Nodal market power detection under locational marginal pricing

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Abstract

This paper proposes an index for nodal market power detection in power market under locational marginal pricing (LMP). This index is an ex-ante technique to detect the market power. More precisely, this criterion detects the potential of exercising market power regardless of detecting the actual market power. Also it is obvious that pricing and market clearing method affect the potential of exercising market power. Different potential of market power exists in different pricing methods. This index has been analyzed under LMP method which seems to be a desirable environment to exercise market power. In LMP method by load growth, in some determined load levels which is called Critical Load Levels (CLLs), locational marginal prices have step change. This step change in locational marginal prices causes step change in revenue and benefit of Gencos. So it is significant to detect the behavior of Gencos in the CLLs. The proposed criterion has been tested on constant system load and CLLs of system.

Keywords Nodal Market Power, Market Power Detection, Locational Marginal Pricing

1. Introduction

Market power detection is a complex issue in restructured power market. Techniques that have been applied to detect market power are primarily classified to two categories [1]: 1-ex-ante technique, which are applied to detect the potential for market power and 2- ex-post techniques, which are applied to detect the actual market power. The most usual index for ex-ante techniques is HHI index [2]. This index representing the number of market participants and their market shares in power market. The HHI is calculating through a sum of the squares of market share of market participants. This index has been formulated as below:

$$HHI = \sum_{i=1}^{N} S_i^2 \qquad (1)$$

Where N is a number of market participants and S_i is the ith market participant share. If the HHI is greater than 1000 in percentage, the market power exists in power market. This index express that as much as the number of power market participants decrease and their market share increase the potential of power market exercising increase. This index is not a comprehensive index since in some cases a market participant with a small share of market could profitably change the price especially in the situation that demand is close to the system generation capacity. Also this index does not consider the transmission constraint and also load variation.

Another technique in market power detection from the view point of load elasticity is Lerner Index (LI) [3, 4]. This index has been formulated as below:

$$LI_i = \frac{\rho_i - mc_i}{\rho_i} = \frac{1}{\varepsilon_d^i} \tag{2}$$

Where ρ denotes the market clearing price and mc is marginal cost at the firm profit-maximizing output and the term ε_d^i denotes the elasticity of demand seen by the firm. This criterion varies from 1 to 0. When the market is completely competitive the LI is zero since $\rho_i - mc_i$ denotes that marginal cost of unit is equal to the market price. The major difficulty with this index is determining marginal cost of generation units.

Another market power detection index is called NMRS which is the abbreviation of Nodal Must Run Share [5]. Based on this index the potential of exercising market power by every Genco in the system is proportion to the minimum delivered power of a generator at each node of system ($P_{gk,i}^{must}$). The NMRS for generators of Genco A at the bus i of system has been formulated as below:

$$NMRS_{A,i} = \frac{\sum_{k \in A} P_{gk,i}^{must}}{p_{di}}, i = 1,2,...,N. \tag{3}$$

The above index doesn't consider the load variation and generation cost of Gencos. The generation cost of a Genco and in another word, how this Genco is efficient in comparison to the other Gencos in the power market determines its power generation through OPF problem. So OPF problem determines the generation commitments in the system and considering the minimum delivered power of a generator at each node of system can not comprehensively express the efficiency and real situation of a Genco in power market especially when the market has abundant Gencos.

In different pricing and market clearing mechanism, different potential of power market exists [6]. In the LMP method, after the bids submitted by the generators, the ISO will run OPF and if there is no system constraint violation the price profile is uniform in all system buses, but if a system constraint violates its limit, the ISO will re dispatch the generation so as the constraint violation removed [7].

One of the desirable pricing environments for market power seems to be LMP system since the system constraint violation encourages Gencos to exercise market power [8-11]. Investigating and monitoring the potential of exercising market power under LMP system is necessary and significant since LMP opens the door for exercising market power under certain condition of system. In another word LMP does not guarantee competitive markets, nor does it prevent the market power exercising. Some features of LMP system which may increase market power exercising are [7,12]:

1- If a generator capacity is fully dispatched, the locational price at this generator bus will be determined by the bids of other generators and will be greater than or equal to the generator's energy bid for that capacity segment.

2-In most situations, but not all, the locational marginal prices at most locations will be determined by the bids of generators at other locations.

