

# 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 for two test system.

**Keywords:** Locational Marginal Pricing, Market Power Detection, Nodal Market Power.

## 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:

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

where  $N$  is a number of market participants and  $S_i$  is the  $i$ th 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:

$$LI_i = \frac{\rho_i - mc_i}{\rho_i} = \frac{1}{\varepsilon_d^i} \quad (2)$$

where  $\rho$  denotes the market clearing price and  $mc$  is marginal cost at the firm profit-maximizing output and the term  $\varepsilon_d^i$  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 ( $P_{gk,j}^{must}$ ). The NMRS for generators of Genco A at the bus  $i$  of system have been formulated as below:

$$NMRS_{A,j} = \frac{\sum_{k \in A} P_{gk,j}^{must}}{P_{di}}, i = 1, 2, \dots, N. \quad (3)$$

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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't comprehensively express the efficiency and real situation of a Genco in power market especially when the market has abundant Gencos.

To probe further about the defects of this index, consider the simple 3 bus system of [6] which has been depicted in Fig. 1. The detail data of this system is available in chapter 6 of [6].

The nodal market power of each Genco based on [5] index has been depicted in Table 1. Based on the above index Gencos A, C and D has no potential of exercising market power since without each of these Gencos the system load and other system constraint according to the optimization problem of [5] can be satisfied and the minimum delivered power of these Gencos to each system bus is zero (according to the proposed index of [5]). So Gencos A, C and D have no potential of exercising market power according to this index. Only Genco B has the potential of exercising market power since without this Genco the system load can't be met and other system constraint in proposed optimization problem in [5] can't be satisfied.

So this index that considers the minimum delivered power of Gencos to each bus of system may be equated to zero for Gencos which has small share in system load supply as above example. But during the period which demand is closed to generation capacity (peak time) a Genco with small share in system load supply, can exercise market power. Also a Genco with low generation cost that has small share in system load supply can have more potential of exercising market power in comparison to a Genco with high generation cost that has major share in system load supply [7]. Also in this index the load assumed to be constant and load variation and CLLs of system have not been considered in this index.

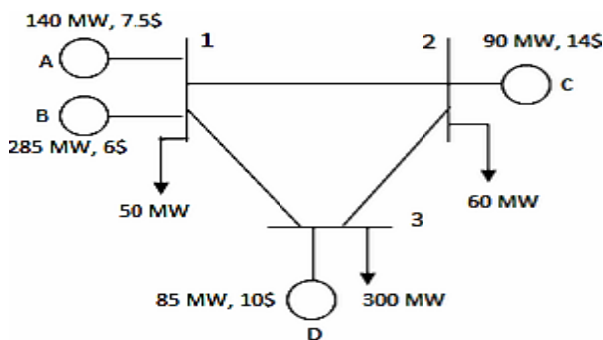


Fig. 1 Three bus system with generation and load data.

Table 1 The nodal market power of each Genco in each bus of system based on [5] index.

NMRS index	Genco A	Genco B	Genco C	Genco D
BUS1	0	0.401	0	0
BUS2	0	0.16	0	0
BUS3	0	0.21	0	0

From another aspect in different pricing and market clearing mechanism, different potential of power market exists [7-9]. 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 [6].

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 [10-13]. 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 [6, 14]:

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 [15]. 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 CLLs. So detecting the market power in the different load levels of a system is vital for each market operator.

LMP system is a vulnerable pricing system due to its dependency on the structure of system. So the nodal prices are depending on the structure of the system. This dependency has been shown in detail in section 4-2. So it's vital to propose an index to detect the structural potential of market power under LMP system which has

been done in this research. Also the load variation in LMP system based on the structural situation of system can increase the structural potential of exercising of market power in some buses of system or decrease the structural potential of exercising of market power in the same buses of system for a special Genco. So it is vital for system operator to identify the Gencos' potential of exercising market power in different load levels and monitor the behaviors of Gencos with great potential of exercising market power.

In this paper an index has been proposed to detect the nodal potential of market power of Gencos in LMP system. This index has been studied in two conditions, first in constant load and the then in CLLs of system to consider the load variation of system. By calculating this index the market operator can monitor the Gencos with high potential of exercising market power. 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 test system in two conditions. The proposed index has been concluded in section 5.

