Journal of Electrical and Electronics Engineering Research Vol. 2 (6), pp. 143-153, December 2010
Available online at http://www.academicjournals.org/jeeer
ISSN – 2141 – 2367 ©2010 Academic Journals

Full Length Research Paper

Locational marginal pricing approach to minimize congestion in restructured power market

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Accepted 25 November, 2010

The privatization and deregulation of electricity markets has a very large impact on almost all the power systems around the world. Competitive electricity markets are complex systems with many participants who buy and sell electricity. Much of the complexity arises from the limitations of the underlying transmission systems and the fact that supply and demand must be in balance at all times. When the producers and consumers of electric energy desire to produce and consume in amounts that would cause the transmission system to operate at or beyond one or more transfer limits, the system is said to be congested. In this paper, Locational Marginal Pricing approach is adopted to locate the spots of congestion in the Indian utility system under various critical conditions of the system, such as transmission line outage, increase in loads and generation failure and the results are found efficient in minimizing the congestion.

Keywords: Electricity, markets, transmission, congestion.

INTRODUCTION

Electricity Supply Industry (ESI), throughout the world, is undergoing restructuring for better utilization of the resources and for providing quality service and choice to the consumer at competitive prices. Restructuring of the power industry aims at abolishing the monopoly in the generation and trading sectors, thereby, introducing competition at various levels wherever it is possible. Electricity sector restructuring, also popularly known as deregulation is expected to draw private investment, increase efficiency, promote technical growth and improve customer satisfaction as different parties compete with each other to win their market share and remain in business. Electricity markets throughout the world continue to be opened to competitive forces. The underlying objective of introducing competition into these markets is to make them more efficient. In competitive environment, the price is determined by stochastic supply and demand functions. As a consequence of increased volatility, a market participant could make trading contracts with other parties to hedge possible risks and get better returns. Congestion occurs when transmission lines or transformers are overloaded and this prevents the system operators from dispatching additional power from a specific generator.

Locational marginal pricing (LMP) is a market-pricing approach used to manage the efficient use of the transmission system when congestion occurs on the bulk power grid. Congestion arises when one or more restrictions on the transmission system prevent the economic, or least expensive, supply of energy from serving the demand. For example, transmission lines may not have enough capacity to carry all the electricity to meet the demand in a certain location. This is called a “transmission constraint.” LMP includes the cost of supplying the more expensive electricity in those locations, thus providing a precise, market based method for pricing energy that includes the “cost of congestion.” LMP provides market participants a clear and accurate signal of the price of electricity at every location on the grid. Amarasinghe et al (Amarasinghe, 2008) describes the basics of LMP and also when LMPs are used for settlement of transactions, consumers are charged more

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than the average cost of production of electricity due to the nonlinear nature of the power flow and the constraints imposed by the Optimal Power Flow (OPF). This difference which is accumulated with the Independent System Operator (ISO) is referred to as network rental. It is made up of two components known as loss rental and constraint rental. Loss rental is due to the difference in average losses and marginal losses, caused by the nonlinear nature of losses. This paper develops a method to calculate these different rental components paid by each consumer, by combining the power flow tracing and optimality conditions.

The general formulation of the LMP with necessary components is described elaborately (Eugene et al., 2004; Tina and George, 2007). It gives some insights regarding the evaluation of the LMP components, in general, and the distinct characteristics, including the limitations, of the various proposed decomposition approaches, in particular. It deals with the salient features of the formulation that is the role of the generators with the ability to vary their output, as well as the impact of the network congestion on the price setting, are explicitly recognized. The formulation's comprehensiveness brings numerous insights into the various decompositions, provides a platform for their comparative analysis, and allows us to understand the direct implications and the role of the policy specified. Moreover, the formulation reveals the limitations of any decomposition into the components due to the underlying structural interdependencies among them. Paper (Silpa, 2007) describes the advantages and disadvantages of deregulation of which congestion is the main factor. It gives a brief description about the various congestion management schemes available and also tabulates the methods practiced in various power markets. It also provides two options for congestion management that is load shedding and using VAR support. The given options have been implemented in the Standard IEEE 24 bus system and results have been obtained. It also states that the VAR support is more advantageous than the load curtailment.

The impact of reactive power with regulating devices is described in Srivastava and Verma (2000) and Daniel and Christopher (2007). The effectiveness of locational marginal pricing (Kim, 2006; Xie et al., 2006; Keshi et al., 2006; Hamoud and Bradley, 2001; Fangxing et al., 2004) as a market signal for reserve supply is discussed on the basis of network constrained integrated energy and reserve market arrangement. Revenue recovery based on LMP is explored as an assessment tool in the presence of serious network outage. The model is solved by using DC-OPF. In particular, marginal loss factor is incorporated into energy and reserve integrated market to overcome the absence of network loss price component in DC-based optimal power flow. In these papers, locational marginal pricing as a possible market signal tool of reserve supply for system security is discussed in the presence of network outage. In particular, revenue recovery of reserve supply on the basis of the locational marginal pricing environments is explored in the platform of energy and reserve integrated market. Paper (Fangxing and Rui, 2007) deals about the different energy prices resulted due to transmission constraints. It suggests a computer program to calculate, for a given period of time, transmission congestion cost (TCC) in dollars per unit time and locational marginal pricing (LMP) in dollars per megawatt-hour (MWh) at any selected bus in the transmission system. In addition, the information provided by the program output on congested transmission elements is used to identify buses in the network whose LMPs are representative of the entire network. The computed LMPs at these buses are used to define zones in the network where each zone has its LMP. The proposed methodology can be used to carry out sensitivity studies to determine the impact of changes in system parameters and operating conditions on the LMPs. The proposed method is illustrated using the IEEE Reliability Test System (RTS). Reference papers (Enzo and Shmuel, 2007; Kwok, 2004; Commission for Energy Regulation (CER), http://www.pjm.com, http://www.iso-ne.com, Fu and Zuyi, 2006; Chen et al, 2002; Shariati et al, 2008; Goncalves et al., 2003; Scott and William, 2000; Jeffrey et al, 1999) describe the overview of Locational Marginal Pricing scheme and how it will be used in the new market structure. It also defines and stresses the need for LMP by discussing the zonal congestion management and how it is alleviated by practicing LMP. It is explained through an illustrative example and also the tariff definition of LMP.

