplying additional load. LMP provides a specific, market-based method for the value of the energy that includes the congestion cost. The LMP has three components:

- Energy component—the energy price in an uncongested system free of losses,
- Loss component—reflects the marginal cost of system losses at the location,
- Congestion component—represents the marginal cost of transmission congestion at each location [13].

2.2 LMP Calculation

Calculation of LMP in a market environment involves solving an optimization problem. Locational marginal pricing (LMP) is a method to provide price for small increment of load in a deregulated power system. There are two common methods to determine the pricing structures in a competitive energy market based on congestion:

- Uniform congestion—pricing method is marginal cost pricing,
- Non-uniform congestion—pricing method is locational marginal pricing.

The independent system operator (ISO) acts midway between generating companies and load centers for financial transactions [14]. The LMP is the summation of the costs of marginal energy, marginal loss, and congestion.

$$\begin{aligned}\mathbf{LMP}\left(\$/\text{MWH}\right) = {} & \text{Energy component} + \text{Loss component}\\ & + \text{Congestion component}\end{aligned}$$

The LMP difference at each node is due to the congestion component. If a transmission line is congested between two buses, the congestion component is added to the LMP at one bus and the LMP at another bus is subtracted by same amount. If the congestion component is absent, i.e., if no transmission line is congested, the LMP at each bus is same until economic loading happens. The profit difference comes only to supply the system losses. [13].

2.3 Mathematical Calculations

The locational market price at bus is summation of (energy component + loss component) at the bus and congestion component.

$$\begin{aligned}\text{LMP}\left(\$/\text{MWh}\right) = {} & (\text{Energy component} + \text{Loss component})\\ & + \text{Congestion component}\end{aligned} \tag{1}$$

$$\text{Profit component} = \text{LMP} - \text{Energy Cost} \tag{2}$$

2.4 Market Model

The power generated at generating stations is to be transmitted immediately as there is no provision to store. The transmission network is used to transfer the power. The market model mainly concentrates on controlling the amount of power to be transacted at a particular interval. If the number of participants competes to transact the power, the transmission network is to be shared. The congestion is unavoidable in such circumstances. In bilateral transactions, there should be control over the flow of power in the line. If the power flow is not controllable, the cost of unit energy which they intended to transact will be affected [15].

The transmission line congestion will be obstructing the power transfer which will indirectly affect price of the generating companies [16]. There should be disciplined transactions in the network to eliminate the effect of the congestion on market price. Individually, controlling the power flow is not possible in the deregulated network. There is definitely a need for an ISO to accept bids and settle them based on the transacted power for the particular period of time. The ISO is also responsible for dispatching power from generation to the load in an economic manner based on the bids. The generating companies and load centers will be submitting the bids to the ISO, and ISO decides the price of the energy by taking congestion into account.

2.5 Congestion Management Using D-Fact

The D-Facts act as an impedance controller of the transmission line. The D-Facts are less costly than traditional FACTS controllers. The control of the D-Fact devices is included in the voltage control loop of the power flow solution. The reactance compensated by D-Facts will increase the line power handling capability. If the controller of D-Fact is made to act during congestion, the congestion can be relieved and congestion cost can be eliminated.

2.6 Limitations

The analysis is limited to study the congestion effect on LMP-based profit calculations at both buyer and seller. The cost of ancillary services is not included in the calculation of profit.

3 Results and Discussion

The test systems considered for the analysis are simulated using power world simulator. The generators are considered as sellers, and load is considered as buyers throughout the paper. A three-bus system consisting of two generators at bus 1 and bus 2, and one load at bus 3 is considered for analysis to study the effect of congestion on LMP. Initially, OPF is done on the three-bus system. Bus 1 and bus 2 are identified as sellers. The profit of generator (seller) at bus 1 is monitored by increasing the load at bus 2, and the following conclusions are drawn which are shown in Table 1.