## 2 Nodal Supplying Power of a Generator

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

According to the Fig. 2 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:

$$PI_i = \sum_{j \in Ns} pl_{ji} + pg_i \quad (4)$$

where  $pl_i$  is the 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.

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

The matrix form of above equation can be written as:

$$M * PI = Pg \quad (6)$$

$$m_{ij} = \begin{cases} 1 & j = i \\ \frac{-pl_{ji}}{PI_j} & j \in Ns \\ 0 & otherwise \end{cases} \quad (7)$$

$$PI = M^{-1} * Pg \quad (8)$$

where  $PI$  is nodal power inflow vector,  $Pg$  is nodal generation vector and  $M$  is distribution matrix which the  $m$ th element of this matrix is defined as the above equation.

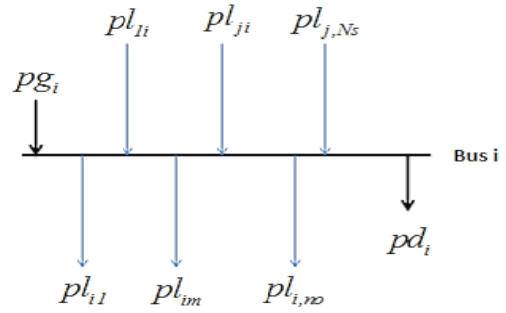


Fig. 2 A general node  $i$  in the system.

The  $i$ -th element of  $PI$  can be written as:

$$PI_i = \sum_{j \in Ns} [M^{-1}]_{ij} * Pg_j \quad (9)$$

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 Eq. (9).

$$\begin{aligned} pd_i &= \frac{pl_i}{PI_i} * PI_i = \frac{pl_i}{PI_i} * \sum_{j \in Ns} [M^{-1}]_{ij} * Pg_j = \sum_{j \in Ns} \frac{pl_i}{PI_i} * [M^{-1}]_{ij} * Pg_j \\ &= \frac{pl_i}{PI_i} * ([M^{-1}]_{i1} * Pg_1 + \dots + [M^{-1}]_{ik} * Pg_k + \dots) \end{aligned} \quad (10)$$

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

$$P_{gk,i} = \frac{pd_i}{PI_i} [M^{-1}]_{ik} * Pg_k \quad (11)$$

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 structural 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:

$$NMP_i^k = \frac{P_i^k - P_i^{k,uncons}}{d_i} \quad (12)$$

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 (Eqs. (13)-(17)), 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.

It should be noted that it has been assumed that ISO will know the approximation of marginal cost of generation units according to their types and will run DCOPF by marginal cost of units before real market clearing which Genco submitting their bids to ISO. So this index is an ex-ante index and more precisely structural ex-ante index which look to find the potential for market power, whereas behavioral indices typically looking for actual evidence of the exercise of market power [1].

Below equation represent the DCOPF formulation. Eqs. (16) and (17) in this index denotes that generation capacity of each Genco and transmission constraint has been considered indirectly in proposed index trough DCOPF problem.

**DCOPF problem:**

$$GC(P_G) = a \cdot P_G + b \cdot P_G^2 \tag{13}$$

$$\min_{P_G, \delta} \{ \sum (GC(P_G)) \} \tag{14}$$

Subject to:

$$PG-PD=P(\delta)=B \cdot \delta \tag{15}$$

$$P_G^{Low} \leq P_G \leq P_G^{Up} \tag{16}$$

$$-Tmax \leq H \cdot \delta \leq Tmax \tag{17}$$

**4 System Studies**

In this paper the potential of market power studied in two conditions on two test cases to study the proposed index comprehensively in different condition. The two conditions are:

- 1- The first condition is analyzing the proposed index when load is constant at each bus of system.
- 2- The second condition 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 cases to study are PJM 5 bus and 30 bus test case. Fig. 3 shows the diagram of PJM 5 bus test case with generation and transmission limit data. This test case has 6 lines, 3 load buses and 4 Gencos at each generation bus, it means that the two generators at bus 1 consider as a unit Genco. The detail data about this test case is available in [16].

**4.1 Five Bus Test Case in Condition A**

In this condition a system with the constant load has been analyzed. The DCOPF has been applied to obtain the proposed index in section 3 .By running DCOPF and unconstrained DCOPF the contribution of each generator in supplying power of each node has been calculated through Eqs. (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.