From another view, load variation in LMP system can increase the potential of exercising of market power. Load growth causes the step change in locational marginal prices due to the system constraint violations [13]. In the determined load level which is called critical load level (CLLs) the OPF constraints violation cause the step change in locational marginal prices. The step change of locational marginal prices at each bus is a golden opportunity for each Genco to increase its benefits. So the possibility of exercising market power between market participants increase in critical load levels (CLLs). So detecting the market power in the different load level of system is vital for each market operator.

In this paper in section 2 some basics has been explained to define proposed index. In section 3 the proposed index has been introduced and then the proposed index has been studied in section 4 for two cases. The proposed index has been concluded in section5.

2. Nodal supplying power of a generator

By running DCOPF the generation vector of generator has been obtained ($\mathbf{p_g}$). To calculate the delivered power of a generator to each bus as Ref [5] the below equations have been applied to the generation vector p_g.

According to the below picture which represents the inflow power, outflow power, load (Pd_i) and generation (Pg_i) at the bus i of system, the below equation can be obtained:

$$PI_i = \sum_{j \subset Ns} pl_{ji} + pg_i \tag{4}$$

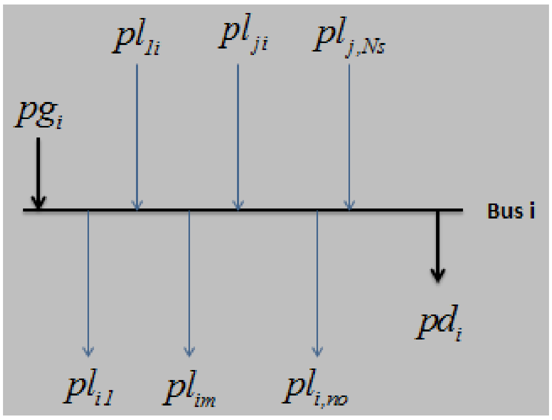

Fig.1 A general node i in the system

Where PI_i is total power inflow into the bus i. The Pl_{ji} denotes the inflow power from bus j to bus i and the number of inflows to bus i is Ns. The above equation can be written as below for N node system.

$$PI_i - \sum_{j \subset Ns} \left(\frac{pl_{ji}}{PI_j} * PI_j \right) = pg_i, i = 1,2,...N \tag{5}$$

The matrix form of above equation can be written as:

$$M * PI = Pg \tag{6}$$

$$m_{ij} = \begin{cases} 1 & j = i \\ \dfrac{-pl_{ji}}{PI_j} & j \in Ns \\ 0 & otherwise \end{cases} \tag{7}$$

$$PI = M^{-1} * Pg \tag{8}$$

Where PI is nodal power inflow vector, Pg is nodal generation vector and M is distribution matrix which the mth element of this matrix is defined as the above equation.

The ith element of PI can be written as:

$$PI_i = \sum_{j \in Ns} [M^{-1}]_{ij} * Pgj \tag{9}$$

The above equation represent that the contribution of each system generator in power inflow to bus i. The load in bus i can be written as below, considering the equation 9.

$$pd_i = \frac{pd_i}{PI_i} * PI_i = \frac{pd_i}{PI_i} * \sum_{j \subset N} [M^{-1}]_{ij} * Pg_j = \sum_{j \subset N} \frac{pd_i}{PI_i} * [M^{-1}]_{ij} * Pg_j = \tag{10}$$

$$\frac{pd_i}{PI_i} * ([M^{-1}]_{i1} * Pg_1 + \ldots + [M^{-1}]_{ik} * Pg_k + \ldots)$$

Ultimately the kth element of above equation which denotes the each generator contribution in load of bus i can be written as below:

$$P_{gk,i} = \frac{pd_i}{PI_i} [M^{-1}]_{i,k} * P_{gk} \tag{11}$$

After running DCOPF, the generator delivered power to each node's load can be obtained through the above equations.