A detailed comparison of Nodal and Zonal Congestion management methods ay analyzing their advantages and limitations through a number of illustrative examples and a supporting theoretical analysis are elaborated in Jeffrey et al. (1999) This paper examines the assertion that administrative aggregation of many nodes into larger zones would ensure competition across a wider area and constrain this power of the monopolist. Also it emphasizes the point of zonal pricing always subsidizes the dominant local generator and increases monopoly profits above those that would occur under nodal pricing. It also states the argument that market power dictates a need for zonal aggregation motivates the detailed demonstration that this is both wrong and creates a set of new problems that could be avoided with nodal pricing or splitting congested zones.

PROBLEM FORMULATION

In a competitive electricity market, the settlement between the independent system operator (ISO) and the participants is based on locational marginal prices (LMPs). LMP at a given node of a power system is the sensitivity of operational cost to the change in load at that node, and it is calculated using an optimal power flow (OPF) program. When LMPs are used for settlement of transactions, consumers are charged more than the average cost of production of electricity due to the nonlinear nature of the power flow and the constraints imposed by the OPF.

The objective function may be represented as the minimization of total cost of generation (Eugene et al., 20042):

$$\min G(P) = \sum_{k=1}^{N} S_k P_{gk} \tag{1}$$

If bus *k* is a pure load bus, then $P_{gk}=s_k=0$.

The power balance equation considering the losses is:

$$\sum_{k=1}^{N} P_{gk} - P_{dk} = P_{loss} \tag{2}$$

Let us assume that the line constraint sensitivity matrix is *T* with elements t_{jk} that give the change in flow on circuit *j* to a change in real power injection at bus *k*, under a specified slack distribution. Thus:

$$t_{jk} = \frac{\Delta F_j}{\Delta P_k} \tag{3}$$

In the matrix form, Equation (3) becomes:

$$\underline{F} = \underline{TP} \tag{4}$$

It is important to note that the sensitivity factors of (3) are computed under a so-called “slack-bus” assumption which indicates how the change *ΔPk* is assumed to be compensated. It could be compensated from another certain bus, or from several other buses, or from all other buses, and the elements of *T* will change depending on which of these is assumed. It is generally considered best to employ a so-called distributed slack bus assumption here where the compensation is assumed to come from all other generator buses. We know that the “normal” flow constraints on every circuit is:

$$-\underline{F_{\max}} \le \underline{F} \le \underline{F_{\max}} \tag{5}$$

Substitution of Equation (4) in (5) results in:

$$-\underline{F_{\max}} \le \underline{TP} \le \underline{F_{\max}} \tag{6}$$

We assume at this point that high flows in our network are unidirectional, that is we need not be concerned with high flows in both directions. This does not prevent bidirectional flows; it merely enables us to be concerned with reaching the upper bound in only one direction. Therefore, we may ignore the lower bound in Equation (6) so that our circuit flow constraint is:

$$\underline{TP} \le \underline{F_{\max}} \tag{7}$$

In scalar form, Equation (7) is:

$$\sum_{k=1}^{N} t_{jk} P_k \le F_{j\max}, \quad j = 1,\ldots\ldots., M \tag{8}$$

Replacing injection with difference between generation and load, we obtain:

$$\sum_{k=1}^{N} t_{jk}\left(P_{gk} - P_{dk}\right) \le F_{j\max}, \quad j = 1,\ldots\ldots., M \tag{9}$$

The OPF problem determines the optimal generator dispatch subject to a set of constraints which represents the operational and physical limits of the power system. A competitive market environment is considered, where generators make offers to sell electricity as price-quantity pairs. For the purpose of simplicity, no demand side bidding is considered and hence, loads are known constants for the dispatch. Therefore, the OPF can be written as a problem of minimizing the total cost of generation subjected to real and reactive power are balanced, real power generation is within the limits specified by the offer quantity, reactive power generation is within the limits, line flows are within the thermal limits, and voltages are within specified limits, respectively. Therefore, The Lagrangian function for linear optimized power flow (LOPF) becomes:

$$L(P_g, \lambda, \mu) = \sum_{k=1}^{N} S_k P_{gk} - \lambda\left[\sum_{k=1}^{N} P_{gk} - P_{dk} - P_{loss}\right]$$
$$-\sum_{j=1}^{M} \mu_j \left[\sum_{k=1}^{N} t_{jk}(P_{gk} - P_{dk}) - F_{j\max}\right] \tag{10}$$

The first order conditions for finding the optimum to LOPF include:

$$k \in gen: \frac{\partial L}{\partial P_{gk}} = S_k - \lambda(1 - \frac{\partial P_{loss}}{\partial P_{gk}}) - \sum_{j=1}^{M} \mu_j t_{jk} = 0 \tag{11}$$

But we are more interested in the load buses. Consider:

$$k \in load: \frac{\partial L}{\partial P_{dk}} = \lambda(1 + \frac{\partial P_{loss}}{\partial P_{dk}}) + \sum_{j=1}^{M} \mu_j t_{jk} \tag{12}$$

Note that P_{dk} is not a decision variable, and therefore we do not set it as 0. Equation (12) gives the change in the optimal value of the objective function due to a small change in the parameter P_{dk}.

