Transmission Network Congestion in Deregulated Wholesale Electricity Market

N S Modi, *Member IEEE*, B R Parekh *

Abstract—**Electricity market plays an important role in improving the economics of electrical power system. Transmission network is vital entity in open access deregulated wholesale electricity market. Whenever transmission network congestion occurs in electricity market, it divides the market in different zones and the trading price of electricity will no longer remains the same for the whole system. Bidding strategies in electricity market, where by changing the bid, market player changes the revenue of every participant of the market. This paper, after presenting a conceptual understanding of electricity market, gives performance analysis of electricity market for a small three bus system. How network congestion segregates the wholesale electricity market and forces the market to change its price from a common market clearing price to locational market price has also been illustratively demonstrated. Concept of strategic bidding by the participant of the market and its effect on the revenue generation of the players has been computed and analyzed with revising the cost function of one of the generator.**

Keywords: Power System Deregulation, Energy Auction, Network Congestion, Strategic Bidding

1 Introduction

The success of privatization of most of the industries led people to think for the deregulation of electric power system. This yields to restructuring of currently vertically integrated utility (VIU) to the main three utilities, namely generation company (GENCO), transmission company (TRANSCO) and distribution company (DISCO). The success in the energy privatization in the countries like UK, USA, Norway and Australia has encouraged many more countries to privatize their electricity industry. India has also participated in the process and most of the states of India have restructured their electricity boards. Ever since the restructuring has taken palce, the electric power industry has seen tremendous changes in its operation and governance. Electricity, being a concurrent entity, can not be stored easily. This emphasis on generation and consumption of electricity at the same moment of time. Ascertain of electricity market gave new dimension on power system engineer and the economics of power system.

*N. S. Modi is with Department of Electrical Engineering, G H Patel College of Engineering & Technology, Vallabh Vidyanagar, Gujarat, India. Email: nileshsmodi@gmail.com
B. R. Parekh is Professor & Head at Department of Electrical Engineering, Birla Vishwakarma Mahavidyalaya - Engineering College, Vallabh Vidyanagar, Gujarat, India. Email: brp.bvm@gmail.com

In develop countries Electricity market is already functioning and it is being started to introduce in developing countries. The sole purpose of introduction of deregulation and electricity market is to create a healthy competition among the participant of the market and to make electricity market more efficient, liquid and complete [1]. The fundamental objectives behind the establishment of electricity market are the secure operation of power system and facilitating an economic operation of the system. Key entities of the electricity market are Generating companies (GENCOs), independent system operator (ISO) - many a times known as system operator (SO), Transmission companies (TRANSCOs) and Distribution companies (DISCOs) [2]. The development of electricity market also aims for the maximum participation from the electric utilities to provide transparent and non-discriminatory platform for energy producers.

The efficiency of market decreases in the event of transmission line congestion. The congestion results in price change and reduces the market efficiency. Congestion can be managed by different approaches. One of the approach is real and reactive power rescheduling [3]. Strategic bidding is the gaming of players of the market by which the players in the market submits bid to accomplish maximum benefit.

As it proceeds, the paper explains the structure of electricity market and its major components. The different types of energy market are also being explained to assist non-familiar researcher of electricity market. After giving the background of electricity market architecture and operation, paper elucidates the concepts of network congestion in deregulated environment. Network congestion divides wholesale market to different zones with different local marginal prices is being shown with the help of a three-bus system. And lastly the concept of gaming in electricity market is being illustrated with strategic bidding from the supplier.

2 Electricity Market

In almost every areas of technology, privatization has always made a positive impact on the performance of the industry. In 1989, UK became one of the pioneer country to unbundle their electricity industry [4]. After the success of deregulation in the UK, most of the countries of Europe have started to unbundle their vertically integrated utilities. The successes of these countries have encouraged the other countries to privatize their electricity industry which includes Finland, Australia, New Zealand, Taiwan and Brazil. In India the unbundling procedure has been carried out by most of the states and there exist a state regulatory commission in all states who has opted for deregulation of electricity industry. The development of electricity market in India is still at nascent stage.

One of the objective behind privatization of electricity industry is to introduce competition at every stage. This leads the engineer to develop a common place for trading electricity assets and this in turn develops the term electricity market. Electricity market is a place where trading of power takes place between power producers and consumers. Along with the trading of active power, trading of ancillary services can also been carry out in electricity market. The reforms of electricity has not only emerged electricity market but also increase the number of private players and radically changed the scenario of power system economics.