The load at bus 2 is increased such that transmission line 1–2 is congested up to 80%. It is observed that both sellers are making profits. The LMP at node 2 is 2**0.00 $/MWh** and is shown in Table 1. The LMP is constant at all remaining bus as there is no congestion. The sellers at bus 1 and 2 are making a profit of **2000.6 $/MWh** and **800 $/MWh**, and no congestion cost is included in LMP.

The load at bus 2 is increased such that transmission line 1–2 is congested up to 100%. It is observed that the seller at node 1 is not making any profit due to congestion, and seller at 2 is making profit. The LMP at node 2 is **29.95 $/MWh** as shown in Table 2. The congestion has changed the LMP at all buses. The seller at bus 2 is making a profit of **1795 $/MWh**, and congestion cost of **9.95 $/MWh** is included in LMP for the seller at bus 2.

3.1 Analysis with Seven-Bus System

A seven-bus system consisting of four generators is considered for analysis to study the effect of congestion on LMP. Initially, OPF is done on the seven-bus system. The

Table 1 LMP and profit for buyer and seller of three-bus system

Line 1–2 congested 80%				
Bus	LMP $/MWH	Energy cost $/MWH	Profit ($)	Load MW
1	20.00	20.00	2000.6	200
2	20.00	20.00	800	100
3	20.00	20.00	0.17	30

Table 2 LMP and profit for buyer and seller of three-bus system with congestion

Line 1–2 congested 100%				
Bus	LMP $/MWH	Energy cost $/MWH	Profit $/MW	Load MW
1	10.00	10.00	0	199
2	29.90	10.00	1795	100
3	20.00	10.00	0.13	94.5

bus 5 is identified as buyer. The profit of generator at bus 2 is monitored by increasing the load at bus 5, and the following conclusions are drawn.

Case 1: Fig. 1 shows power flow from bus 2 to bus 5. Here, the load at bus 5 is increased such that transmission line 2-5 is congested up to 86%. It is observed that both buyer at bus 5 and seller at bus 2 are making profits. The LMP calculated at bus 2 is **9.72 $/MWh** as shown in Table 3. This is constant at all remaining node. The seller is making a profit of **102.6 $/MWh**, and no congestion cost is included in LMP. The total profit of the sellers in the seven-bus system is 610 $/MW.

Table 3 shows the LPM at each bus for both buyer and seller, and the profit made when there is no congestion.

Case 2: The load at bus 5 is increased such that transmission line 2-5 is congested up to 100%. It is observed that both buyer at bus 5 and seller at bus 3 are making

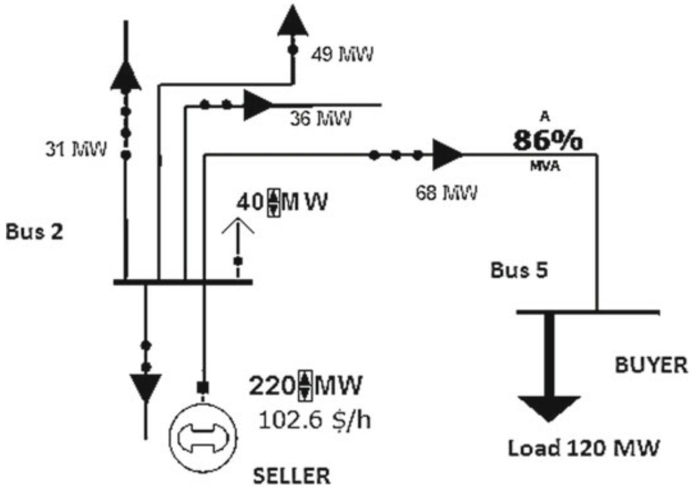

Fig. 1 Line diagram with power flows in 86% congested line from bus 2 to bus 5 of seven-bus system

Table 3 LMP and profit for buyer and seller when line congested up to 86%

Line 2–5 congested 86%				
Bus	LMP $/MWH	Energy cost $/MWH	Profit $/Hr	Load MW
1	9.72	9.72	0	0
2	9.72	9.72	102.6	220
4	9.72	9.72	23	122
6	26.95	26.95	341	250
7	21.80	21.80	144	200
3	9.72	9.72	642	150
5	9.72	9.72	634	120

profits. Figure 2 shows power flows from bus 2 to bus 5. The LMP at bus 2 is 9.25 $/MWh. This is not the same at all remaining node as congestion component is included. The seller is making a profit of 0 $/MWh because a congestion cost of **1.92 $/MWh** is included in LMP of seller at bus2.