We call $\frac{\partial L}{\partial P_{dk}}$ the LMP for bus *k*, that is,

$$k \in load: LMP_k = \lambda(1 + \frac{\partial P_{loss}}{\partial P_{dk}}) + \sum_{j=1}^{M} \mu_j t_{jk}$$

Written slightly different,

$$k \in load: LMP_k = \lambda + \lambda \frac{\partial P_{loss}}{\partial P_{dk}} + \sum_{j=1}^{M} \mu_j t_{jk} \tag{13}$$

Equation (13) consists of three components.

$$k \in load:$$

$$\left.\begin{aligned} LMP_k &= \lambda \text{ ..... Energy component} \\ &+ \lambda \frac{\partial P_{loss}}{\partial P_{dk}} \text{ .... Loss component} \\ &+ \sum_{j=1}^{M} \mu_j t_{jk} \text{ .... Congestion component} \end{aligned}\right\} \text{Delivered energy component}$$

Where LMP$_k$ is the Locational Marginal Price at bus ‘k’, λ is the Lagrange Multiplier associated with the Power balance equation, $\frac{\partial P_{loss}}{\partial P_{dk}}$ is the real power loss sensitivity factor at bus ‘k’, μ_j is the vector of Lagrange multipliers associated to the network constraints on line ‘j’ and t$_{jk}$ is the sensitivity factor of the network at bus ‘k’ due to network constraints on line ‘j’. The Lagrange multipliers determined from the solution of the optimum power flow provide important economic `information’ regarding the power system. A Lagrange multiplier can be interpreted as the derivative of the objective function with respect to enforcing the respective constraint. Therefore, the Lagrange multipliers associated with enforcing the power flow Equations of the OPF can be interpreted as the marginal cost of providing addition energy ($/MWh) to that bus in the power system. This marginal cost is known as LMP and sometimes is called the shadow price of the power injection at the node. The LMP is decomposed into three components which are the cost of energy, cost of marginal losses and cost of marginal congestion.

The main aim of decomposition is to reflect the cost of system marginal cost, loss compensation and congestion management as well as voltage support. These components are all important cost terms in the deregulated electricity market and can be forwarded to the generators and consumers as control signals to regulate the level of their generations and consumptions. Many methods have been followed to minimize the transmission congestion (Silpa, 2007) viz.

1. Adding a transmission line across the congestion path
2. Increase the capacity of power system components
3. Generation Re-dispatch
- Modification of generating schedules
4. Load Re-dispatch
- Shedding - reduce specific loads
- Encouraging some specific load serving
5. Using VAR Support

Increasing the capacity of the components is much complicated as the components have to be completely disconnected from the power system. Hence this method does not hold good. Also, in the competitive market, it becomes a serious issue to re-dispatch certain generators or loads as in some cases the generating companies fail to accept the modifications of their schedules and therefore the re-dispatching methods are also not preferred. Hence the best ways to minimize congestion were found to be the addition of transmission line and the usage of VAR support.

STEP – BY – STEP ALGORITHM

The procedure to manage the congestion in the system is given as the following Step-by-Step algorithm. The procedure for finding the location for adding a transmission line and for installing regulating devices to reduce congestion is given as thus explained in the following steps:

Step 1: Obtain the Generator data, line data, bus data, generator cost data and other power flow constraints of the utility test system.