3. The proposed index to detect the potential of market power under LMP

In this section an index has been introduced to detect the potential of Nodal Market Power (NMP) in LMP system. It should be noted that this index detect only the potential of exercising market power by a Genco but in real power market a Genco may apply the market power with its bid strategy or may not apply market power. It is obvious that a possibility of exercising market power by a Genco with great potential of exercising market power is high. So it is significant for ISO to identify and monitor the behavior of Gencos with great potential of exercising market power. The proposed index to detect the potential of exercising market power by Genco k at bus i of system is formulated as below:

$$NMP_i^k = \frac{p_i^k - p_i^{k,uncons}}{d_i} \tag{12}$$

Where NMP_i^k denotes the nodal potential of exercising market power by Genco k in the bus i of system. p_i^k denotes the generator delivered power at each node after running the DCOPF (Eq 13-20), and $p_i^{k,uncons}$ denotes the generator delivered power at each node after running unconstrained DCOPF without the transmission constraint. Based on this index the potential of nodal market power for Genco k at bus i is proportion to the difference between the generator delivered power to each node between DCOPF and unconstrained DCOPF. According to this criterion the market power potential exists if the NMP is greater than zero. More precisely, this index express that the market power potential exist when the Genco generation increase in ordinary DCOPF in comparison to unconstrained DCOPF. In another word the structural situation like transmission power limit cause that the more costly Gencos' generation increases.

DCOPF problem:

$$GC(P_G) = a.\times * P_G + b.* P_G .\hat{}2 \qquad (13)$$

$$\min_{P_G,\delta}\left\{\sum(\mathbf{GC}(P_G))\right\} \qquad (14)$$

Subject to:

$$P_G - P_D = P(\delta) = B.*\delta \qquad (15)$$

$$P_G^{Low} \le P_G \le P_G^{Up} \qquad (16)$$

$$-T_{max} \le H.*\delta \le T_{max} \qquad (17)$$

4. System studies

In this paper the potential of market power studied in two cases. The first case is detecting the nodal market power with constant load at each bus. The second case is detecting market power in different load level of system which causes the step change in locational marginal prices. As expressed previously in LMP system by increase of load, the bus prices at buses have a step change. In CLLs since the step change of prices, the opportunity and potential of exercising power market increase. So it is significant for market operator to anticipate the potential of market power of each Gencos in CLLs and monitor the behavior of Gencos in CLLs. The selected test case to study is PJM 5 bus. Below is the diagram of this test case with generation and transmission limit data.

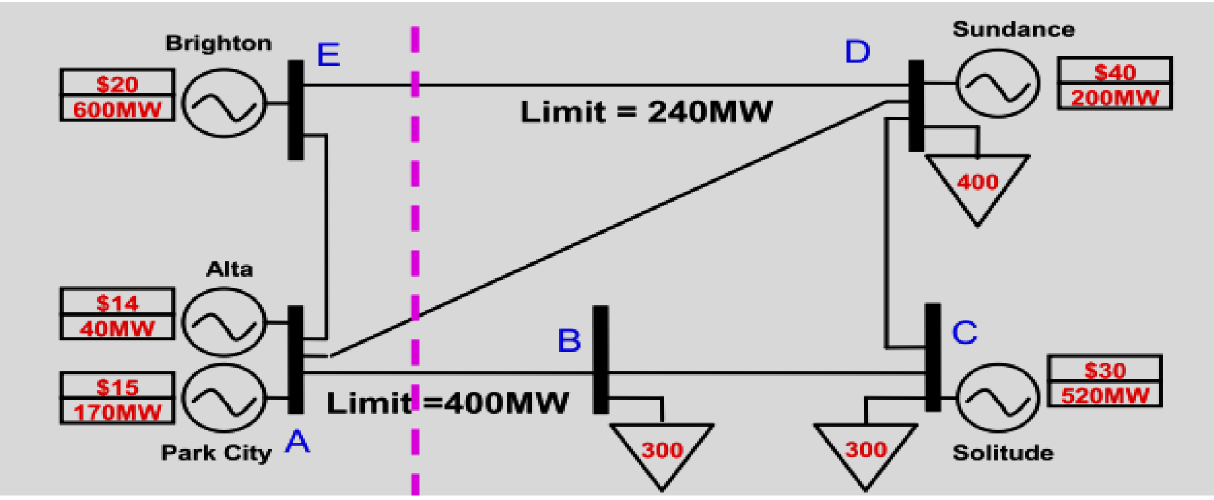

Fig.2 the five bus test system diagram

4-1. Case A

In this case a system with the constant load has been analyzed. In this test system the DCOPF has been applied to obtain the proposed index in section3 .By running DCOPF and unconstrained DCOPF the contribution of each generator in supplying power of each node has been calculated through equation 4-11 for DCOPF and unconstrained DCOPF.