Table 4 shows the LPM calculated at each bus for both buyer and sellers and the profit when there is congestion. It is observed that due to congestion, the LMP at all

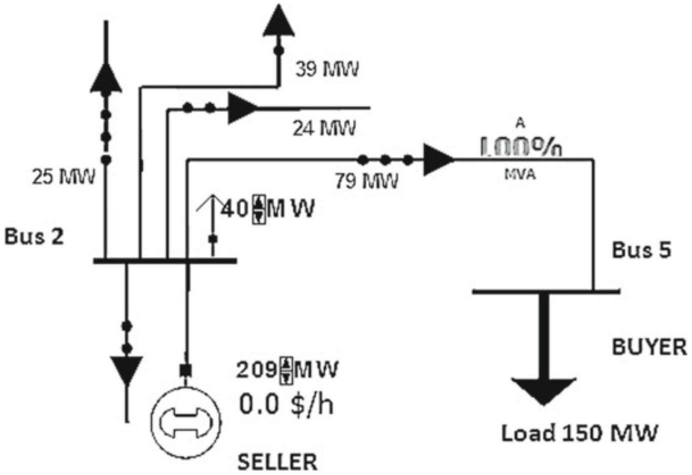

Fig. 2 Line diagram with power flows in 100% congested line from bus 2 to bus 5 of seven-bus system

Table 4 LMP and profit for buyer and seller

Line 2–5 congested 100%				
Bus	LMP $/MWH	Energy cost $/MWH	Profit $/Hr	Load MW
Sellers				
1	9.33	11.17	0	0
2	**9.25**	**11.17**	**0**	**209**
4	9.87	11.17	45.9	152
6	26.95	28.23	341	250
7	21.80	21.80	144	200
Buyers				
3	9.73	11.17	641	150
5	11.86	11.17	471	150

The values are bold in order to highlight them for explaining the concept and to show the profit-making is zero nodes changed affecting the market share and profits for both buyers and sellers. The profit 102.6 \$/MW made by seller 2 when line not congested and is now reduced to zero as shown in Table 4 due to congestion. The following calculation explains why seller at bus 2 is not making any profit. Profit calculations based on Eqs. (1) and (2) for seller at bus 2.

LMP at node 2 = 9.25 \$/MWH + 1.92 \$/MWH = 11.17 \$/MWH and 1.92 \$/MWH is congestion cost on generator at bus 2.

Profit component = LMP − energy cost = 11.17 \$/MWH − 11.17 \$/MWH = 0 \$/MWH.

As shown in Table 4, the profit for seller at bus 2 is 0\$/MW since profit component calculated was 0\$/MW as calculated above. The total profit of the system is also reduced to 530 \$/MW from 610 \$/MW due to congestion. The load of 30 MW is added at bus 5 so that load increased from 270 to 300 MW so as to make lines 2–5 congested up to 100%.

3.2 Analysis with IEEE Nine-Bus System

An IEEE nine-bus system consisting of three generators is considered for analysis to study the effect of congestion on LMP. Initially, OPF is done on the nine-bus system. Here, bus 9 is identified as buyer. The profit of generators at bus 1, bus 2, and bus 3 is monitored by increasing the load at bus 6. Figure 3 shows the line flows from bus 4 to bus 6. The line is not congested.

Table 5 shows the profit of buyer and sellers without congestion. The total load on the system is 385 MW.

