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SIMULATION TO OBSERVE THE EFFECT OF PARAMETER VARIATION ON LOCATIONAL MARGINAL PRICE IN RESTRUCTURED POWER SYSTEM BY USING POWER WORLD SIMULATOR

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Abstract:

The restructured electricity market plays an important role in the economics of country. It is indispensable to develop an effective pricing mechanism to address the transmission network issues and to generate accurate economic signals. Locational marginal pricing (LMP) is a valuable mechanism for pricing electricity in restructured electricity markets. LMP provides the economic signals for market participants, informing them when & where power is cheap or expensive. LMP may vary at different time and locations based on transmission congestion, losses & parameter variation of network. It is essential for the market participants to be acquainted with effect of parameter variation on LMP and it helps for reliable decisions about investment, enable higher levels of grid stability & produce competitive markets for reliable power sources.

This paper presents formulation of LMP in Optimal Power Flow (OPF) by considering the system constraints. The effect of network parameter variation on LMP is observed on standard IEEE 6-bus test system. The simulation is carried out on IEEE-6 bus test system by using Power World Simulator and obtained results have been presented. The presented analysis based on results is useful for decision about investment, to upgrade transmission network, to increase competition and improve system efficiency & ability for accomplishing the power demand.
Keywords: Electricity Market, Locational Marginal Pricing, Optimal Power Flow, Power World Simulator

1. Introduction

In Restructured electricity market, Uniform pricing structure (Market Clearing Price-MCP) and Non-uniform pricing structure (Locational Marginal Price-LMP) are the two-pricing structure. When there is no transmission congestion means normal operation in the power system then MCP is the only electricity price for the power system. The intersection point of supply bids curve and demand bids curve represents MCP. In case of transmission congestion, the electricity market has to clear the system on bus level instead of system level. The clearing price at each bus is known as Locational Marginal Price (LMP) also referred to as Nodal Price. LMP is a pricing concept used in deregulated electricity markets to manage the efficient use of the transmission system when congestion occurs on the bulk power grid. The congestion may occur mainly due to transmission line outages, generator outages & change in load demand and it impact on the entire system as well as on the individual market participants.

LMP is determined through the solution of Optimal Power Flow (OPF) by considering the system constraints. The Federal Energy Regulatory Commission (FERC) has proposed LMP as a pricing structure to achieve short term and long-term efficiency in restructured electricity markets.LMP may vary at different time and locations based on transmission congestion, losses & parameter variation of network. In normal operation of power system, low cost generating units are used to meet the load demand but if congestion occurs in the transmission system then it prevents the demand to be met by the lowest-priced generating units due to system constraints and this leads to the allocation of higher price generating units.

LMP can be summation of following components:

LMP = Generation marginal cost + Congestion cost + Marginal loss cost

For observing the effect of parameter variation on LMP following parameter of test system is change and simulation results are observed for detailed understanding.

- Voltage
- Line flow limit
- Connected Load

The basic concepts of nodal price modeling in a competitive electricity market and some special considerations on its formulation have been presented [1]. LMP calculation at each bus when system is under normal and congested condition has been discussed and presented [2]. Genetic Algorithm (GA) based security constrained economic dispatch approach to evaluate LMP at each bus while minimizing system fuel cost with and without considering system losses is presented. The proposed approach is applied on IEEE 14 bus, 75 bus system and obtained results are compared with conventional Linear Programming based DCOPF using Power World Simulator [3]. TCSC optimal location problem with maximization of benefits in addition to minimize the congestion cost is discussed. Also presented Uniform and Non-Uniform pricing structure for price calculation in competitive electricity market [4]. DCOPF model is developed to perform the financially consistent locational marginal pricing for the generalized AC-DC system without compromising significantly with the power flow accuracy [5]. The comparative results of locational marginal pricing on IEEE 7 bus test system using both PTDF (Power Transfer Distribution Factors) based on DC load flow and Numerical conventional GSF matrix is presented. The analysis shows the effect of GSF on congestion charges and the losses in the system and their formulation and formation of total locational pricing scheme [6]. In [7,16], different AC and DC optimal power flow (OPF) models are presented to help understand the derivation of LMPs. As a byproduct of this analysis, a rigorous explanation of the basic LMP and LMP-decomposition formulas is presented. Variation of LMP values with transmission constraint conditions also studied. Simulation is carried out on IEEE 30 bus test system and the results are presented [8]. Focused on implementing power systems optimization for forecasting Market Prices in deregulated electricity markets and necessary solution is computing by collecting the clearing price from the generating station and load center and bids are offered in the closed loop form [9]. The variation of LMP with change in load and system conditions in deregulated power system is presented and also used LPOPF to evaluate LMP for PJM 5 bus test system [10,15]. The algorithm is compared with ACOPF algorithm for accuracy of LMP results at various load levels using the PJM 5-bus system. The result shows that the