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

1.0000	0	0	0	0.5189	210
0.5776	1.0000	0.1676	0.0128	0.3069	0
0.0327	0	1.0000	0.0765	0.0600	323
0.4279	0	0	1.0000	0.7844	0
0	0	0	0	1.0000	466

$$= \begin{bmatrix} 452.0697 \\ 318.6853 \\ 358.3559 \\ 455.7801 \\ 466.0000 \end{bmatrix} \tag{18}$$

The quantity of each element of  $M^{-1}$  denotes the share of each generator in power inflow of each system bus.

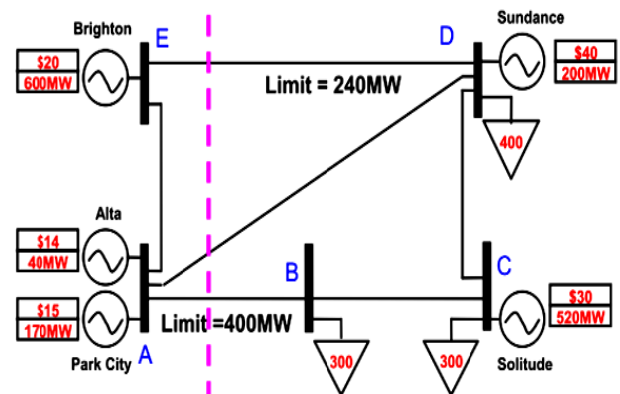


Fig. 3 The five bus test system diagram.

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 Eq. (11) each Genco contribution in load supplying of each bus has been calculated and depicted in Table 2.

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 unconstrained DCOPF.

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

$$\begin{bmatrix} 1.0000 & 0 & 0 & 0 & 0.6016 \\ 0.6025 & 1.0000 & 0 & 0 & 0.3625 \\ 0.1558 & 0.0554 & 1.0000 & 0.3080 & 0.2707 \\ 0.3975 & 0 & 0 & 1.0000 & 0.8136 \\ 0 & 0 & 0 & 0 & 1.0000 \end{bmatrix} \begin{bmatrix} 210 \\ 0 \\ 190 \\ 0 \\ 600 \end{bmatrix} = \begin{bmatrix} 570.9832 \\ 344.0053 \\ 385.1220 \\ 571.6267 \\ 600.0000 \end{bmatrix} \quad (19)$$

Following the above equation, according to Eq. (11) each Genco contribution in load supplying of each bus has been calculated and depicted in Table 3 for unconstrained DCOPF (without transmission constraint).

Ultimately by applying Eq. (12) the nodal market power has been calculated for each Genco at each bus of system as depicted in Table 4.

**Table 2** The share of each Genco in load supplying of each bus in DCOPF in 5 bus test case.

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

**Table 3** The share of each Genco in load supplying of each bus in unconstrained DCOPF in 5 bus test case.

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

**Table 4** The nodal market power (NMP) for each Genco at each system bus in 5 bus test case.

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 Five Bus Test Case in Condition B

In this condition 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. Table 5 depicts the CLLs of five bus system that cause step change in bus prices.

**Table 5** The critical load levels and the locational marginal prices at each bus in 5 bus test case.

load	Locational Marginal Prices at each system bus [\$/h]				
	CLLs (MW)	LMP@ A	LMP@ B	LMP@ C	LMP@ D
600	14	14	14	14	14
676.8	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
1171.7	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 Eqs. (4)-(11) in each 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 has been analyzed in the CLLs.

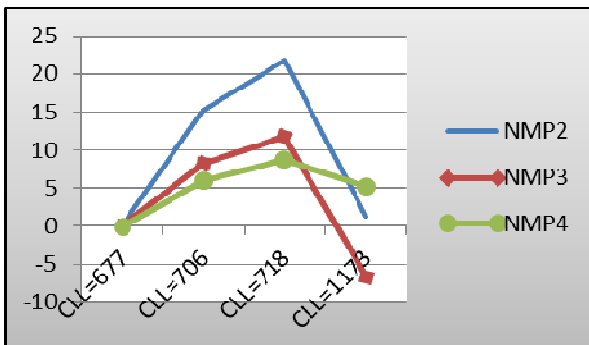
Results (Table 6) demonstrate that potential of market power exercising changes considerably with system load variation. So load variation in detection of market power can't be neglected. For Genco A the potential of market power exercising at first increases and after a special load level this potential decreases, so the load increase sometimes decreases 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 maximum potential of market power for Genco A occurs when the system load increases up to 718 MW at bus 2. As depicted in Fig. 4 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.