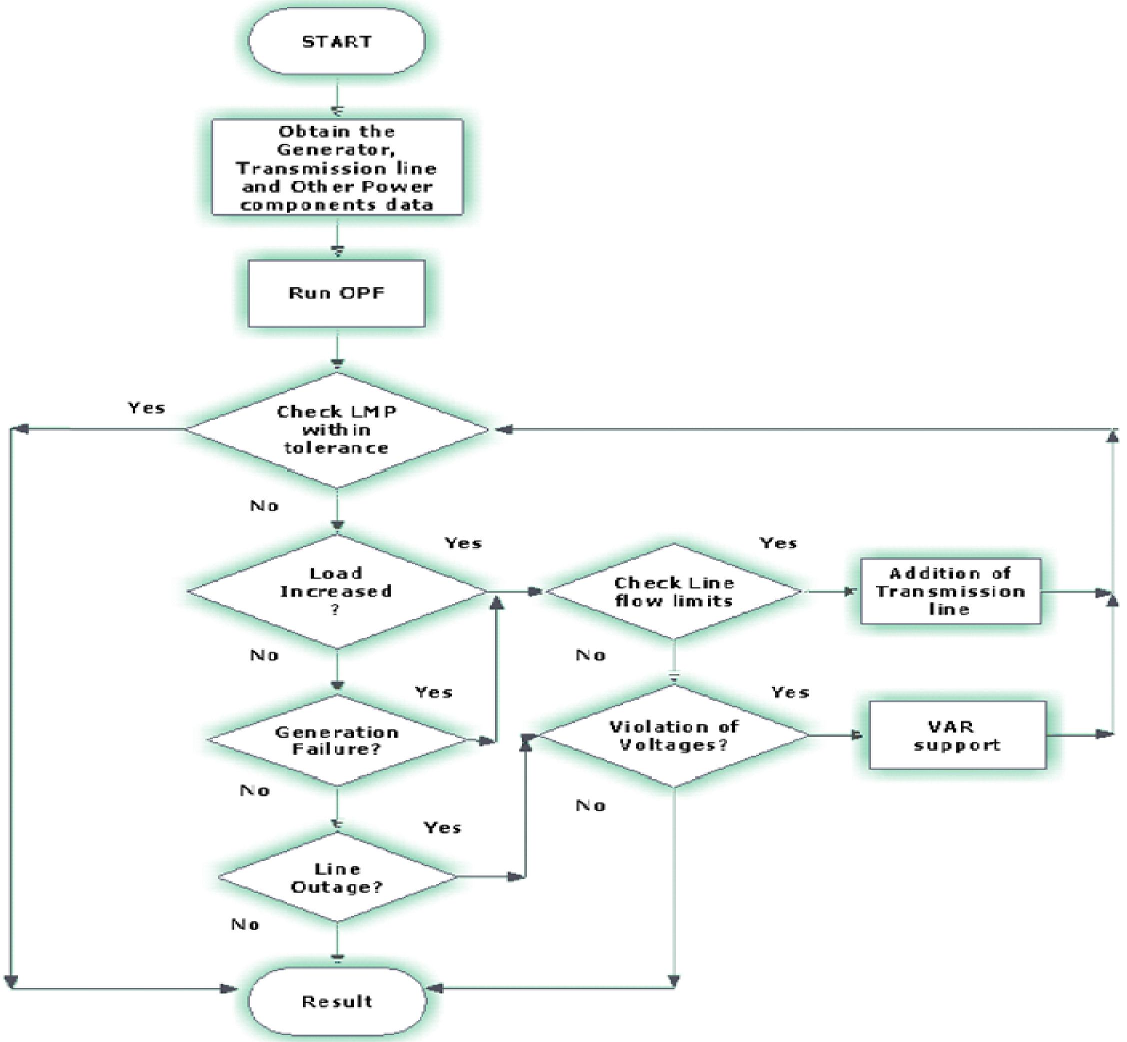

Figure 1. Flow diagram – Computation of locational marginal price.

Step 2: Run optimal power flow (OPF) analysis and obtain the LMP values from it and check out the tolerance limit.
Step 3: If the LMP is not within limits, then check whether it is an abnormal condition of load increased.
Step 4: If the load is found to be increased then check for line flow limits. If the limits exceeds then add a new transmission line in the required buses.
Step 5: If the line flow limits are not seen to be violating then the voltage profile has to be checked. If the voltages are seen to be violating then reactive power is injected in voltage defective buses.
Step 6: If the load is not seen to be increased then the generation is checked. If the generator outage is to be occurred, then repeat the steps 4 and step 5.
Step 7: If the congestion is not due to generation failure, then the transmission line limits are checked. If the line outage is found to occur then voltage profile is checked and VAR is injected in voltage deficient buses.
Step 8: The congestion relief method is carried out and OPF is to be executed again and LMP values are computed again and the system is checked for congestion.
Step 9: Stop.

The flow diagram of the aforementioned procedure is shown in Figure 1.

SIMULATION RESULTS AND DISCUSSION

The locational marginal price is computed by executing the optimal power flow program in MATPOWER software. It is computed in base load, increase in load and vulnerable conditions. If there is any increase in LMP value in certain buses, the remedy action is carried out to