FND algorithm is a good estimate of the LMP calculated from the ACOPF algorithm and outperforms the lossless DCOPF algorithm [16,17]. The effect of allocation of distributed generation to different potential locations of congestion zones has been analyzed in order to manage congestion. The TCSC optimal location problem with maximization of benefits in addition to minimize the congestion cost is presented. The techno-economic benefits of TCSC in the IEEE-14 bus system are also analyzed and discussed [18]. The fundamental concept of locational marginal price (LMP) in the electricity markets and presents some special observations on LMP. Under market environment, LMP based settlement strategy is used to determine the amount of money earned from ISO by the energy sellers and paid to ISO by the energy buyers. Thus, depending on different market designs, four different calculation models and corresponding properties on LMP are discussed [19,20]

This paper is organized as follows: Section 2 includes the formulation of LMP. Section 3 presents the Simulation of IEEE-6 bus test system, Section 4 consists of results and discussion. Section 5 contains some relevant conclusion.

2. Formulation of Locational Marginal Price

LMP is the Non-Uniform pricing method of reallocating an extra 1MW at specific buses of power system. Following is the formulation of LMP in Optimal Power Flow (OPF) by considering the system constraints.

The objective function of the system is obtained by summing the cost functions of each generator unit.Ci(Pi) is the cost function of generation unit i [12,13,14]:

$$C_i(P_i) = a_i + b_iP_i + c_iP_i^2$$

Optimization of Cost function of Generator unit i

$$\text{Minimize} \quad C_T = \sum_{i=1}^{n} C_i(P_i)$$

Subject to,

$$\left(\sum_{i=1}^{n} P_i - \sum_{i=1}^{n} P_D\right) = P_L \qquad \lambda$$

$$P_L = LF^T\left(\sum_{i=1}^{n} P_i - \sum_{i=1}^{n} P_D\right) \qquad \psi$$

$$SF\left(\sum_{i=1}^{n} P_i - \sum_{i=1}^{n} P_D\right) \leq S_{max}\,\pi^+$$

$$-SF\left(\sum_{i=1}^{n} P_i - \sum_{i=1}^{n} P_D\right) \leq S_{max}\,\pi^-$$

$$P_{i\,min} \leq P_i \leq P_{i\,max} \qquad \mu$$

Where, *Ci(Pi)*is the quadratic cost function of gen. unit *i*

a_i, b_i and c_i are the fuel cost coefficients for unit *i*.

Pi is the power output of generation unit *i*

n is the number of generators

P_D is the total system load

$P_i^{\min}$, $P_i^{\max}$ are the lower and upper limits of gen. unit i, resp. and
P_L is the total system losses

Lagrange function is formed as a mixture of objective function and functions of constraints along with proper Lagrange coefficients. The optimal point of Lagrange functions is the solution to the OPF problem.

$$\begin{aligned} L = \sum_{i=1}^{n} C_i(P_i) &- \lambda\left[\left(\sum_{i=1}^{n} P_i - \sum_{i=1}^{n} P_D\right) - P_L\right] - \psi\left[P_L - LF^T\left(\sum_{i=1}^{n} P_i - \sum_{i=1}^{n} P_D\right)\right] \\ &- \pi^+\left[S_{max} - SF\left(\sum_{i=1}^{n} P_i - \sum_{i=1}^{n} P_D\right)\right] \\ &- \pi^-\left[SF\left(\sum_{i=1}^{n} P_i - \sum_{i=1}^{n} P_D\right) - S_{max}\right] - \mu^{max}(P_{i\,max} - P_i) \\ &- \mu^{min}(P_i - P_{i\,min}) \end{aligned}$$

To obtain the optimum point, the Karush-Kuhn-Tucker (KKT) necessary condition should be met. The same is derived from the Lagrange function L.