Table 6 shows the profit of buyer and sellers without congestion. The total load on the system is 385 MW. An extra load of 40 MW at bus 6 has made line 4-6 congested and is shown in Fig. 4. A congestion cost of 1.71\$/MWh is levied on buyer at bus 6. Therefore, the profit is reduced from 323**\$/MWh** to 40.61**\$/MWh.**

3.3 Congestion Management

The congestion in the system is handled by re-dispatch, countertrade, and load curtailment [17]. The D-Fact devices can help reliving the congestion. The congestion is relieved on the line 2-5 by introducing D-Facts into the line. The D-Facts injected 64-j100, i.e., impedance of 118.72 ohms into the line relieving the line congestion from 100% to 86% loading. Table 6 shows the profits for seller and buyer for 150 MW load at bus 5.

By using D-Fact devices, the profit for the seller at node 2 is increased from 0\$/MW to 136.6 \$/MW. For the same load supplied (220 MW), the seller at node 2 is making an additional profit of 34 \$/MW.

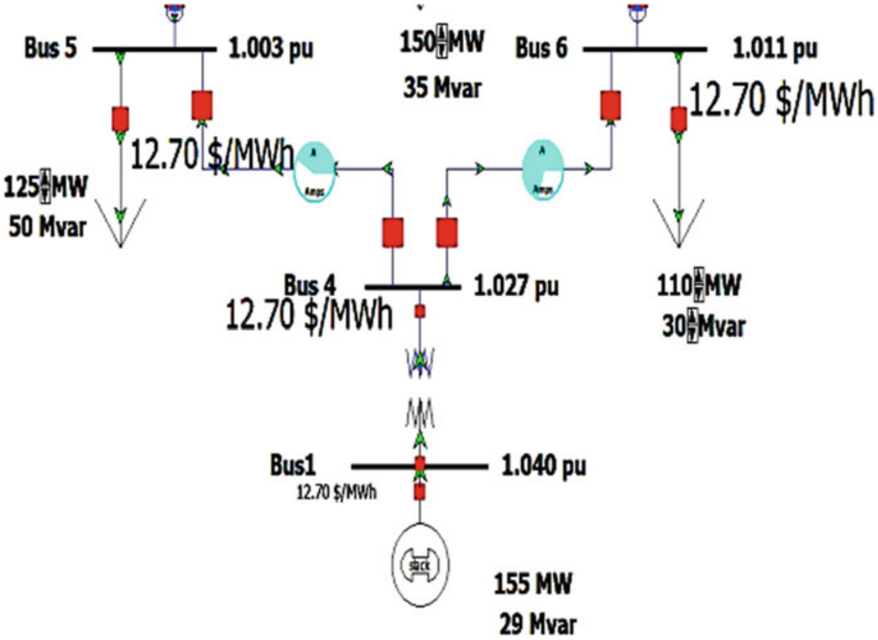

Fig. 3 Line diagram with power flows of uncongested line from bus 4 to bus 6 of nine-bus system

Table 5 LMP and profit for buyer and seller

Line 4–6 without congestion				
Bus	LMP $/MWH	Energy cost $/MWH	Profit $/Hr	Load MW
Sellers				
1	12.7	12.7	78.33	154.8
2	12.7	12.7	81.44	144
3	12.7	12.7	62	90
Buyers				
5	12.7	12.7	362.5	125
6	12.7	12.7	323	110
8	12.7	12.7	295	150

By using D-Fact devices, the profit for the seller at bus 6 is increased from 40 $/MW to 196 $/MW for the same load supplied (150 MW).

Table 6 LMP and profit for buyer and seller

Line 4–6 congested 99%				
Bus	LMP $/MWH	Energy cost $/MWH	Profit $/Hr	Load MW
Sellers				
1	12.7	12.7	64.58	177
2	13.36	12.7	176.48	163.3
3	13.82	12.7	162.52	90
Buyers				
5	12.9	12.7	337.85	125
6	**14.4**	12.7	**40.61**	**150**
8	13.54	12.7	168.89	150

The values are bold in order to highlight them for explaining the concept and to show the profit-making is zero