#### 4.3 30 Bus Test Case in Condition A

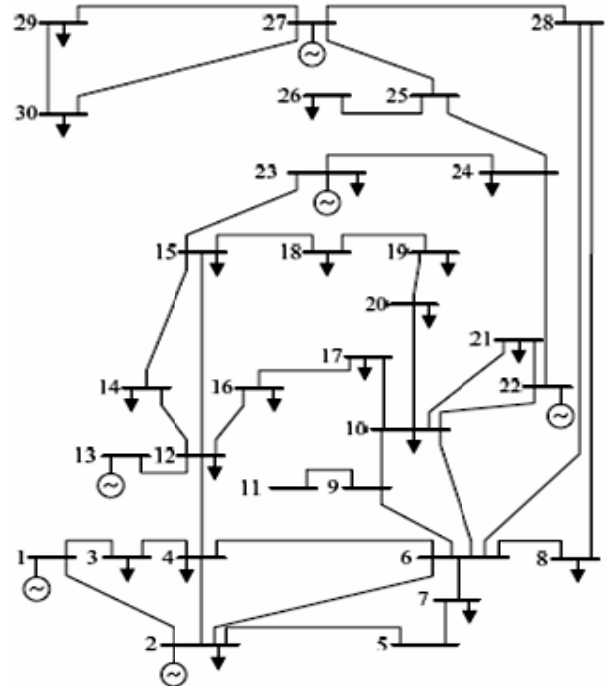
In this condition the IEEE 30-Bus test system (Fig. 5) has been analyzed on the constant load at each bus. This test case has 6 generators at 6 buses (as depicted in Table 7) and here each generator considered as a one Genco and also this test system has 41 branches. The detail data about this test case is available in [15]. The diagram of this test case has been depicted in Fig. 5.

**Table 6** The potential of nodal market power (NMP) of Genco A in CLLs in 5 bus test case.

Genco A	CLL = 677	CLL = 706	CLL = 718	CLL = 1173
NMP2	0.046	15.26	21.81	0.67
NMP3	0.005	8.2	11.85	-6.57
NMP4	0.012	5.96	8.76	4.73



**Fig. 4** The potential of nodal market power for Genco A in critical load level of system (CLLs).



**Fig. 5** The diagram of IEEE 30-Bus test system.

**Table 7** The Gencos location in IEEE 30-Bus test system.

Genco no	Genco1	Genco2	Genco3	Genco4	Genco5	Genco6
location	Bus1	Bus2	Bus3	Bus4	Bus5	Bus6

For this condition the system load is typically equated to 189.2 MW and in this condition no congestion exists in the system, so no nodal price exists in the system and all buses have the uniform price of 3.789 \$/h. Therefore the proposed index to detect the potential of market power under nodal pricing has no meaning in this condition and equated to zero for all Gencos.

#### 4.4 30 Bus Test Case in Condition B

In this condition the potential of exercising market power analyzed in the CLLs of the IEEE 30-Bus test system. For this test case the CLLs of system and nodal price in each CLL have been depicted in Table A.1 in appendix A. As Table A.1 demonstrates when system load raise from the CLL of 253 to CLL of 259, the maximum change occurs in nodal prices. It should be noted that five CLL of system has been considered and also in this condition the system load change is assumed to be distributed to all bus loads in proportion to their base case load.

By running DCOPF and unconstrained DCOPF the contribution of each generator in supplying power of each node has been calculated by Eqs. (4)-(11) in each CLLs of IEEE 30-Bus test system. For this test case the final result for CLL of 259MW has been depicted in Table 8 and other results for other CLLs have been depicted in appendix (Tables A.2-A.4).