The KKT condition for Loss variable is,

$$\frac{\partial L}{\partial P_L} = -\lambda(-1) - \psi(1) = 0$$

$$\lambda - \psi = 0$$

$$\lambda = \psi$$

The Locational Marginal Price (LMP) is defined as,

$$\begin{aligned} \text{LMP} &= \frac{\partial L}{\partial P_D} \\ &= -\lambda(-1) - \psi[-LF(-1)] - \pi^+[-SF(-1)] - \pi^-[SF(-1)] \\ &= \lambda - \psi[LF] - \pi^+[SF] - \pi^-[-SF] \\ &= \lambda - \psi[LF] - \pi^+[SF] + \pi^-[SF] \\ &= \lambda - \psi[LF] - SF(\pi^+ - \pi^-) \\ \text{LMP} &= \lambda - \lambda[LF] - SF(\pi^+ - \pi^-) \end{aligned}$$

LMP = Marginal cost of generation + Marginal cost of losses +Congestion cost

3. Simulation of IEEE-6 Bus Test System

The LMP formulation has been tested on IEEE-6 bus test system in congestion condition having 03 generators and 11 transmission lines. The connected load in the system is increased to 344 MW & 285 MVAr. The generator data and buses data of test system are given in table –1 & 2. The bus no.-1 has been taken as a reference bus with its voltage adjusted to 1.05 (p.u).

Power World Simulator is used as simulation tool and fig.1 shows the OPF solution in congestion condition for demand of 344 MW & 285 MVAr load. The obtained results are tabulated in table-3

Table-1 Generator Data [11,12]

Bus	PGi Max MW	PGi Min MW	QGi Max MVAr	QGi Min MVAr	ai \$/MWh	bi $\$/MW^2h$
1	132.5	112.5	150.0	-150.0	8.5	0.0005
2	165.0	140.0	150.0	-150.0	9.0	0.0005
3	80.0	60.0	150.0	-150.0	9.5	0.0005

Table-2 Bus Data

Bus	**Volt**	**Angle**	**Load MW**	**Load MVAr**	**Gen MW**	**Gen MVAr**
1	1.05	0	-	-	132.5	48.95
2	1.05	-3.03	-	-	163.25	104.45
3	1.07	-6.38	-	-	68.56	141.81
4	0.9601	-4.86	95	90		
5	0.9265	-8.64	145	105		
6	0.974	-8.5	104	90		

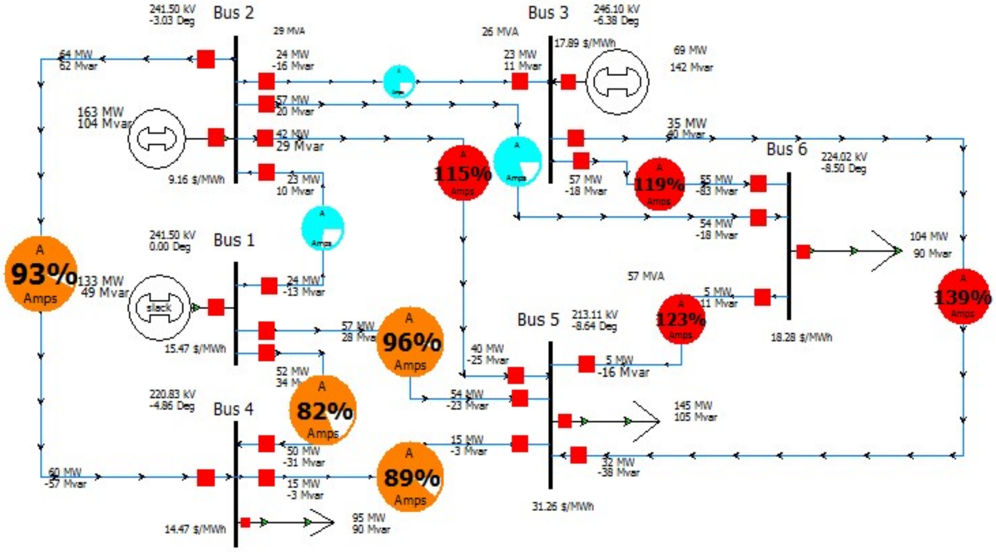


Fig.-1. Simulation of test system for LMP (OPF solution)

4. Results and Discussion

The simulation results of test system show that the power flow in line-6 (buses 2-5), line-8 (buses 3-5), line-9 (buses 3-6), line-11 (buses 5-6) is congested. The power flow in line - 6, 8, 9 & 11 is higher than that of its MVA limit of line as shown in table -2 and in fig.-2.