Below matrix equation denotes the contribution of each system generator in power inflow to node i by running DCOPF.

$$M^{-1} * Pg = PI \Rightarrow$$

$$\begin{bmatrix} 1.0000 & 0 & 0 & 0 & 0.5189 \\ 0.5776 & 1.0000 & 0.1676 & 0.0128 & 0.3069 \\ 0.0327 & 0 & 1.0000 & 0.0765 & 0.0600 \\ 0.4279 & 0 & 0 & 1.0000 & 0.7844 \\ 0 & 0 & 0 & 0 & 1.0000 \end{bmatrix} \begin{bmatrix} 210 \\ 0 \\ 323 \\ 0 \\ 466 \end{bmatrix} = \begin{bmatrix} 452.0697 \\ 318.6853 \\ 358.3559 \\ 455.7801 \\ 466.0000 \end{bmatrix}$$

The quantity of each element of M^{-1} denotes the share of each generator in power inflow of each system bus. The number one in M^{-1} denotes that the whole generation of a Genco delivers to a determined bus.

Following the above equation, according to Eq11 each Genco contribution in load supplying of each bus has been calculated and depicted in Table1.

Table1. The share of each Genco in load supplying of each bus in DCOPF

Nodal supplying power of Gencos	Genco A	Genco C	Genco D	Genco E	SUM
BUS2	112.4	52.9	0	134.7	300
BUS3	5.7	270.8	0	23.5	300
BUS4	93	0	0	307	400

Now the system has been analyzed under unconstrained DCOPF (without transmission constraint). The below matrix equation denotes the contribution of each system generator in power inflow to node i by running unconstraint DCOPF.

$$M^{-1} * Pg = PI \Rightarrow$$

$$\begin{bmatrix} 1.0000 & 0 & 0 & 0 & 0.6016 \\ 0.6025 & 1.0000 & 0 & 0 & 0.3625 \\ 0.1558 & 0.0554 & 1.0000 & 0.3080 & 0.2707 \\ 0.3975 & 0 & 0 & 1.0000 & 0.8136 \\ 0 & 0 & 0 & 0 & 1.0000 \end{bmatrix} \begin{bmatrix} 210 \\ 0 \\ 190 \\ 0 \\ 600 \end{bmatrix} = \begin{bmatrix} 570.9832 \\ 344.0053 \\ 385.1220 \\ 571.6267 \\ 600.0000 \end{bmatrix}$$

Following the above equation, according to Eq11 each Genco contribution in load supplying of each bus has been calculated and depicted in Table2 for unconstrained DCOPF (without transmission constraint)

Table2. The share of each Genco in load supplying of each bus in unconstraint DCOPF

Nodal supplying power of Gencos	**Genco A**	**Genco C**	**Genco D**	**Genco E**	**SUM**
BUS2	110.4	0	0	189.6	300
BUS3	25.4	190	0	84.5	300
BUS4	74.1	0	0	325.9	400

Ultimately by applying equation 12 the nodal market power has been calculated for each Genco at each bus of system in below table.

Table3. The nodal market power (NMP) for each Genco at each system bus

Genco \ NMP	NMP2	NMP3	NMP4
A	0.67	-6.57	4.73
C	17.63	26.93	0
D	0	0	0
E	-18.3	-20.33	-4.72

The NMPs which are greater than zero denote the potential of exercising nodal market power can be exist. According to the results the potential of market power exercising by Genco D is zero in all system buses since this generator doesn't participate in market in both DCOPF and unconstrained DCOPF .The maximum NMP belongs to Genco C at bus 3. This means Genco C at bus 3 has the great potential of exercising market power. Also Genco E has negative NMP in all buses and this Genco has no potential to exercise market power in system. Genco A could have the potential of exercising market power at bus 2, 4 especially at bus 4.

4-2. Case B

In this case the potential of exercising market power analyzed in the CLLs of system. Since in CLLs the bus prices have a step change and so the revenues of a Gencos have a step change too, it is significant to detect and monitor the behavior of Gencos. In this case the system load change is assumed to be distributed to all bus loads in proportion to their base case load. Below is the CLLs of five bus system that cause step change in bus prices.