**Table 8** The potential of nodal market power (NMP) of Gencos in CLL of 259 MW in IEEE 30-Bus test system.

Genco \ NMP	Genco1	Genco2	Genco3	Genco4	Genco5	Genco6
bus2	0.006	-0.008	0	0	0	0
bus3	-0.002	0	0	0	0	0
bus4	0.006	-0.007	0	0	0	0
bus7	0.016	-0.041	0	0	0	0.023
bus8	0.01	-0.021	0	0	0	0.009
bus10	-0.126	-0.163	0	0.317	0.012	-0.041
bus12	-0.249	-0.141	0.389	0	0	0
bus14	-0.141	-0.08	0.29	0	-0.071	0
bus15	-0.068	-0.038	0.161	0	-0.057	0
bus16	-0.249	-0.141	0.389	0	0	0
bus17	-0.162	-0.173	0.212	0.169	0.006	-0.054
bus18	-0.068	-0.038	0.161	0	-0.057	0
bus19	-0.109	-0.115	0.11	0.101	0.047	-0.037
bus20	-0.126	-0.163	0	0.317	0.012	-0.041
bus21	0	0	0	0.116	0.003	-0.12
bus23	0	0	0	0	-0.002	0
bus24	0	0	0	0	0.089	-0.091
bus26	0	0	0	0	0	-0.002
bus29	0	0	0	0	0	-0.002
bus30	0	0	0	0	0	-0.002

The CLL of 259MW has been chosen because of the maximum nodal prices change occurs in this CLL. The omitted buses in Table 8 have no load or having the equal share of Gencos in DCOPF and unconstrained DCOPF.

In this test case because of greater network and more Gencos, the structural condition of system can face the proposed index to more challenges and so more conclusions have been obtained. The positive NMPs in Table 8 denote the existence of potential of exercising nodal market power.

As result demonstrates in Table 8, a Genco can have a potential of exercising market power in special buses. These buses are buses which are close to a Genco. For instance Genco3 can have the potential of market power in bus 12 and 14-19 which are close to Genco3. Although the vicinity of buses to Gencos cause that a Genco have the potential of exercising market power on those buses, but the structure of system and also the quantity of generation of a Genco in DCOPF problem can create the potential of exercising market power on far buses from a Genco. For instance Genco1 and Genco6 have the potential of exercising market power in bus7 which is almost far away from these Gencos. This is due to high quantity of generation in Genco1 and Genco6

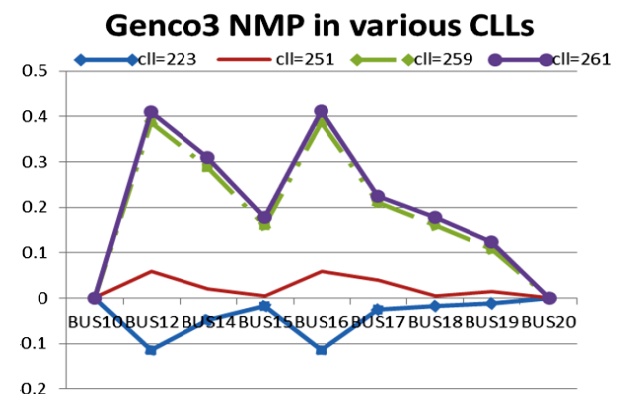
and also the structure of power system including the transmission capacity, load and generation location so on.

To analyze the Table 8 in detail, the results demonstrate that the NMP for Genco2 is negative or zero in all buses (column2) which denote that this Genco has no potential to exercise market power in this system in CLL of 259MW. Genco1 like Genco2 has the negative or zero NMP in most buses of system except buses number 2, 4, 7 and 8 (column1). The maximum NMP between Gencos belong to Genco3 in bus 12 and 16 of system which are close to Genco3, also Genco3 has the positive NMP in most system buses. Genco4 like Genco3 has the positive NMP in most system buses and the maximum NMP for this Genco is seen in buses 10 and 20. Gencos 5 and 6 have the positive NMP in some buses and negative or zero NMP in some other buses but Genco6 has the negative NMP in most system buses.

Now to study the potential of exercising market power in various CLLs for a Genco, the NMP of Genco3 in various CLLs has been depicted in Fig. 6. Genco3 has the maximum NMP between the other Gencos in the CLL of 259MW. So this Genco has been chosen between other Gencos to study the potential of exercising market power in various CLLs.