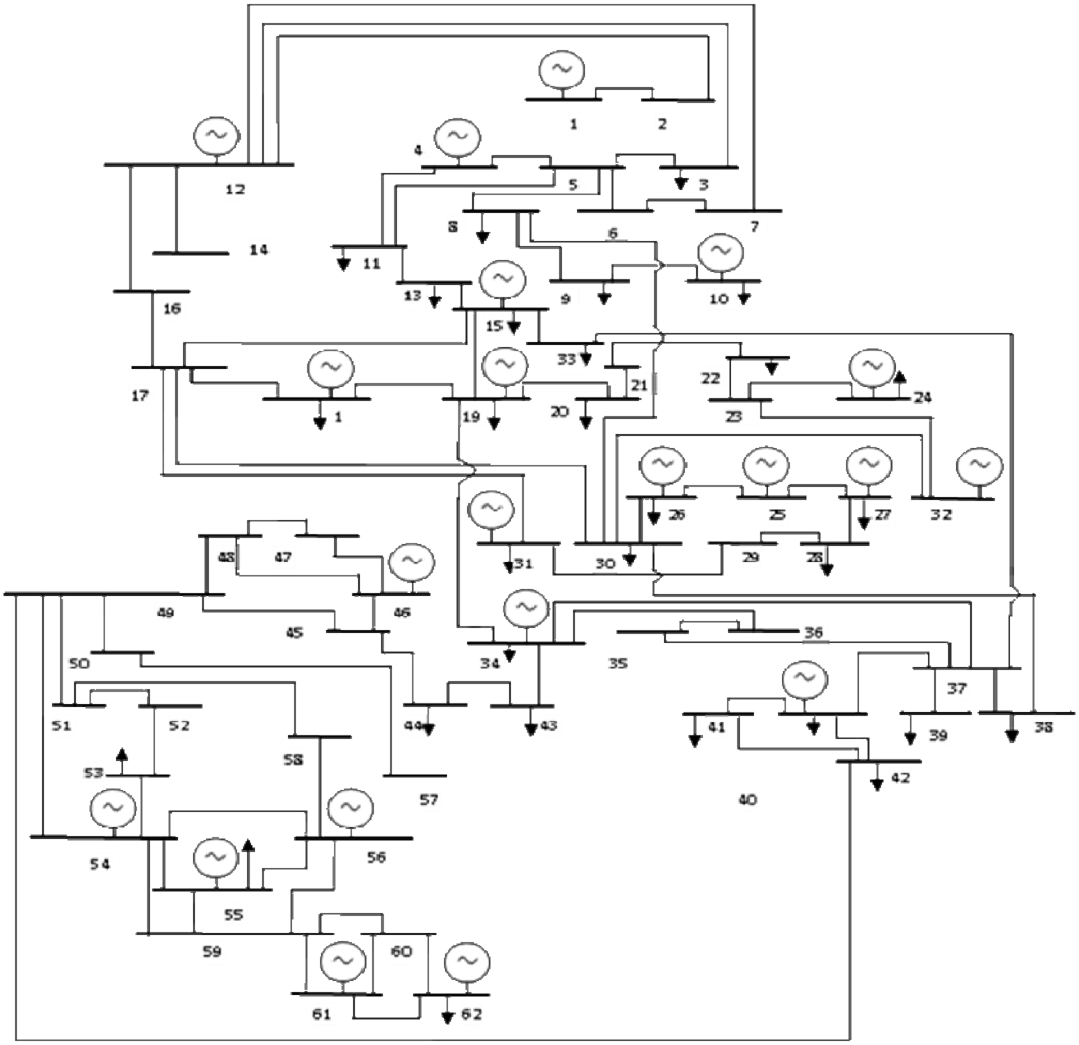

Figure 2. Oneline diagram of indian utility system.

make the LMP almost same in all the buses. The aforementioned cases studies were demonstrated on the practical Indian utility bus system. The Indian utility system consists of 25 generators, 89 (220KV) transmission lines and 11 tap changing transformers and 57 loads. Its one line diagram is shown in Figure 2. The total demand in the system is 2909 MW. The optimal power flow of the above test system was carried out and the corresponding LMP values in the different buses were obtained. Using the values of LMP, congested spots are identified and the congestion relief methods are adopted to relieve congestion.

Increased in load condition

The loads at all nodes of the Indian utility system were increased by 25% and the optimal power flow was carried out. The LMPs of the corresponding buses were determined using the above execution. During this condition, it was observed that there was a drastic increase in LMP at the bus 13, 20, 21, 33, 35, 36 and also notable increase in some buses. Five transmission lines are added in the system to minimize the congestion. The transmission lines are added in the place where the LMP is found to be increased drastically. In this system the line is added from bus 11 to 13, 9 to 10, 22 to 23, 26 to 30 and 53 to 54. After adding the transmission lines, OPF program was run again and the results were given in Table 1. In case if immediate relief was needed and there was violation of voltage limits, then injection of reactive power in voltage affected buses served good in neutralizing the congestion. In this case, the reactive power was injected in buses 13, 20, 22, 33, 37, 38, and 53 and again OPF was executed and results were given in Table 1. Figure 3 shows the comparison of LMP values for abnormal condition of all the loads increased by 25% and the reduced values of LMPs resulted from the

Table 1. Increased in load condition.

Bus No.	Increase in loads (25%)		Line added		Injection of reactive power	
	Voltage (p.u)	LMP ($/MWh)	Voltage (p.u)	LMP ($/MWh)	Voltage (p.u)	LMP ($/MWh)
13	0.989	67.036	0.991	56.651	1.004	51.142
20	0.980	65.884	0.991	56.260	1.001	48.314
21	0.978	64.393	0.996	54.902	1.023	42.319
33	1.011	64.870	1.016	55.697	1.045	49.300
35	1.025	63.477	1.029	54.602	1.046	48.890
36	1.028	63.226	1.032	54.379	1.049	48.658

