Locational Marginal Pricing (LMP) Assessment for Wheeling Transaction in Optimal Power Flow (OPF) using Particle swarm optimization

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Abstract --- **This Paper presents a new methodology for the optimal placement of Independent power producer (IPP) based on Locational marginal pricing (LMP) calculation and technical challenges in alleviating transmission network congestion using LMP framework. LMP is determined as the lagrangian multiplier of the power balance equation in Optimal Power Flow (OPF) using PSO. This analysis explains how LMP calculation is performed at each node to locate the spots of congestion for the base case and under the critical conditions such as generation outage and how the LMP signal serves as the economic signal in electricity market. The proposed methodology is demonstrated on IEEE-30 bus system.**

Keywords— Congestion, Independent power producer, Locational Marginal pricing, Market clearing price, Optimal power flow, Particle swarm optimization, Wheeling transaction.

I. INTRODUCTION

Under the deregulated electricity market, a transmission network plays an essential role in supporting the transaction between producers and consumers [1]. One drawback on transmission of power flow is congestion. Congestion occurs when transmission lines operate at or above its thermal limits or violating the operating limits of the system and this prevents the system operators from dispatching additional power from a specific generator which causes the increase in cost of dispatching units [2, 3]. Congestion has the effect of increasing overall cost of power delivery in the system. There are two pricing structures that are currently being used in a competitive energy market to report congestion [4]: the uniform pricing method market clearing price (MCP) and the non-uniform pricing method (LMP). In the uniform pricing method all generators payments are equal i.e., MCP which is based on the generators bids submitted by each marginal generator dispatching in the absence of congestion. The second method (LMP) has been the basic nodal pricing approach in power markets in order to manage transmission congestion. The theory of spot pricing has been employed in the form of LMP within an OPF framework [5].

In this competitive environment the primary approach adopted for market operation and planning has been the Locational marginal pricing (LMP) methodology to determine the nodal prices and control or alleviate the congestion of transmission system. LMP is necessary in delivering market price signals and market settlements. The general formulation for LMP evaluation is proposed in [6]. The LMP at a specific location is defined as the marginal cost of supplying an additional increment of power to that location while the system security limits are not violated. LMP varies significantly from one location to another due to the effects of both transmission system losses and transmission system congestion [7].

Mathematically, LMP at a node in the system is the twin variable (called a shadow price) for the equality constraint at that node (sum of injections and withdrawals is equal to zero). Or, LMP is the change in production cost for providing one additional MW at a certain node. Buyers pay ISO based on their bid prices submitted by market participants for dispatched energy. The ISO in turn pays the sellers based on their relevant prices. The difference in LMP between two neighboring buses is the congestion cost which emerges when the energy is transferred from one location (injection) to another location (withdrawal). Marginal losses characterize incremental changes in system losses which occur due to incremental changes in demand. Thus LMP also includes the summation of the costs of marginal energy, marginal loss and congestion [8, 9]. Hence LMP is stated as,

LMP = marginal cost of generation + congestion cost + marginal cost of losses.

In a competitive restructured electricity market, the market settlement between the independent system operator (ISO) and the participants is based on locational marginal prices (LMPs). LMPs can be derived by using OPF model either ACOPF model or a DCOPF model [10]. The OPF is performed using Particle swarm optimization (PSO) which schedules the power with the objective of minimizing the total cost of generation [11-13].Transmission management in deregulated market in significant concerning optimal power flow, price and transaction [14]. The LMP obtained from the OPF serves as a market economic signal in placing the optimal Distributed generation (DG) or IPP placement which maximizes the social welfare and profit [15]. Also different calculation models for LMP evaluation and its properties are discussed in [16].

II LOCATIONAL MARGINAL PRICING

LMP is the effective market pricing approach in finding the cost to serve the next MW of load at a specific location using the available cheapest generation, by considering all the transmission network limits. The market uses LMPs as energy signal at specific locations and at the time it is delivered. If the lowest priced electricity can reach all locations to meet the demand, market clearing prices are same at all the spots. Energy cannot be freely flowing in certain locations in times of transmission congestion. In such conditions, more expensive generation is intended to meet that demand. Hence, the locational marginal price is higher in those locations.