Fig. 6 denotes that in which CLL the Genco3 can have the more potential of exercising market power. The CLL of 261MW and 259MW are desirable load levels for Genco3 to exercise market power according to Fig. 6. Also in the CLLs of 223 MW, Genco3 has no potential of exercising market power.

From another aspect the Fig. 6 denotes that in which buses the Genco3 can have the more potential of exercising market power. In bus1 up to bus10 this Genco has negative or zero potential of exercising market power because these buses are approximately far from this Genco. In bus12 and 16 in CLL of 261MW Genco3 has the maximum potential of exercising market power whereas in the same buses in CLLs of 223MW this Genco has no potential of exercising market power.



**Fig. 6** The NMP of Genco3 in different CLLs of system.

**Appendix:**

**Table A.1** The critical load levels and the locational marginal prices at IEEE 30-bus test system.

System Load	LMP @				
CLLs	bus1 (\$/h)	bus2 (\$/h)	bus3 (\$/h)	bus4 (\$/h)	bus5 (\$/h)
190MW	3.79	3.79	3.79	3.79	3.79
223MW	4.01	4.01	4.01	4.01	4.01
252MW	4.2	4.2	4.21	4.21	4.2
259MW	3.87	3.85	3.91	3.92	3.82
261MW	3.86	3.84	3.9	3.91	3.8

System Load	LMP @				
CLLs	bus1 (\$/h)	bus2 (\$/h)	bus3 (\$/h)	bus4 (\$/h)	bus5 (\$/h)
190MW	3.79	3.79	3.79	3.79	3.79
223MW	4.01	4.01	4.01	4.01	4.01
252MW	4.19	4.19	5.88	4.29	4.34
259MW	3.78	3.79	23.49	4.49	4.86
261MW	3.76	3.78	24.65	4.51	4.91

System Load	LMP @				
CLLs	bus1 (\$/h)	bus2 (\$/h)	bus3 (\$/h)	bus4 (\$/h)	bus5 (\$/h)
190MW	3.79	3.79	3.79	3.79	3.79
223MW	4.01	4.01	4.01	4.01	4.01
252MW	4.29	4.34	4.34	4.36	4.38
259MW	4.49	4.99	4.99	5.24	5.44
261MW	4.51	5.05	5.05	5.32	5.53

System Load	LMP @				
CLLs	bus1 (\$/h)	bus2 (\$/h)	bus3 (\$/h)	bus4 (\$/h)	bus5 (\$/h)
190MW	3.79	3.79	3.79	3.79	3.79
223MW	4.01	4.01	4.01	4.01	4.01
252MW	4.34	4.34	4.37	4.36	4.35
259MW	4.94	4.88	5.24	5.12	5.05
261MW	4.99	4.93	5.31	5.18	5.12

System Load	LMP @				
CLLs	bus1 (\$/h)	bus2 (\$/h)	bus3 (\$/h)	bus4 (\$/h)	bus5 (\$/h)
190MW	3.79	3.79	3.79	3.79	3.79
223MW	4.01	4.01	4.01	4.02	4.02
252MW	4.37	4.38	4.35	4.5	4.9
259MW	5.04	5.09	4.4	5.83	8.95
261MW	5.1	5.15	4.39	5.93	9.23

System Load	LMP@				
CLLs	bus26 (\$/h)	bus27 (\$/h)	bus28 (\$/h)	bus29 (\$/h)	bus30 (\$/h)
190MW	3.79	3.79	3.79	3.79	3.79
223MW	4.02	4	4.01	4	4
252MW	4.9	4.04	4.52	4.04	4.04
259MW	8.95	4.12	7.89	4.12	4.12
261MW	9.23	4.12	8.12	4.12	4.12

**Table A.2** The of nodal market power of Gencos in CLL of 223MW in IEEE 30-Bus test system.

NMP of Gencos in IEEE 30-Bus test system in CLL of 223 MW					
NMP@	bus3	bus4	bus5	bus8	bus9
Genco1	-0.04	-0.126	-0.083	-0.039	-0.007
Genco2	-0.085	0	-0.043	-0.058	-0.004
Genco3	0	0	0	0	0
Genco4	0	0	0	0	0
Genco5	0	0	0	0	0
Genco6	0	0	0	-0.028	-0.115