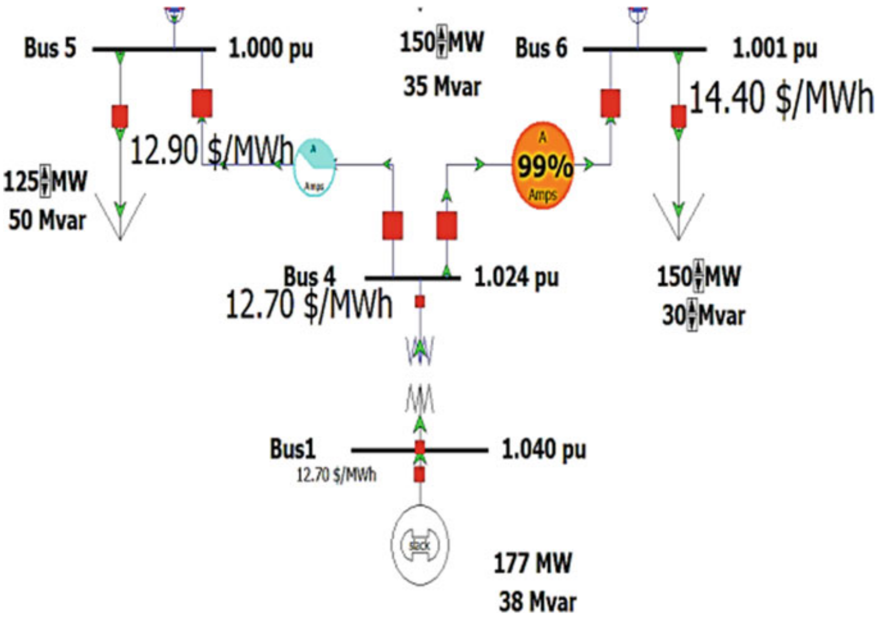

Fig. 4 Line diagram with power flows in 99% congested line from bus 4 to bus 6 of nine-bus system

3.4 Observations

The profit of the buyer at bus 5 is also reduced due to congestion. The LMP at bus 5 is raised from 9.9 to 11.86 $/MWH. If there is no congestion, the LMP for 150 MW load is 9.9 $/MWH. The buyer loses 769 – 471 $/MWH = 298 $/MWH due to congestion.

Table 7 Profit of the sellers and buyer at node 2 and 5 without D-Facts

Line 2–5 congested 100%				
Bus	LMP $/MWH	Energy cost $/MWH	Profit $/Hr	Load MW
Sellers				
2	9.25	11.17	0	209
Buyers				
5	11.86	11.17	471	150

The LMP at each node remains same until any line is constrained and equal to the highest MW marginal cost of generator in that area or zone. Congestion cost does not have any impact on selection of slack bus. LMP is the price of energy at a location the profit is affected by selection of slack bus.

The sellers and buyers will pay based on their location LMP. The difference in LMPs is due to congestion and marginal loss.

The congestion affects the total profit of the sellers. The total profit is also reduced to 530 $/MW from 610 $/MW incurring a loss of 80$/MW due to congestion. The buyer's social welfare is reduced from 1276 to 1112 $/MW incurring a loss of 164 $/MW as shown in Table 7.

4 Conclusion

In this paper, the congestion effect on LMP calculation is studied. The profit at each bus is affected by the line congestion connected to it. The congestion effect is observed for the seller and buyers. The seller profit as well as social welfare affected by congestion. The buyer's social welfare has a loss of 164 $/MW, and sellers lose a profit of 80 $/MW in the seven-bus system for a load of 150 MW. IEEE nine-bus system is studied, and the buyer at bus 6 has got a loss of 282.39 $/MW as line 4–6 is congested. The effect of congestion is reduced by inserting Fact devices at bus 2 of a seven-bus system and bus 6 of the nine-bus system. The buyer at bus 5 of the seven-bus system and buyer at bus 6 of the nine-bus system started gaining profits. The gain in social welfare is more when Fact devices are used and is shown in Tables 8 and 9. The congestion effect on LMP at each bus is studied and minimized by using D-Fact devices.