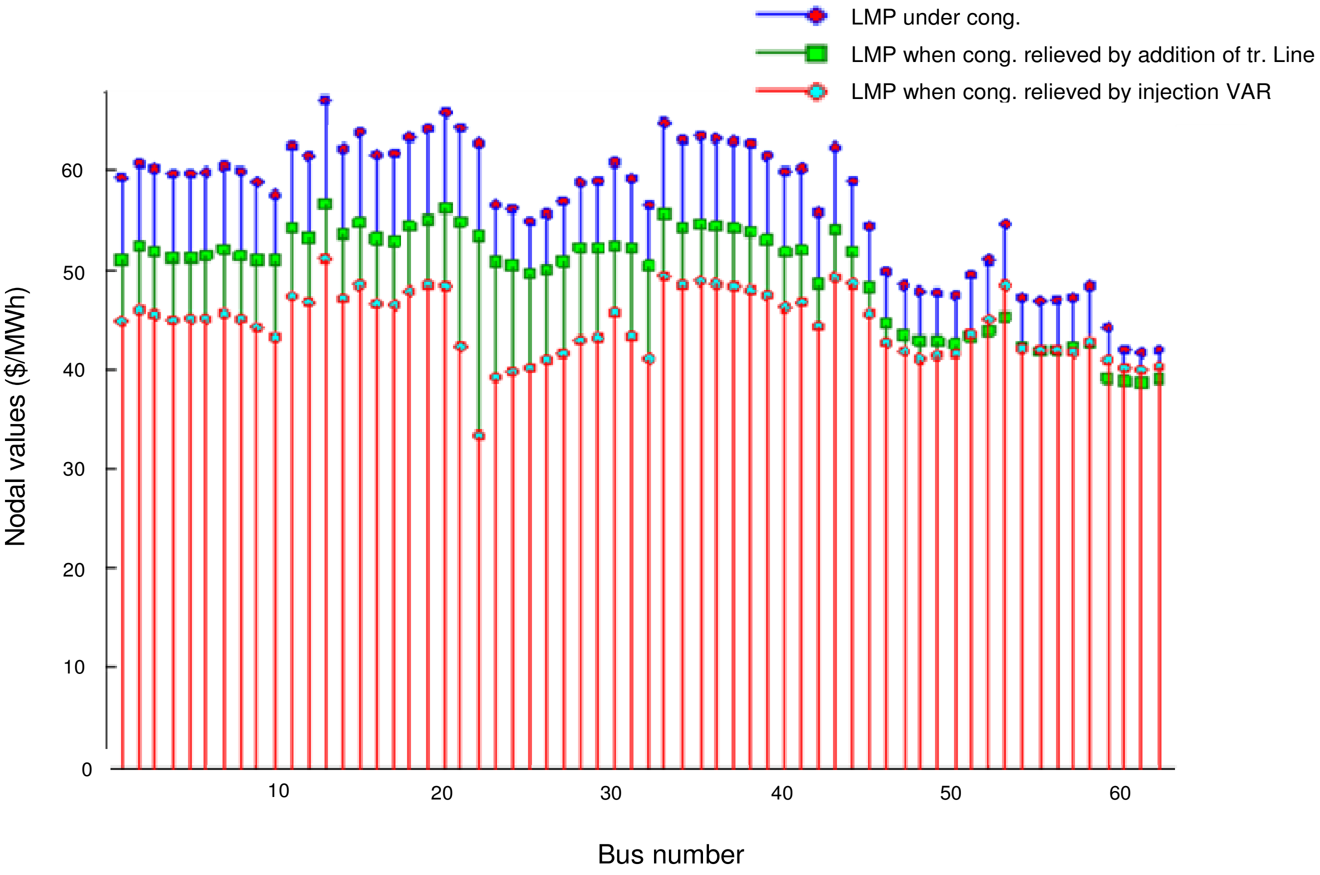

Figure 3. Comparison of LMPs – Increased in load condition.

addition of a transmission line and the installation of VAR devices. The contour representation of normal LMP values of the 62 bus system, covering the state of Tamil Nadu is given in Figure 4. Since the increase in load condition is the major cause of congestion, the variations in LMPs are given in the Figure 4. The areas of the state where drastic increase in LMPs are pronounced during congestion can be easily determined from the contour. The number of generating units in and around the Tamilnadu State capital (Chennai) is large and the congestion spots are also found to be crowded in the Chennai city and hence a zoomed view of Chennai contour is produced.

Transmission line contingency condition

In the Indian utility system, four transmission lines connected between the buses 11 to 12, 2 to 12, 3 to 12 and 23 to 32 were made out of service to carry out the contingency study and the corresponding optimal power flow solution was obtained. During the lines outage, it was observed that there was a drastic increase in LMP at the bus 13, 20, 21 and 33 and a notable increase at some