Resumption of NMP of Gencos in IEEE 30-Bus test system in CLL of 223 MW					
NMP@	bus11	bus13	bus15	bus16	bus17
Genco1	-0.005	-0.009	0.005	0.006	-0.009
Genco2	-0.003	-0.003	0.004	0.004	-0.003
Genco3	0	-0.114	-0.049	-0.019	-0.114
Genco4	-0.025	0	0	0	0
Genco5	-0.004	0	-0.086	-0.116	0
Genco6	-0.088	0	0	0	0

Resumption of NMP of Gencos in IEEE 30-Bus test system in CLL of 223 MW					
NMP@	bus18	bus19	bus20	bus21	bus22
Genco1	-0.007	0.006	0.004	-0.005	0
Genco2	-0.001	0.004	0.007	-0.003	0
Genco3	-0.027	-0.019	-0.013	0	0
Genco4	-0.016	0	-0.005	-0.025	-0.006
Genco5	-0.003	-0.116	-0.072	-0.004	-0.009
Genco6	-0.071	0	-0.045	-0.088	-0.111

Resumption of NMP of Gencos in IEEE 30-Bus test system in CLL of 223 MW					
NMP@	bus24	bus25	bus27	bus30	
Genco1	0	0	0	0	
Genco2	0	0	0	0	
Genco3	0	0	0	0	
Genco4	0	0	0	0	
Genco5	-0.126	-0.003	0	0	
Genco6	0	-0.122	-0.126	-0.126	



**Table A.3** The nodal market power of Gencos in CLL of 251 MW in IEEE 30-Bus test system.

NMP of Gencos in IEEE 30-Bus test system in CLL of 251 MW			
NMP@	Genco1	Genco2	Genco3
bus2	0.001	-0.001	0
bus4	0.001	-0.001	0
bus7	0.013	0.016	0
bus8	0.051	0.053	0
bus10	0.025	0.024	0
bus12	-0.038	-0.022	0.06
bus14	-0.028	-0.016	0.02
bus15	-0.015	-0.009	0.005
bus16	-0.038	-0.022	0.06
bus17	0.015	0.009	0.04
bus18	-0.015	-0.009	0.005
bus19	-0.006	-0.009	0.014
bus20	0.025	0.024	0
bus21	0	0	0
bus24	0	0	0
NMP of Gencos in IEEE 30-Bus test system in CLL of 251 MW			
NMP@	Genco4	Genco5	Genco6
bus2	0	0	0
bus4	0	0	0
bus7	0	0	-0.029
bus8	0	0	-0.104
bus10	0.032	0.004	-0.085
bus12	0	0	0
bus14	0	0.024	0
bus15	0	0.02	0
bus16	0	0	0
bus17	0.01	0.003	-0.076
bus18	0	0.02	0
bus19	-0.006	0.063	-0.056
bus20	0.032	0.004	-0.085
bus21	0.092	0.011	-0.103
bus24	0	0.091	-0.091

## 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 determined load levels, prices of buses have a step change. These load levels called 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 has been applied in two conditions to two test systems with small and large network to face the proposed index to more challenges and so more conclusions obtained. In the first condition the load of system is constant and the potential of exercising of market power market has been detected for each Genco of system. In the second condition the potential of market power has been analyzed in critical load levels of system.

**Table A.4** The nodal market power of Gencos in CLL of 261 MW in IEEE 30-Bus test system.

NMP of Gencos in IEEE 30-Bus test system in CLL of 261MW			
NMP@	Genco1	Genco2	Genco3
bus2	0.007	-0.007	0
bus4	0.007	-0.007	0
bus7	0.017	-0.044	0
bus8	0.009	-0.024	0
bus10	-0.135	-0.172	0
bus12	-0.257	-0.145	0.402
bus14	-0.146	-0.083	0.303
bus15	-0.07	-0.04	0.169
bus16	-0.257	-0.145	0.402
bus17	-0.169	-0.18	0.215
bus18	-0.07	-0.04	0.169
bus19	-0.113	-0.12	0.113
bus20	-0.135	-0.172	0
bus21	0	0	0
bus24	0	0	0
NMP@	Genco4	Genco5	Genco6
bus2	0	0	0
bus4	0	0	0
bus7	0	0	0.027
bus8	0	0	0.016
bus10	0.339	0.011	-0.043
bus12	0	0	0
bus14	0	-0.074	0
bus15	0	-0.059	0
bus16	0	0	0
bus17	0.183	0.006	-0.055
bus18	0	-0.059	0
bus19	0.113	0.044	-0.037
bus20	0.339	0.011	-0.043
bus21	0.123	0.001	-0.124
bus24	0	0.087	-0.087

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.