3 Electricity Market Architecture

The electricity market architecture comprises of main four entities namely GENCOs, TRANSOs, DISCOs and an independent system operator (ISO) [2]. GENCO is not necessary to have its own generating plants, but it can negotiate on behalf of generating companies. In ancillary market GENCO has opportunity to sell its reserves and reactive power. The GENCO will try to maximize its own profit, whatever way it can, by selling the power in the market. TRANSCO transmit the power from power producer to power consumer. It also maintains the transmission system to increase overall reliability of power system. DISCO distributes the power to retail companies, brokers or to its own consumers. ISO is an independent body which maintains the instantaneous power balance in the system. ISO is also responsible for secure operation of the grid. There could be two types of ISO, one is known as MinISO and the other is MaxISO [2]. While MinISO, look looking after the grid security and has no role in power market, MaxISO model includes power exchange (PX). The function of power exchange is to provide a competitive market place for all the participant of the market. ISO uses the assets of TRANSCO for its functioning. The role of ISO also encompasses the fare use of transmission network, maximizing social welfare of the market, running power exchange (PX), maintaining grid security and to run separate market for ancillary services. The calculation of system price and bid matching can be carried out by power exchange [2, 4].

The electricity market can be classified by the entity which it trades. The broader classification of electricity market includes power market, ancillary service market and transmission market. The classification can also be carried out by the operating mechanism of market, which leads to forward market, spot market and pool market. Sport market is also known as real time market [5]. The market can also be classified as wholesale market and retail market.

The price in this type market can be calculated by finding equilibrium point of the supply and demand curve. Fig. 1 illustrates this mechanism.

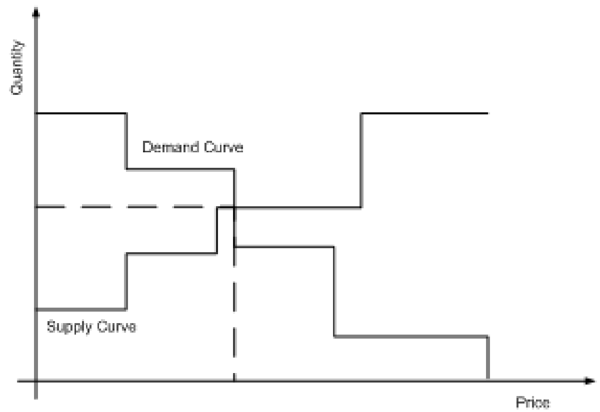

Figure 1: Market Equilibrium Point

The equilibrium point is known as market clearing price (MCP). The ISO or PX accepts bids from all the players of the market and determines the MCP. Whenever there is no network congestion, MCP is the only one price for every node of the system. But because of the congestion the whole system is being segregated in different zones and zonal market clearing price is used for different zones. This price is also known as locational marginal price (LMP). LMP can be understood as the cost of next MW of power at that particular node. The following section explains the network congestion and its consequences on market price.

4 Network Congestion

Whenever the network component is overloaded the network is called congested network [6]. In a competitive market, network congestion has its own importance because of the complexity involved. This congestion may be due to overloading of transmission line or transformer. The problem of network congestion can be alleviated with the help of phase shifter, tap changing transformers and curtailment of loads. It can also be solved by removing the overloaded component from the system. But this might aggregate the network congestion.

5 Strategic Bidding

In a pool electricity market every player, whether power producer or consumer, submit the bid. The PX collects all the bids and the MCP is declared for the operation of the market. Now if any players strategically bids then even at common MCP the player can gain profit. This is known as gaming in electricity market. It is also known as strategic bidding by the player to avail maximum benefit from the market. Under ideal market condition, power producers have every reason to bid on marginal cost of their generating plants [5]. The gaming can be played by withdrawing some portion of the operating capacity or by modifying the marginal cost or operating cost while bidding.

In this paper, gaming has been illustrated by modifying the cost function of the generator connected to bus B. By the strategic bidding the change in the social welfare is calculated and analyzed.

6 Example Power System

To illustrate congestion and bidding strategy in electricity market operation under deregulated environment a simple 3-bus system has been used. Fig. 2 shows the schematic of a loss less electric power system under study.

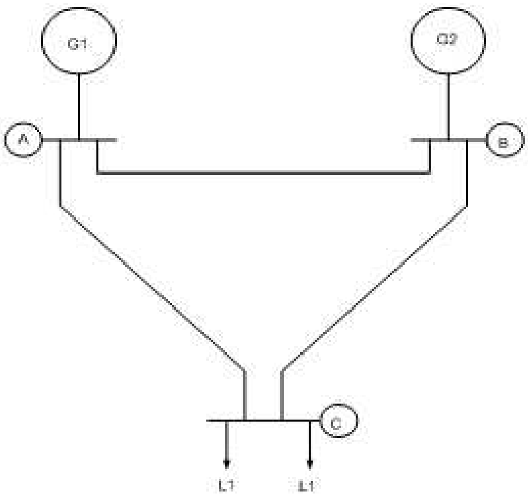

Figure 2: A Sample Power System

Both the generator have quadratic cost curve [4,8] and its operating limits are as showing in (1) and (2). The operating limits are in MW .