Table4. The critical load levels and the locational marginal prices at each bus

System load	Locational Marginal Prices at each system bus ($/h)				
CLLs(MW)	LMP@A	LMP@B	LMP@C	LMP@D	LMP@E
600	14	14	14	14	14
676.78	14	19.38	21.44	27.13	10
705.2	15	21.72	24.31	31.42	10
717.4	16.98	26.38	30	39.93	10
1171.75	17	26.42	30.04	40	10
1400	17	26.42	30.04	40	10

By running DCOPF and unconstrained DCOPF the contribution of each generator in supplying power of each node has been calculated as equation 4-11 in each critical load levels (CLLs) of system. According to case A, the Gencos A & C have the potential of exercising market power in this system, so in this case Genco A behavior analyzed in the CLLs.

Table5. The potential of nodal market power (NMP) of Genco A in CLLs

Genco A	CLL=677	CLL=706	CLL=718	CLL=1173
NMP2	0.046	15.26	21.81	0.67
NMP3	0.005	8.20	11.85	-6.57
NMP4	0.012	5.96	8.76	4.73

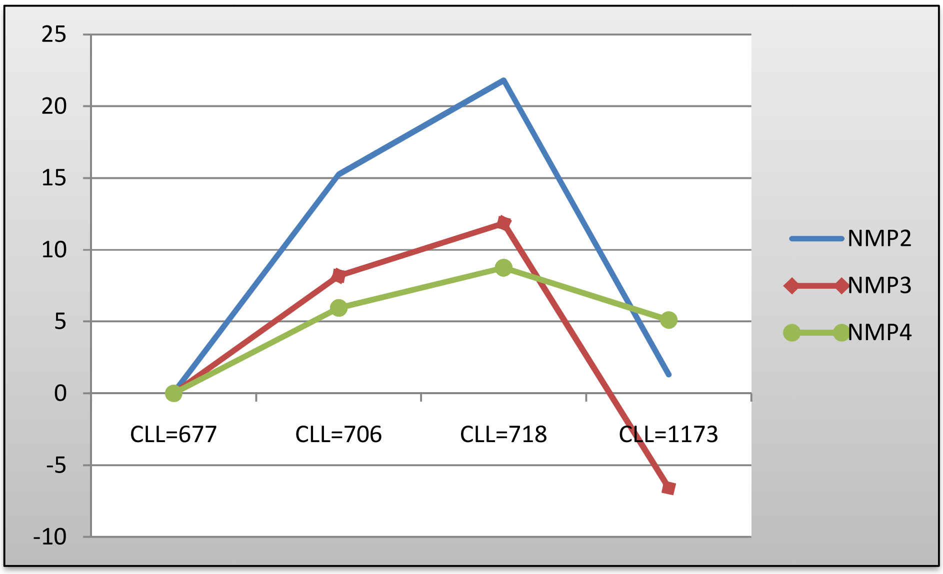

Fig.3 The potential of nodal market power for Genco A in critical load level of system (CLLs)

Results demonstrate that potential of market power exercising changes considerably with system load variation. So load variation in detection of market power can not be neglected. For Genco A the potential of market power exercising at first increases and after a special load level this potential decreases, so the load increase sometimes decrease the potential of market power exercising. Also there is a harmony in the NMP of all bus of system, in another word the NMP of buses increase together and decrease together. The max potential of market power for Genco A occurs when the system load increase up to 718 MW at bus 2. As depicted in Fig.3 between three NMPs, the NMP2 is above all NMPs in most CLLs, so the Genco A can exercise market power at bus 2 more than the other system buses.

5. Conclusion

In this paper an index has been introduced to detect the potential of nodal market power exercising under LMP system. LMP is the result of system constraint violation like transmission limits. So under LMP system the structural situation of system provide an environment to exercise market power. Especially in LMP system in some load levels, prices of buses have a step change. These load levels called critical load levels (CLLs). Detecting and monitoring the behavior of a Genco under CLLs is significant since the step change of bus prices caused step change in Genco revenue in CLLs.

In this paper after introducing an index, this index applied to a test system in two cases to detect the potential of market power. In the first case the load of system is constant and the potential of exercising of power market detects for each Gencos of system at each system buses. In the second case the potential of market power has been analyzed in critical load level of system.

Based on results, the structural situation of system affects the potential of market power exercising. Results demonstrate that the potential of market power exercising considerably varies with load variation. Also the load increase in system sometimes decreases the potential of exercising market power.

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