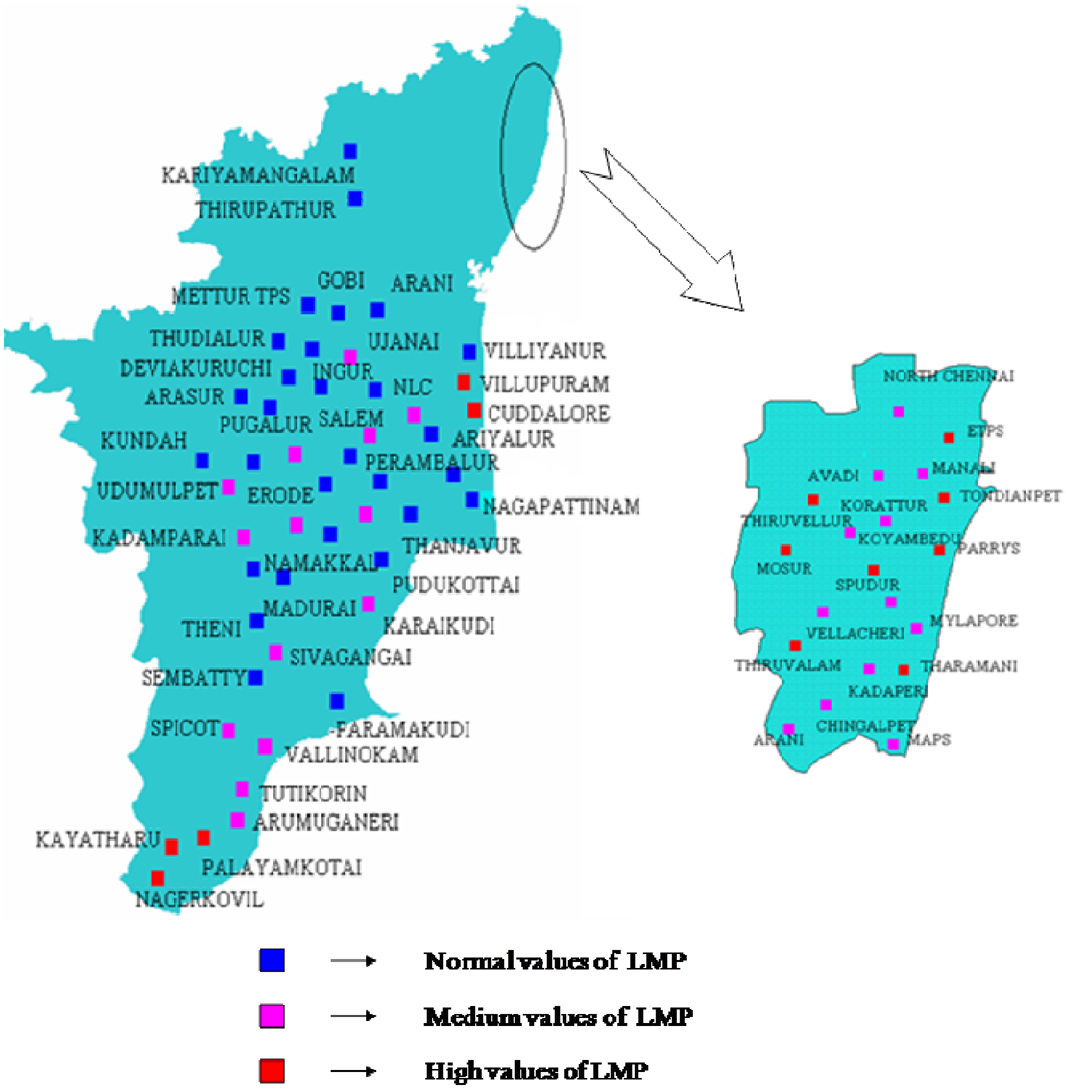

Figure 4. Contour representation of Tamil Nadu Bus system under congestion due to increased load.

buses. The relief method suggested for this case was the addition of reactive power source in the corresponding location to control the voltage violations. According to this proposal, the reactive power was injected in the voltage affected buses which served well in neutralizing the congestion. In this case, the reactive power was injected in buses 9, 10, 13, 34, 37, 48 and 59 and again OPF was carried out and results were given in the Table 2. Figure 5 shows the comparison of LMP values for abnormal condition of line outages and the reduced values of LMPs resulted from the installation of VAR devices.

Generation failure condition

To analyze the worst vulnerable condition, it is assumed that the generators at bus 12, 19 and 61 were made out of order and optimal power flow solution was obtained. During this condition, it was observed that there was a drastic increase in LMP at the bus 13, 19, 20, 21, 33, 35, 43. According to the first method of congestion relief, four transmission lines were included to minimize the congestion. The transmission lines were added in the nodes of high LMP, at 13 to 15, 22 to 23, 26 to 30 and 53 to 54. After adding the transmission line OPF program was run again and the results were given in the Table 3. In case, if immediate relief was needed and there was violation of voltage limits, then injection of reactive power in voltage affected buses served good in neutralizing the congestion. In this case, the reactive power was injected in buses 9, 13, 21, 34, 37, 38, and 53 and again OPF was run and results were given in Table 3. Figure 6 shows the comparison of LMP values for abnormal condition of generation failure and the reduced values of

Table 2. Transmission line contingency condition.

Bus no.	Line outage		Injection of reactive power	
	Voltage (p.u)	LMP ($/MWh)	Voltage (p.u)	LMP ($/MWh)
13	0.982	48.322	1.059	47.603
20	0.996	47.071	1.008	46.384
21	0.991	46.274	1.001	45.742
33	1.029	46.128	1.036	45.837

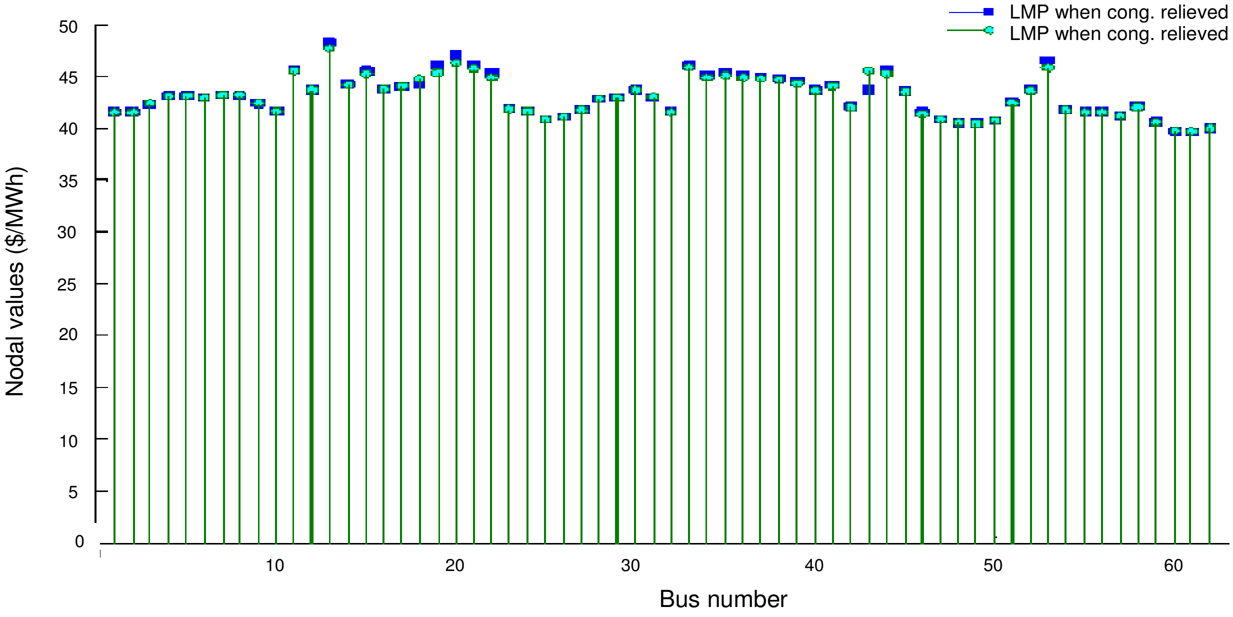

Figure 5. Comparison of LMPs – Transmission line contingency condition.