$$C(G_1) = 0.012P_1^2 + 10P_1 + 250 \text{ INR}/h; 50 \leq P_1 \leq 500 \quad (1)$$

$$C(G_2) = 0.02P_2^2 + 9P_2 + 475 \text{ INR}/h; 100 \leq P_2 \leq 700 \quad (2)$$

where,P_1 and P_2 are the power generation by respective generators. The two loads have quadratic cost function and its operating limits are given by (3) and (4). The operating limits are in MW.

$$C(L_1) = -0.018L_1^2 + 30L_1 \text{ INR}/h; 0 \leq L_1 \leq 900 \quad (3)$$

$$C(L_2) = -0.012L_2^2 + 20L_2 \text{ INR}/h; 0 \leq L_2 \leq 200 \quad (4)$$

The loads are assumed to be elastic in nature so depending upon the power offered from market; both the utilities will change its demand so as to obtain equilibrium point between received power and demand. The maximum operating capacity of each line is as show in Table 1.

Line	Limit(MW)
AB	100
AC	200
BC	400

Table 1: Operating Limits of Lines

Line AC and BC have same impedance and AB has impedance equals to twice of AC. It is assumed that bid offered by every utility in the market, whether the generating utility or the utility which receives power from market, is on its marginal cost.

7 Unconstrained System

In the central auction type of market, all the suppliers and consumers will submit the bid to central pool or exchange and market will decide the market clearing price (MCP) based on the equilibrium point of the bids. For the system shown in Fig. 2, with bidding function being the marginal cost, the market clearing price would come to 16.9552 INR/MWh. With this MCP the output of each generators and catered demand of each consumers is tabulated in Table 2.

The individual producer surplus is defined by (5).

$$Surplus = (MCP \times P_i) - C(P_i) \text{ where} i = 1, 2, ..., n \quad (5)$$

where, $MCP \times P_i$ is known as revenue generated with market clearing price and $C(P_i)$ is known as revenue under offer. The individual consumer surplus is defined by (6).

Generator/ Load	Price (INR/hr)	Quantity MW	Surplus(Profit) (INR/hr)
G1	16.9552	289.96	757.80
G2	16.9552	198.978	316.06
L1	16.9552	362.244	2363.4
L2	16.9552	126.70	193.41

Table 2: Market Clearing, Transmission Unconstrained

$$Surplus = C(L_i) - (MCP \times L_i) \text{where} i = 1, 2, ..., n \quad (6)$$

Where, $MCP \times L_i$ is known as payment with market clearing price and $C(L_i)$ is known as actual benefits.

The social welfare of the market can be calculated by (7).

$$\psi = \sum_{i=1}^{n} C(L_i) - \sum_{i=1}^{m} C(G_i) \quad (7)$$

In the unconstrained solution of the system, the social welfare is equal to 3613 INR/hr.

7.1 DC Power Flow [7]

However a full ac power is the accurate method to know the line loading of the system under study, DC power flow has been used throughout the work. While giving the idea of MW flows on transmission line, DC power flow solution does not give any indication of what happens to voltage magnitudes. With its usual notations, DC power can be solved with the following equations.

$$P_{ik} = \frac{1}{x_{ik}}(\theta_i - \theta_k) \quad (8)$$

$$P_i = \sum_{\substack{k=buses \\ onnectedtoi}}^{n} P_k \quad (9)$$

The system has been solved for DC power flow and the loading of the lines is calculated. Table 3 gives the loading on each line.

Line	MW
AB	22.74
AC	267.21
BC	221.71

Table 3: Line Flow, Transmission Unconstrained

8 Constrained System

It can be observed from the above analysis that, with this bidding and a common MCP leads to the network congestion for the system under study by overloading of line AC. To relieve the network from congestion, the above system has to be solved under transmission line capacity constraints. This will alter the output of generator (supplier) and the catered demand (consumer). Because of network congestion the MCP is not valid for all the nodes of the market and will lead to different locational marginal price (LMP) at each node. The results of constrained DC power flow are as shown in Table 4.

Gen/ Load	LMP (INR/hr)	Quantity MW	Surplus(Profit) (INR/hr)
G1	15.34	222.75	345.41
G2	14.27	131.36	-127.24
L1	18.89	308.46	1714.3
L2	18.89	46.03	25.66

Table 4: Market Clearing, Transmission Constrained

It can be seen that the price on bus A is more than bus B as costly generator is attached to that bus. Load L_1 and L_2 are connected to bus C so the LMP on that is bus is same for L_1 and L_2 .

The significant observation, the outcome of network congestion, is that the payment received by generator located on bus B is less than its production cost. It is under the loss in network congested electricity market. The social welfare has reduced to 3359 INR/hr.