Table-3. Line flow data in congestion condition

Line	Buses	MVA Limit	MVA Power Flow

1	(1-2)	36	27
2	(1-4)	72	61.8
3	(1-5)	63.6	63.8
4	(2-3)	36	28.6
5	(2-4)	92	88.9
6	(2-5)	42	50.8
7	(2-6)	72	60
8	(3-5)	41	53.4
9	(3-6)	89	107.3
10	(4-5)	18	15.4
11	(5-6)	15	16.3

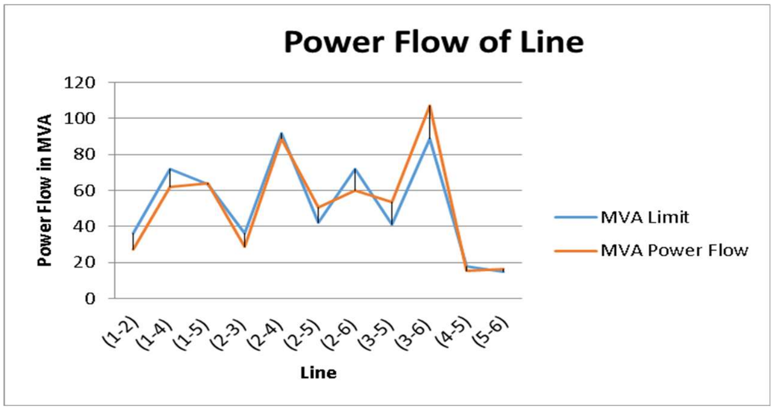


Fig. 2 Power flow of line

After simmulation the Locational Marginal Price (LMP) and each components at each bus is as shown in table-4 and fig.3.

Table-4. Simulation Results in Congestion

Bus No	LMP Component			LMP in $/MWh
	Energy $/MWh	Congestion $/MWh	Losses $/MWh	
Bus 1	15.47	0	0	15.47
Bus 2	15.47	-6.74	0.43	9.16
Bus 3	15.47	1.36	1.05	17.89
Bus 4	15.47	-2.25	1.24	14.47
Bus 5	15.47	13.61	2.17	31.26
Bus 6	15.47	1.18	1.63	18.28