Table 8 Profit of the sellers and buyer at node 2 and 5 with D-Facts

Line 2–5 congested 100% and after applying D-Fact to relieve congestion by 20%				
Bus	LMP $/MWH	Energy cost $/MWH	Profit $/Hr	Load MW
Sellers				
2	9.87	9.87	136.6	220
Buyers				
5	9.9	9.87	769.3	150

Table 9 Profit of the sellers and buyer at bus 2 and 5 with D-Facts of nine-bus system

Line 4–6 congested 99% and after applying D-Fact to relieve congestion by 2%				
Bus	LMP $/MWH	Energy cost $/MWH	Profit $/Hr	Load MW
Sellers				
1	13.36	13.36	180.81	180
2	13.36	13.36	176.48	160.3
3	13.36	13.36	121.4	90
Buyers				
5	13.36	13.36	280	125
6	13.36	13.36	196	150
8	13.36	13.36	196	150

Implications for Future Research This study has given an insight on how congestion affects the profit share of generating companies participating in the auction. The study also helps in market splitting mechanism which is adopted to clear the bids submitted by companies.

References

1. J.Vijaya Kumar, S. Jameer Pasha, D.M. Vinod Kumar, Congestion influence on optimal bidding in competitive electricity market. in *16th National Power Systems Conference, 15–17th Dec* (2010)
2. P.N. Kumar, G. Parambalath, E. Mahesh, P. Balasubramanian, Big data analytics: a trading strategy of nse stocks using bollinger bands analysis, in *Advances in Intelligent Systems and Computing*, vol. 839, pp. 143–154 (2019)
3. A. Kumar, S.C. Shrivastava, S.N. Singh, A zonal congestion management approach using real and reactive power rescheduling. IEEE Trans. Power Syst. **19**, 01 (2004)
4. L.L. Lei, Power System Restructuring and Deregulation, (Ed) Wiley (2001)
5. J.D. Weber, T. J. Overbye, A two-level optimization problem for analysis of market bidding strategies, in *Proceedings of IEEE Power Engineering Society 1999 Summer Meeting*, pp. 682–687 (1999)

6. Annual report of CERC for the AY-2018. http://www.cercind.gov.in/2018/MMC/AR18.pdf
7. Media Reports, Press Releases, Press Information Bureau (PIB), PE Roundup—August'18 report by EY. https://www.ibef.org/industry/power-sector-india.aspx
8. A. Pillay, S.P. Karthikeyan, D.P. Kothari, Congestion management in power systems—a review. Int. J. Electr. Power Energy Syst. **70**, 83–90 (2015)
9. D.J. Swider, Sequential bidding in day-ahead auctions for spot energy and power systems reserve institute of energy economics and the rational use of energy, University of Stuttgart, Hessbruehl str. 49, pp. 70565 Stuttgart
10. W.W. Hogan, Contract networks for electric power transmission. J. Regul. Econ. **4**, 211–242 (1992)
11. F.C. Scheweppe, M.C. Caramanis, R.D. Tabors, R.E. Bohn, *Spot pricing of electricity, Norwell* (Kluwer, MA, 1988)
12. https://www.powerworld.com/files/M02Optimal-Power-Flow.pdf
13. Power System & LMP Fundamentals, Eugene Litvinov-2017. http://www2.econ.iastate.edu/classes/econ458/tesfatsion/lmp.AdvancedWPM.ELitvinovWEM301.pdf
14. V. Manikuttan, in *Proceedings of the 2017 IEEE Region 10 Conference (TENCON), Malaysia, Nov 5–8, 2017 Optimization of Market Clearing Price Using Firefly and PSO Algorithm in Bilateral Electricity Market*
15. Causes of wholesale electricity pricing abnormalities in the midwest during June 1998, Staff Report to the Federal Energy Regulatory Commission, Sept 22 1998. http://www.ferc.fed.us/news1/staffreports.htm
16. P.R. Rejula, S. Balamurugan, Price area congestion management for an interconnected system with loop flows, in *International Conference on Innovations in Power and Advanced Computing Technologies [i-PACT2017]*, VIT, Vellore, Chennai, 2017
17. V.R. Pandi, A. Biswas, S. Dasgupta, B.K. Panigrahi, A hybrid bacterial foraging and differential evolution algorithm for congestion management. Eur. Trans. Electr. Power (2010)