LMP Methods

The evaluation of LMP can be solved by either using AC optimal power flow (ACOPF) model or DC optimal power flow (DCOPF) model. DCOPF model is simple, fast and also higher satisfactory level of power flow accuracy. This model is characterized by ignoring losses as there is no well-defined rule to provide unique solution the loss distribution energy. Whereas ACOPF formulation is fully based upon power flow characteristic of the network which also takes losses in to consideration.

Hence three schemes of LMP are introduced LMP-lossless, LMP-loss, and LMP-TUT. LMP-TUT is called LMP-Transmission usage tariff which is formulated based on the LMP- loss but transmission usage also taken into consideration. Here we have considered the LMP-loss model using ACOPF model which is tested in IEEE30 bus system.

LMP at each node is based on:

- Actual energy flow
- Actual system operating conditions

A) LMP Energy component $\left(LMP^{ref}\right)$

It is defined as the marginal cost at a reference bus or the nodal price at the reference bus. The nodal price at each bus shares this same component. This nodal price includes an implicit congestion component. That is, the nodal price at the reference bus is the least marginal cost of supplying the next increment of load at the reference bus taking into account the physical aspects (i.e., constraints) of the transmission network (i.e., potential congestion).At the reference bus both loss price and congestion price are always zero. Hence the price at the reference bus is equal to the energy component.

B) LMP Loss component $\left(LMP^{loss}\right)$

It is defined as the marginal cost of losses from the reference bus to bus i. $\left(LMP^{loss}\right)$ is calculated by,

$$LMP^{loss} = LMP^{ref} \times \left(DF_i - 1\right) \qquad (1)$$

Where,

i =number of buses

The delivery factor $\left(DF_i\right)$ at the i^{th} bus represents the effective MW delivered to the customers to serve the load at that bus. It is defined as,

$$DF_i = 1 - \frac{\partial P_{loss}}{\partial P_i} \qquad (2)$$

C) LMP Congestion component $\left(LMP^{congestion}\right)$

It is defined as the marginal cost of transmission congestion from the reference bus to bus i.

$$LMP^{congestion} = -\sum_{k=1}^{M} GSF_{k-i} \times \mu_k \qquad (3)$$

Where,

μ_k - Shadow price (\$/MW h) associated with a binding constraint.

GSF_{k-i} - Generation shift factor to line 'k' from bus 'i'.

M - Number of lines

Shadow price

A binding constraint, for example, is when the flow on the interface is at the limit of the interface .The value is equal to the incremental change in the system cost divided by an incremental change in the constraint limit.

$$\mu_k = \frac{change\ in\ total\ cost}{change\ in\ constraints\ \ flow}$$

Generation shift factor

Generation shift factor is the ratio of incremental change in power flow of line 'k' to change in power injection at bus i.

$$GSF_{k-i} = \frac{\left(B^{-1}_{(a,i)} - B^{-1}_{(b,i)}\right)}{x_k} \qquad (4)$$

Where,

B^{-1} – Inverse of susceptance (B) matrix

x_k - Reactance of line k

a , b are sending and receiving end buses of line k

Flow of line k after outage of generator = base case flow of line + GSF_{k-i} + base case generation on bus i

III OVERVIEW OF PARTICLE SWARM OPTIMIZATION

Particle swarm optimization (PSO) is an optimization tool conducts searching process using a population of particles corresponding to individuals. In this heuristic method particles usually fly around in a multidimensional search space. During flight every particle will be adjusting its position according to its own experience (which is called pbest) and also according to the neighboring particle's experience (which is called gbest). Particles are being generated by the velocity and position in N-dimensional space. The initialization of each particle's position and velocity is given by,

$$X_i = ((X_{\max} - X_{\min}) \times rand()) \quad (5)$$

$$V_i = ((V_{\max} - V_{\min}) \times rand()) \quad (6)$$

Where i refers to number of particles. The position and velocity are updated by the following equation,

$$X_i^{k+1} = X_i^k + V_i^{k+1} \quad (7)$$

X_i^k is current searching point and X_i^{k+1} is modified searching point.