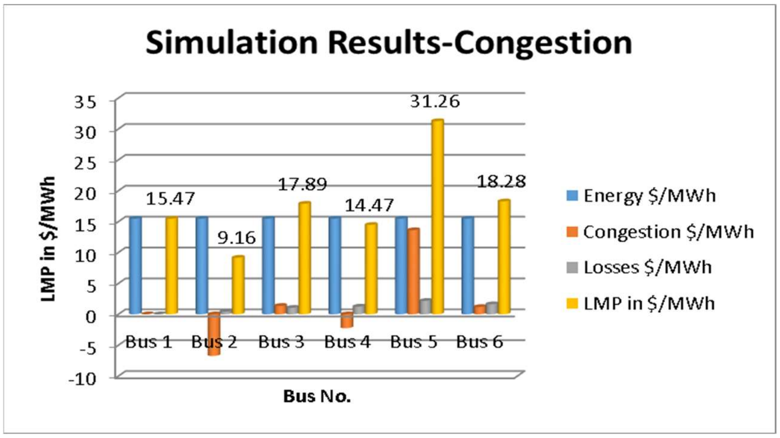


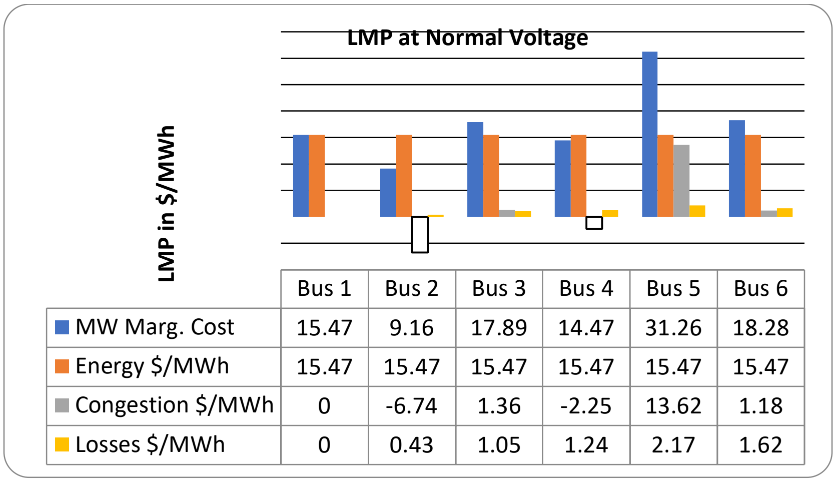
Fig. 3 Simulation results (LMP) of test system.

Effect of parameter variation is observed in the simulation of test system by varying the voltage, changing line flow limit and changing connected load as follow.

4.1 Variation of Voltage

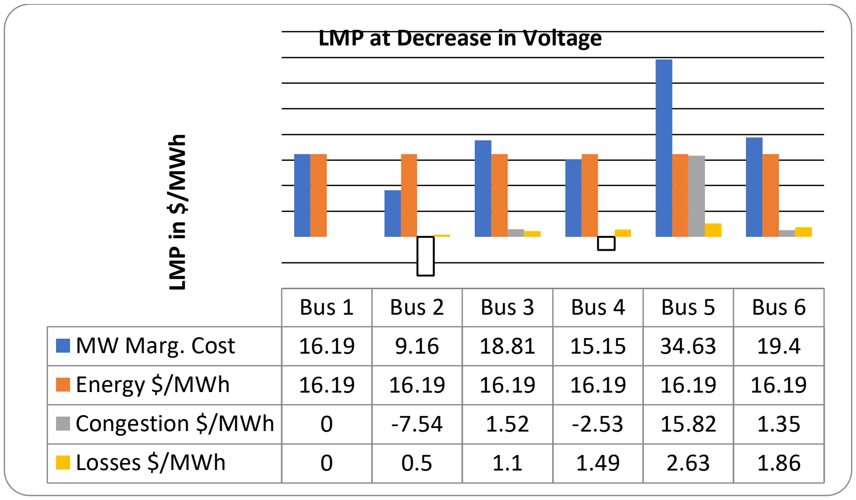
To observe the effect of variation in voltage on LMP at each bus of the system three cases is considered; in case 1 LMP at normal voltage, in case 2 LMP at decrease in voltage and in case 3 LMP at increase in voltage.

The voltage at bus is decreases and observed the simulation result. Same way now voltage at bus is increased and observed the simulation result. The obtained results in each case are presented in fig. 4, 5 & 6. In fig. 7 presents the variation in LMP at each bus of system in case of normal voltage, in case of decrease in voltage and in case of increase in voltage. It is observed that LMP of system buses is increases in case of decrease the voltage with reference to LMP of system at normal voltage. Similarly, LMP of system buses is decreases in case of increase the voltage with reference to LMP of system at normal voltage. So LMP at each bus of system vary significantly with the variation of system voltage.