## References

- [1] P. Twomey, R. Green, K. Neuhoff and D. Newbery, "A review of the monitoring of market power the possible roles of TSOs in monitoring for market power issues in congested transmission systems", *Journal of Energy Literature*, Vol. 2, pp. 1-56, 2005.
- [2] J. Tirole, *The Theory of Industrial Organization*, Cambridge, MA: MIT, 1988.
- [3] W. M. Landes and R. A. Posner, "Market Power in Antitrust Cases", *Harvard Law Review*, Vol. 94, No. 5, pp. 937-996, 1981.
- [4] P. Visudhiphan and M. D. Ilic, "Dependence of Generation Market Power on the Demand/supply Ratio: Analysis and Modeling", *Power Engineering Society Winter Meeting Singapore*, Vol. 2, pp.1115-1122, Jan. 2000.
- [5] P. Wang, Y. Xiao and Y. Ding, "Nodal Market Power Assessment in Electricity Markets", *IEEE Trans. on Power Systems*, Vol. 19, No. 3, pp. 1373-1379, Aug. 2004.
- [6] D. Kirschen and G. Strbac, *Fundamentals of Power System Economics*, J. Wiley & Sons, Ltd. ISBN: 0-470-84572-4, 2004.
- [7] S. Salarkheili and A. Akbari Foroud, "Market Power Assessment in Electricity Markets: Supply Function Equilibrium-based Model", *Int. Trans. on Electrical Energy Systems*, Vol. 23, No. 4, pp. 553-569, May 2013.
- [8] A. Badri, S. Jadid and M. Parsa-Moghaddam, "Impact of Participants' market power and Transmission Constraints on GenCos' Nash Equilibrium Point", *Iranian Journal of Electrical and Electronic Engineering*, Vol. 3, No. 1, pp. 1-9, 2007.
- [9] S. Salarkheili, A. Akbari Foroud and R. Keypour, "Analyzing Capacity Withholding in Oligopoly Electricity Markets Considering Forward Contracts and Demand Elasticity", *Iranian Journal of Electrical and Electronic Engineering*, Vol. 7, No. 4, pp. 292-301, 2011.
- [10] E. Bompard, T. Huang and W. Lu "Market Power Analysis in the Oligopoly Electricity Markets under Network Constraints." *IET Generation, Transmission & Distribution*, Vol. 4, No. 2, pp. 244-256, 2010.
- [11] G. Bautista and V. H. Quintanl, "Screening and Mitigation of Exacerbated Market Power due to Financial Transmission Rights", *IEEE Transactions on Power Systems*, Vol. 20, No. 1, pp. 213-222, 2005.
- [12] A. K. David and W. Fushuan, "Market Power in Electricity Supply", *IEEE Trans. on Energy Conversion*, Vol. 16, No. 4, pp. 352-360, 2001.
- [13] K. Atkins, J. Chen, V. S. A. Kumar, M. Macauley and A. Marathe, "Locational Market Power in Network Constrained Markets", *Journal of Economic Behavior & Organization*, Vol. 70, No. 1, pp. 416-430, 2009.
- [14] M. R. Baghaiypour and A. Akbari Fouroud, "A New Market Clearing Mechanism, Based on Comprehensive Welfare Allocation, Considering Participants Optimality, Efficiency and Extent of Transmission Use", *Int. Trans. on Electrical Energy Systems*, Vol. 23, No. 8, pp. 1335-1364, November 2013.
- [15] F. Li, "Continues Locational Marginal Price (CLMP)", *IEEE Trans. on Power Systems*, Vol. 22, No. 4, pp. 1638-1646, 2007.
- [16] PJM Training Materials (LMP 101), PJM.
- [17] M. Alomoush, "auctionable Fixed Transmission Rights for Congestion Management," *Ph.D. Dissertation, Dept. Elect. Comput. Eng., Inst. Technol., Chicago, IL*, May 2000.



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