$$V_i^{k+1} = wV_i^k + C_1 rand() \times (Pbest_i^k) + C_2 rand() \times (Gbest_i^k - X_i^k) \quad (8)$$

V_i^k is current velocity and V_i^{k+1} is modified velocity.

$$w(k) = w_{\max} - \left(\frac{w_{\max} - w_{\min}}{iter_{\max}} \right) \times iter \quad (9)$$

Where w is weight function or inertia weight. C_1, C_2 acceleration constants which pulls the particles towards Pbest and Gbest. Maximum velocity is expressed as follows:

$$\frac{(X_{\max} - X_{\min})}{N} \quad (10)$$

Where,

N – Number of iterations.

IV PROBLEM FORMULATION

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 based on optimal power flow (OPF) using particle swarm optimization (PSO). LMPs are used for settlement of transactions, while 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. Using OPF optimal generator dispatch is determined subject to a set of constraints representing both operational and physical limits of the power system. The generator and customer bids are assumed to be the inputs to OPF. The base case OPF based on social welfare maximizing algorithm which evaluates the generation dispatch, demands and evaluates prices at each nodes.

A) Objective function

The objective function is then to maximize the total social welfare (TSW) while meeting the load in the system and also should equals to minimize the total cost of generation. The objective function is formulated as a quadratic benefit curve submitted by the buyer (DISCO) minus quadratic bid curve supplied by seller (GENCO).

$$\max \sum_{i=1}^{n} B_i\left(P_{Di}\right) - \sum_{i=1}^{n} C_i\left(P_{Gi}\right) \qquad (11)$$

Where the total production cost and the total customer benefit are given by:

$$C_i\left(P_{Gi}\right) = a_i P_{Gi}^2 + b_i P_{Gi} + c_i$$

$$B_i\left(P_{Di}\right) = d_i P_{Di}^2 + e_i P_{Di} + f_i P_{Di}$$

The main objective function used in OPF is fuel cost minimization for each generator. The objective function for fuel cost minimization can be written as the sum of the quadratic cost model at each generator.

$$F(x) = \min\left(\sum_{i \in G} C_i(P_{Gi})\right) \qquad (12)$$

Here, G is the generator set including slack bus.

P_{Gi} is the active power generated from the generator i

a_i, b_i, c_i are cost coefficients of generator buses.

B) Equality constraints

The power flow equation is the equality constraint in OPF problem. The sum of power flows, active and reactive power injected into a node minus the power flows extracted from the node has to be zero. While minimizing the fuel cost, it is necessary to make sure that generator still supplies the load demand.

$$P_{Gi} - P_{Di} = P_i \qquad (13)$$

Where,

P_i is the calculated real power for the bus i.

C) Inequality constraints

The inequality constraints are generation limit, voltage limit and line flow limits and real power generation limit.

a) Generation limit:

The generating plants always have a maximum and minimum generation capacity but which is not feasible to generate due to technical and economic reasons. Generators are bound to operate between the upper and lower limits for both real and reactive power generated.

$$P_{Gi}^{\min} \le P_{Gi} \le P_{Gi}^{\max} \qquad (14)$$

$$Q_{Gi}^{\min} \leq Q_{Gi} \leq Q_{Gi}^{\max} \qquad (15)$$

Where,

$P_{Gi}^{\min}$, $Q_{Gi}^{\min}$ = minimum real and reactive power generated at bus i

$P_{Gi}^{\max}$, $Q_{Gi}^{\max}$ = maximum real and reactive power generated at bus i

b) Voltage limit:

The bus voltage needs to be maintained within an allowable narrow range of levels to maintain the voltage stability. The performance is improved by maintaining the stability of the system.

$$V_i^{\min} \leq V_i \leq V_i^{\max} \qquad (16)$$

Where,

$V_i^{\min}$ = minimum or lower limit of voltage profile at bus i

$V_i^{\max}$ = maximum or upper limit of voltage profile at bus i

c) Line flow limit:

The line flow limit specifies the maximum power that can be transferred through the given transmission line under given conditions. The limit can be based on thermal or stability considerations.

$$S_{ij} \leq S_{ij}^{\max} \qquad (17)$$

Where,

S_{ij} = complex power flow in the line ij

$S_{ij}^{\max}$ = maximum power transfer capacity of the line ij

V RESULTS AND DISCUSSIONS

The proposed methodology is demonstrated in IEEE-30 bus system. This standard IEEE-30 bus system consists of 4 power suppliers, 20 consumers and 35 transmission lines. The generators are connected at nodes 2,5,8,11,13 and slack bus connected at node 1.

Case 1: Generator scheduling is performed using PSO based OPF for the base case load of 283.4 MW for 25 trials and best optimal cost of generator scheduling is selected. The system is free from congestion for its base case which is checked by calculating complex power flow in transmission line using Newton-Raphson load flow method. The value of LMP is calculated at each node.

TABLE 1 LMP base case

BUS NO	LMP Ref ($/MWh)	LMP Loss ($/MWh)	LMP Cong ($/MWh)	LMP ($/MWh)

1	3.3868	-	0	3.3868
2	3.3868	0.5124	0	3.8992
3	3.3868	0.3645	0	3.7513
4	3.3868	0.1155	0	3.5023
5	3.3868	0.0021	0	3.3889
6	3.3868	-	0	3.3868
7	3.3868	0	0	3.3868
8	3.3868	0.0001	0	3.3869
9	3.3868	-	0	3.3868
10	3.3868	0.1352	0	3.5220
11	3.3868	-	0	3.3868
12	3.3868	0.1103	0	3.4971
13	3.3868	-	0	3.3868
14	3.3868	0.0036	0	3.3904
15	3.3868	0.0493	0	3.4361
16	3.3868	0.0091	0	3.3959
17	3.3868	0	0	3.3868
18	3.3868	0.0037	0	3.3905
19	3.3868	0.0067	0	3.3935
20	3.3868	0	0	3.3868
21	3.3868	0.0003	0	3.3871
22	3.3868	0	0	3.3868
23	3.3868	0.1664	0	3.5532
24	3.3868	0.0227	0	3.3895
25	3.3868	-	0	3.3868
26	3.3868	0	0	3.3868
27	3.3868	-	0	3.3868
28	3.3868	-	0	3.3868
29	3.3868	0.0349	0	3.4217
30	3.3868	0	0	3.3868

Table1 shows the Base case values of LMP at each node. The LMP energy component is same for all buses. It is observed that the LMP values are nearly equal at all buses. If DCOPF is considered the losses in the lines are neglected and LMP values at each node are equal wherein here ACOPF is considered losses are also included for the calculation. This base case LMP values indicates that the system is free from congestion as the LMP congestion cost is indicated as zero. LMP congestion cost is zero because the transmission constraints are not violated.

The LMP value signals that the system is free from congestion for the base case. This LMP calculation is performed repeatedly for every five minutes or less because the load connected in the power system is dynamic. The load may increase or decrease causing the spatial difference of LMP to vary which is explained in case2.

Case 2: In this case the load is increased to 333.4MW by increasing the load at node 6. Now again generator scheduling is performed using OPF to check the line limits. Then contingency case is considered for evaluating the LMP values during congestion. In this generator connected at node13 is assumed to be in outage and the line flow is calculated after the generator outage. The line flow is checked for overloading. The overloaded line is found out and change is system cost is calculated for the evaluation of shadow price.