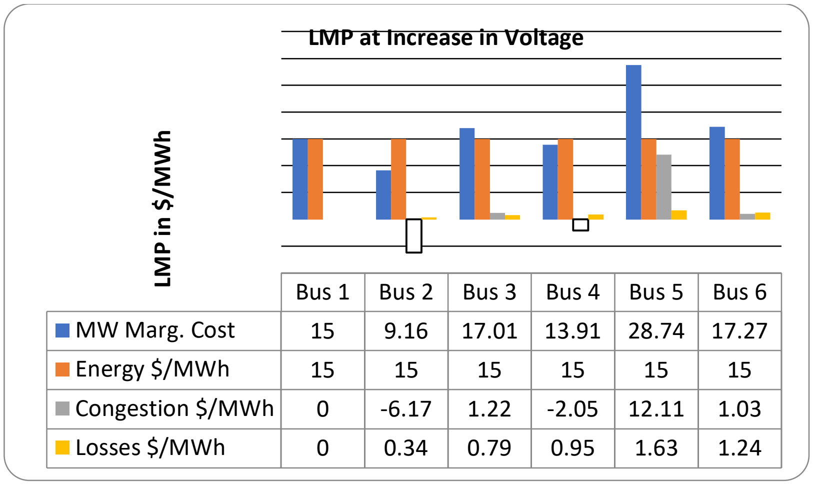
	Bus 1	Bus 2	Bus 3	Bus 4	Bus 5	Bus 6
■ MW Marg. Cost	15.47	9.16	17.89	14.47	31.26	18.28
■ Energy $/MWh	15.47	15.47	15.47	15.47	15.47	15.47
■ Congestion $/MWh	0	-6.74	1.36	-2.25	13.62	1.18
■ Losses $/MWh	0	0.43	1.05	1.24	2.17	1.62

Fig. 4. LMP of each bus at normal voltage.



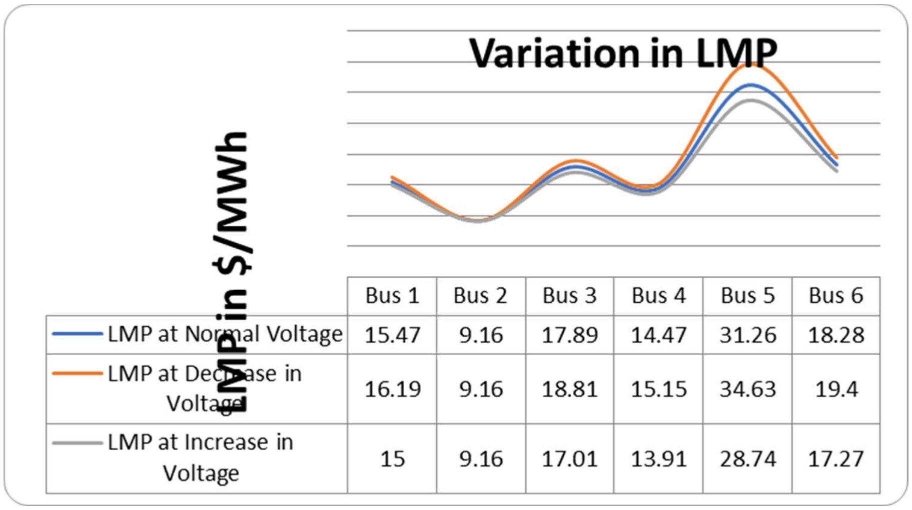
	Bus 1	Bus 2	Bus 3	Bus 4	Bus 5	Bus 6
🟦 MW Marg. Cost	16.19	9.16	18.81	15.15	34.63	19.4
🟧 Energy $/MWh	16.19	16.19	16.19	16.19	16.19	16.19
⬜ Congestion $/MWh	0	-7.54	1.52	-2.53	15.82	1.35
🟨 Losses $/MWh	0	0.5	1.1	1.49	2.63	1.86

Fig. 5. LMP of each bus at decrease in voltage.



	Bus 1	Bus 2	Bus 3	Bus 4	Bus 5	Bus 6
🟦 MW Marg. Cost	15	9.16	17.01	13.91	28.74	17.27
🟧 Energy $/MWh	15	15	15	15	15	15
⬜ Congestion $/MWh	0	-6.17	1.22	-2.05	12.11	1.03
🟨 Losses $/MWh	0	0.34	0.79	0.95	1.63	1.24

Fig. 6. LMP of each bus at increase in voltage.