Table 3. Generation failure condition.

Bus no.	Generation failure		Line added		Injection of reactive power	
	Voltage (p.u)	LMP ($/MWh)	Voltage (p.u)	LMP ($/MWh)	Voltage (p.u)	LMP ($/MWh)
13	0.979	52.065	0.997	49.766	1.013	51.277
19	1.002	50.332	1.018	48.597	1.033	49.731
20	0.975	51.057	0.999	49.058	1.030	50.235
21	0.973	49.789	1.003	47.826	1.043	49.210
33	1.012	50.200	1.024	48.527	1.033	49.671
35	1.036	49.960	1.046	47.435	1.046	48.640
43	1.017	49.275	1.025	47.742	1.024	48.873

LMPs resulted from the addition of a transmission line and the installation of VAR devices.

Conclusion

The transition from monopolistic to a competitive deregulated market though found to be more advantageous, encountered certain drawbacks, such as Congestion and difficulty in pricing. In this work, the Locational Marginal Pricing (LMP) was proved to be an effective solution in overcoming the above said barriers of deregulation. The LMPs are computed for the Indian utility system under normal and contingency conditions. Increase in LMP holds to be a good signal for identifying the Congested locations. Later, the congestion component of LMP is suggested to be used in congestion relief methods, such as addition of transmission line and injection

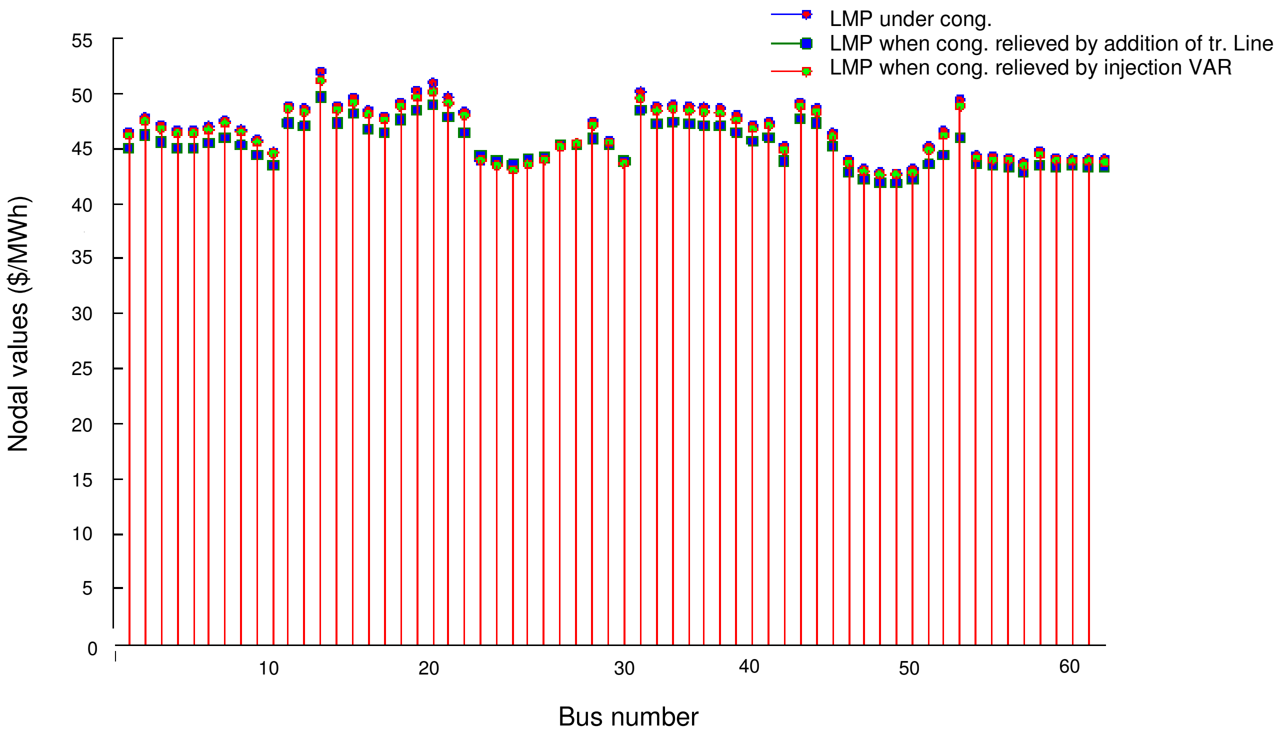

Figure 6. Comparison of LMPs - Generation failure condition.

of VAR sources. These methods proved well in relieving the system from congestion and have brought LMPs within limits.

Nomenclature: P_{gk} - Power generated (MW), P_{dk} - Power delivered (MW), S_k - $/MWh offers being made on an amount of generation of P_{gk} over 1 h, P_{loss} - Total power loss in the system (MW), ΔF_j - The change in flow on circuit *j* (MW), ΔP_k - The change in real power injection at bus *k* (MW), t_{jk} - Sensitivity factor, λ - Loss coefficient, μ - Congestion coefficient, N - No. of generators, M - No. of circuits of power flow.

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