The congestion rent is defined as the difference between total demand charges and total generation payment would come to 1397.3 INR/hr. This amount, which is revenue generation by Independent system operator, can be distributed to transmission companies.

There are number of ways to reduce the revenue loss of generator connected to bus B. One of them is to strategic bidding by generator (supplier). This is popularly known as gaming. The following analysis shows the gaming/strategic bidding done by supplier at bus B, by changing its linear portion of cost function from (2) to (10).

9 Strategic Bidding

The supplier (generator) connected to bus B, changes its cost function from (2) to (10).

$$C(G_2) = 0.01P_2^2 + 12P_2 + 475 \text{ INR}/h \quad (10)$$

With this gaming, the unconstrained and constrained solution of the network yields to Table 5 and 6.

Generator/ Load	Price (INR/MWh)	Quantity (MW)
G1	16.6552	277.29
G2	16.6552	232.75
L1	16.6552	370.68
L2	16.6552	139.36

Table 5: Strategic Bidding, Transmission Unconstrained

The social welfare under unconstrained solution is 3602.56 INR/hr. Further by solving the network for congesting relief, we can get different LMP for every node.

Gen/ Load	LMP (INR/hr)	Quantity MW	Surplus(Profit) (INR/hr)
G1	15.06	211.13	372.75
G2	15.33	166.69	70.64
L1	18.56	317.75	1817.6
L2	18.56	59.96	43.20

Table 6: Strategic Bidding, Transmission Constrained

It can be found that the social welfare is 3534.77 INR/hr and congestion rent is now 1230.68 INR/hr. More importantly, by strategic bidding by the supplier at bus B making profit as compared to loss previously.

10 Conclusion

In this paper, network congestion in deregulated electricity market has been illustrated and evaluated. The concept of game theory in the market has also been demonstrated illustratively. It has been show that how equilibrium point of electricity market deviates under the strategic gaming. The analysis carried out revealed the fact that congestion will reduce the market efficiency and also the social welfare.

References

[1] Indian Electricity Exchange [Online]: Available: http://iexindia.com

[2] M. Shahidehpour, H. Yamin, Z. Li, *Market Operation in Electric Power systems, Forecasting, Scheduling and Risk Management*, John Wiley & Sons, 2002.

[3] A Kumar, S C Shrivastava, S N Singh "A Zonal Congestion Management Approach Using Real and Reactive Power Rescheduling" *IEEE Transaction on Power Systems*, Vol 19, No. 01, Feb 2004

[4] Loi Lai Lei *Power System Restructuring and Deregulation*, (Edited), John Wiley & Sons Limited, 2001

[5] J W Bialek, "Gaming the Uniform-Price Sport Market: Quantitative Analysis" *IEEE Transaction on Power System*, Vol 17, No. 3, August 2002.

[6] M I Alomoush, S M Shahidehpour, "Contingency-constrained Congestion Management with a Minimum Number of Adjustment in Preferred Schedule" *Electrical power and Energy Systems*, vol 22, pp 277-290, 2000.

[7] A J Wood, Woolenberg, *Power Generation Operation and Control*, John Wiley and Sons, 1996

[8] Thilo Krause, "Congestion Management in Liberalized Electricity Markets - Theoretical Concepts and International Application", *EEH Power System Laboratory*, Eidgenossische Technische Hochschele, Zurich, May 2005.

[9] K L Lo, Y S Yuen, L A Snider, "Congestion Management in Deregulated Electricity Market", *International Conference on Electricity Deregulation and Restructuring and Power Technologies*, City University London, 4-7 April 2000

[10] P L Joskow, J Tirole, "Transmission Rights and Market Power on Electric Power Networks" *RAND Journal of Economics*, Vol. 31, No. 3, pp. 450-487, 2000

N S Modi received his B. E. degree in Electrical Engineering and M.E. degree in Electrical Engineering from Sadar Patel University in the year 2001 and 2004 respectively. He is currently working as Lecturer in Electrical Engineering at G H Patel College of Engineering & Technology, Sardar Patel University, Vallabh Vidyanager, India. His research interest includes power system operation, simulation of electrical system, deregulation and electricity market. He is member of IEEE and life member of ISTE and Institute of Engineers (India).

B R Parekh has received B.E. degree in Electrical Engineering from Sardar Patel University, Vallabh Vidyanagar, India in 1979, M.E. degree from same University in 1985, and Ph.D. degree from Indian Institute of Technology, Bombay in 1995. His research interests include power systems operations and control. Application of Computers and Artificial Intelligence in operation of the Power Systems. He is currently Professor and Head of Electrical Engineering Department at Birla Vishvakarma Mahavidyalaya (Engineering College), Vallabh Vidyanagar, India