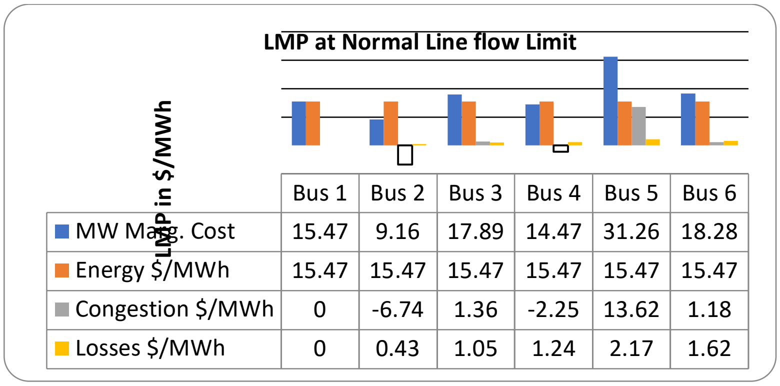
	Bus 1	Bus 2	Bus 3	Bus 4	Bus 5	Bus 6
— LMP at Normal Voltage	15.47	9.16	17.89	14.47	31.26	18.28
— LMP at Decrease in Voltage	16.19	9.16	18.81	15.15	34.63	19.4
— LMP at Increase in Voltage	15	9.16	17.01	13.91	28.74	17.27

Fig. 7. Variation in LMP of each bus at different cases.

4.2 Variation of Line flow limit

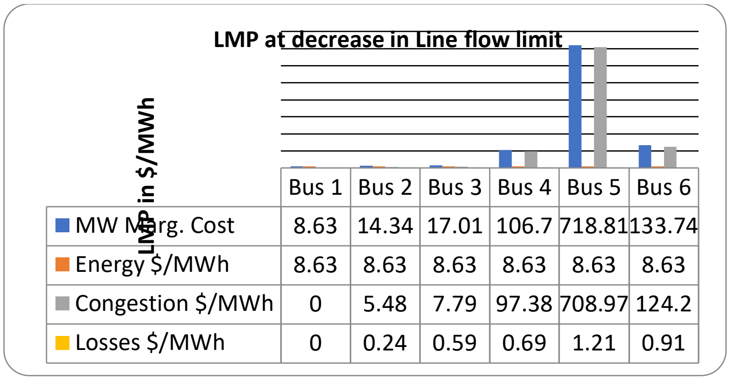
To observe the effect of variation in Line flow limit on LMP at each bus of the system, two cases is considered; in case 1 LMP at normal Line flow limit, in case 2 LMP at decrease in Line flow limit.

The Line flow limit is decreases and observed the simulation result. The obtained result is presented in fig. 8 & 9. In fig. 8 presents the LMP at each bus of system in case of normal Line flow limit and in fig. 9 presents the LMP at each bus of system in case of decrease in Line flow limit. It is observed that LMP at bus no 1, 2 & 3 is slightly change but LMP at bus no 4,5 & 6 increases drastically.



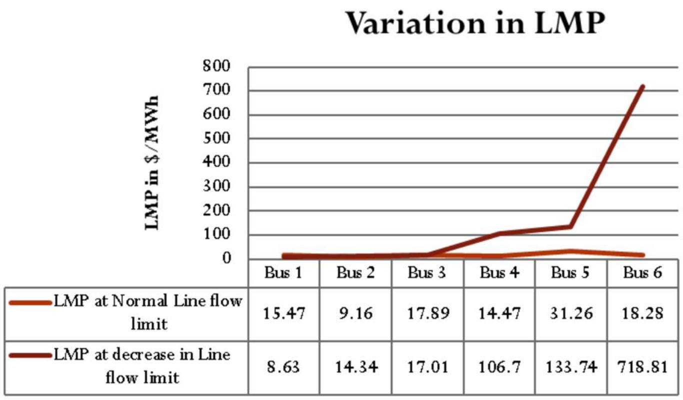
	Bus 1	Bus 2	Bus 3	Bus 4	Bus 5	Bus 6
🟦 MW Marg. Cost	15.47	9.16	17.89	14.47	31.26	18.28
🟧 Energy $/MWh	15.47	15.47	15.47	15.47	15.47	15.47
◼ Congestion $/MWh	0	-6.74	1.36	-2.25	13.62	1.18
🟨 Losses $/MWh	0	0.43	1.05	1.24	2.17	1.62

Fig. 8. LMP of each bus at normal line flow limit



	Bus 1	Bus 2	Bus 3	Bus 4	Bus 5	Bus 6
🟦 MW Marg. Cost	8.63	14.34	17.01	106.7	718.81	133.74
🟧 Energy $/MWh	8.63	8.63	8.63	8.63	8.63	8.63
◼ Congestion $/MWh	0	5.48	7.79	97.38	708.97	124.2
🟨 Losses $/MWh	0	0.24	0.59	0.69	1.21	0.91

Fig. 9. LMP of each bus at decrease in line flow limit.