TABLE 2 LMP during congestion

BUS NO	LMP Ref ($/MWh)	LMP Loss ($/MWh)	LMP Cong ($/MWh)	LMP ($/MWh)
1	3.4978	-	0	3.4978
2	3.4978	0.8618	14.4099	18.7695
3	3.4978	0.6026	-2.4643	1.6361
4	3.4978	0.2564	2.6923	6.4465
5	3.4978	0.0003	4.3831	7.8812
6	3.4978	0.0497	4.8701	8.4176
7	3.4978	0	0	3.4978
8	3.4978	0.0004	0	3.4982
9	3.4978	-	0	3.4978
10	3.4978	0.1316	36.4773	40.1067
11	3.4978	0	0	3.4978
12	3.4978	0.127	-16.5769	-12.9251
13	3.4978	0	0	3.4978
14	3.4978	0.0045	-8.0184	-4.5161
15	3.4978	0.0569	-5.5708	-2.0161
16	3.4978	0.018	-15.4318	-11.916
17	3.4978	0	0	3.4978
18	3.4978	0.0069	18.5246	22.0293
19	3.4978	0.0058	11.5316	15.0352
20	3.4978	0	0	3.4978
21	3.4978	0.0003	9.6628	13.1609
22	3.4978	0	2.1118	5.6096
23	3.4978	0.1617	2.9706	6.6301
24	3.4978	0.0003	-7.0979	-3.5998
25	3.4978	-	-7.0979	-3.6001
26	3.4978	0	0	3.4978
27	3.4978	-	0	3.4978
28	3.4978	-	0	3.4978
29	3.4978	0.035	0	3.5328
30	3.4978	0	0	3.4978

Table 2 shows the LMP values at each node during congestion. The LMP energy component is same for all nodes. As the overloading of line occurs due to generator outage the overall cost of system increases. Hence LMP congestion value is calculated. Now the LMP values differ at every node as the generator contributions to each node varies. This change in LMP values gives the economic signal indicating the spot of congestion. The higher value of LMP indicates that more generation is pressed by demand at that node. The negative value of LMP indicates the lower demand compared to generation is present at that node.

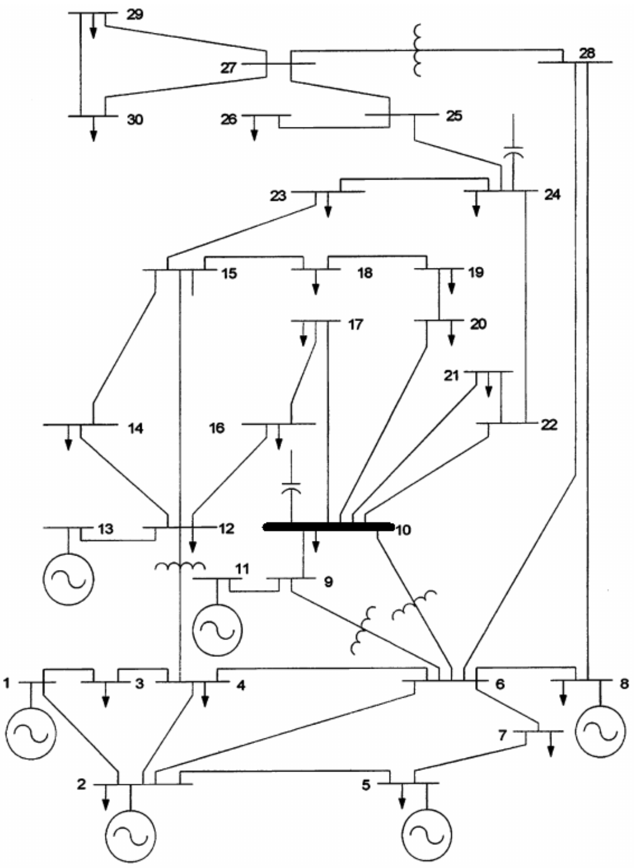

Fig.1: single line diagram of IEEE 30 bus system

Fig.1 and Table 2 indicates that the bus number 10 for the given system has higher LMP value of all the other buses which highlights the highly congested spot in the IEEE 30 bus system. This highly congested spot is well suitable for the optimal IPP placement in maximizing the social welfare in the deregulated electricity market and also relieves the congestion.

VI 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) proved to be an effective solution in overcoming the above said barriers of deregulation. Generator scheduling using PSO based OPF technique has been tested in IEEE30 bus system in order to minimize fuel cost and maximize social welfare. The LMP values are also calculated for IEEE30 bus system under normal and contingency condition. Increase in LMP holds to be a good signal for identifying the congested locations.

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