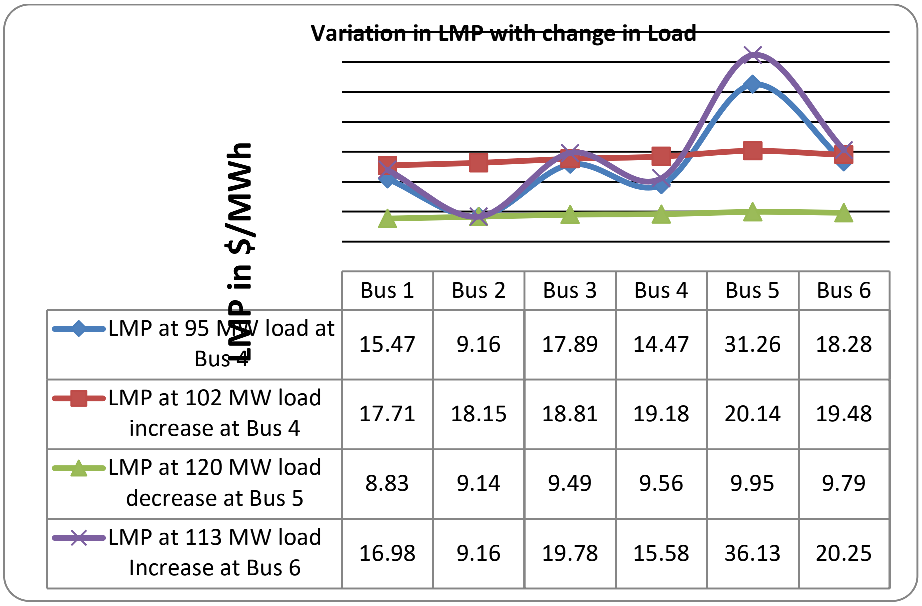
	Bus 1	Bus 2	Bus 3	Bus 4	Bus 5	Bus 6
— LMP at Normal Line flow limit	15.47	9.16	17.89	14.47	31.26	18.28
— LMP at decrease in Line flow limit	8.63	14.34	17.01	106.7	133.74	718.81

Fig. 10. Variation in LMP of each bus at normal & decrease in line flow limit.

4.3 Variation of connected load

To observe the effect of variation in connected load on LMP at each bus of the system, different cases is considered as shown in fig.11. The connected load on bus 4& 6 is increase and observed the simulation result. Same way the connected load on bus 5 is decrease and observed the simulation result. The obtained results in each case are presented in fig. 11.

It shows that LMP is increases in case of increases in connected load and LMP decreases in case of decreases in connected load. So LMP at each bus of system vary significantly with the variation of connected load.



	Bus 1	Bus 2	Bus 3	Bus 4	Bus 5	Bus 6
LMP at 95 MW load at Bus 4	15.47	9.16	17.89	14.47	31.26	18.28
LMP at 102 MW load increase at Bus 4	17.71	18.15	18.81	19.18	20.14	19.48
LMP at 120 MW load decrease at Bus 5	8.83	9.14	9.49	9.56	9.95	9.79
LMP at 113 MW load Increase at Bus 6	16.98	9.16	19.78	15.58	36.13	20.25

Fig. 11. Variation in LMP at each bus with changes in connected load.

5. Conclusion

In this paper Optimal Power Flow (OPF) based Locational Marginal Pricing (LMP) mechanism has been formulated and performed simulation on IEEE-6 bus test system by using Power World Simulator. Effect of variation in different system parameters like Voltage, Line flow limit and change in connected load on system LMP has been simulated and discussed. Simulation results demonstrated that LMP of each bus changes due to variation in Voltage, Line flow limit and change in connected load. The observation and analysis of presented results may be very useful for independent system operator (ISO), Generating companies (GENCOs) and market participants. In deregulated environment of power system, the presented work may be providing new direction to the power system researcher.

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