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RESEARCH ARTICLE

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An approach to locational marginal price based zonal congestion management in deregulated electricity market

Abstract Congestion of transmission line is a vital issue and its management pose a technical challenge in power system deregulation. Congestion occurs in deregulated electricity market when transmission capacity is not sufficient to simultaneously accommodate all constraints of power transmission through a line. Therefore, to manage congestion, a locational marginal price (LMP) based zonal congestion management approach in a deregulated electricity market has been proposed in this paper. As LMP is an economic indicator and its difference between two buses across a transmission line provides the measure of the degree of congestion, therefore, it is efficiently and reliably used in deregulated electricity market for congestion management. This paper utilizes the difference of LMP across a transmission line to categorize various congestion zones in the system. After the identification of congestion zones, distributed generation is optimally placed in most congestion sensitive zones using LMP difference in order to manage congestion. The performance of the proposed methodology has been tested on the IEEE 14-bus system and IEEE 57-bus system.

Keywords locational marginal price (LMP), distributed generation, pool market, deregulated electricity market, congestion management

1 Introduction

With the deregulation of electrical utilities around the world, the way of operation of the power system throughout the years has been changed. Earlier in the regulated power system, the three components of power system, i.e., the generation, transmission and distribution systems, were in control of a single utility. The operation of power system was easier with the main objective of minimizing system generation cost. But, under the new environment, the three components are operated and managed separately and come under the control of different utilities. A new competitive paradigm has evolved which introduces a number of private players for the operation, management and ownership of these components. Although competition has not yet been introduced into the transmission system due to some limitations, it has been introduced into the generation and distribution sides. The new market paradigm is driven by market forces and strict environmental conditions. Besides, the competitive electricity market leads to an increased volume of electricity trading between GENCOS and DISCOS. Although most of the electricity trading is completed through pool, there are situations in which GENCOS and DISCOS undergo bilateral or multilateral transactions of electricity which may cause unpredicted amount of power flow through some transmission corridors. This may lead to the congestion of transmission corridors due to its inability to accommodate all the transactions and thus will hamper system security. Since, in deregulated electricity market, the electricity price is governed by the economics of supply and demand balance, any deviation from this due to congestion may take away the benefits which the deregulation guarantees. Therefore, management of congestion plays a vital role in achieving the economics of deregulated electricity market. In vertically integrated utility where the three components of power system are owned, managed and operated by a single utility, the management of congestion is easier and simpler. But in deregulated electricity market, the scenario is opposite to that of vertically integrated systems. Therefore, congestion management becomes somewhat more complex in deregulated electricity market.

A number of congestion management techniques have been reported [1,2]. Since a congestion management technique for a particular electricity market structure may

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or may not be suitable for other market structures due to differences in their topology, the congestion management techniques are market structure specific. The various congestion management techniques which suit to different electricity market structures have been discussed [3]. The congestion alleviation using optimal rescheduling of generator is one of the basic congestion management methods and has been utilized in deregulated electricity market [4,5]. The generator sensitivity to the flow of power on congested line has been used for both optimally selecting the generators for rescheduling and amount of power output required to increase or decrease by these selected generators. Prioritization of electricity transaction and curtailment strategies related to it is explored [6]. In Ref. [7], different transaction curtailment strategies have been discussed and a factor called willingness-to-pay to avoid curtailment has been introduced. Several other congestion management methods using flexible AC transmission (FACTS) devices and distributed generation have also been reported. Congestion management based on optimal placement of FACTS devices has been discussed [8] wherein congestion is mitigated by optimally placing TCSC and TCPAR considering real power flow performance index. In Ref. [9], locational marginal price (LMP) has been utilized for the optimal placement of TCSC. LMP has also been used in Ref. [10] for optimally placing and sizing the distributed generation in pool electricity market.

Since congestion zone identification in a system reduces the burden involved in computation of re-dispatch and transaction curtailments required for congestion alleviation, several zonal/cluster based congestion management techniques have also been proposed. In Ref. [11], different congestion zones or clusters have been identified by computing the congestion distribution factor in which, type 1 cluster is the most sensitive. A zonal congestion management based on real and reactive congestion distribution factors has been proposed [12]. In Ref. [13], zonal based congestion management technique has been adopted using AC transmission distribution factors.

In this paper, a new zonal based congestion management approach in deregulated electricity market is proposed based on LMP. Since LMP gives an economic signal [14] and the difference of LMP of buses across a line is the measure of the degree of congestion of that line, it can be effectively and reliably utilized in deregulated electricity market. Hence, in this paper, the zones are defined based on the difference of the LMP of the buses across a line. The most congestive zone is that which groups the buses connecting the lines having high and non-uniform LMP difference across them while the other zones have buses connecting the lines of low and uniform LMP difference across them. After the identification of zone most sensitive to congestion, the congestion is managed by optimally placing the distributed generation in that zone using LMP difference.

2 Problem formulation

To evaluate the nodal prices of electricity, the problem is formulated as an optimal power flow (OPF) formulation in pool based deregulated electricity market, having no demand bid, with the objective of minimization of generation cost of electricity given by Eq. (1) while other constraints are satisfied.

$$\text{Minimize}\sum_{k=1}^{n_g} C_k(P_{G_k}), \tag{1}$$

where n_g is the total number of generating units and $C_k\ (P_{G_k})$ is the cost of electricity generation of kth generating unit given as quadratic cost function,

$$C_k(P_{G_k}) = a_k(P_{G_k})^2 + b_k(P_{G_k}) + c_k, \tag{2}$$

where a_k, b_k and c_k are the cost coefficients and P_{G_k} is the amount of electricity generation of kth unit.

The above objective functions are subjected to following constraints.

1) Power balance constraint at each node

$$P_m - P_{G_m} + P_{D_m} = 0,\ m = 1,2,\cdots,n_b, \tag{3}$$

$$Q_m - Q_{G_m} + Q_{D_m} = 0,\ m = 1,2,\cdots,n_b. \tag{4}$$

2) Generator operating limit constraint

$$P_{G_k}^{\min} \leqslant P_{G_k} \leqslant P_{G_k}^{\max},\ k = 1,2,\cdots,n_g, \tag{5}$$

$$Q_{G_k}^{\min} \leqslant Q_{G_k} \leqslant Q_{G_k}^{\max},\ k = 1,2,\cdots,n_g. \tag{6}$$

3) Line flow constraints

$$F_L \leqslant F_L^{\max},\ L = 1,2,\cdots,n_L. \tag{7}$$

4) Bus voltage limit

$$V_m^{\min} \leqslant V_m \leqslant V_m^{\max},\ m = 1,2,\cdots,n_b, \tag{8}$$

where n_b is the total number of system buses, $P_{G_k}^{\min}$ and $P_{G_k}^{\max}$ are respectively the minimum and maximum real power output limits of kth generator, $Q_{G_k}^{\min}$ and $Q_{G_k}^{\max}$ are respectively the minimum and maximum reactive power output limits of kth generator, F_L denotes the flow of power on transmission line L connected between bus m and bus n due to accommodation of all contracts, $F_L^{\max}$ is the power flow limit of line L connected between bus m and bus n, n_L denotes the total number of lines, and $V_m^{\min}$ and $V_m^{\max}$ are respectively the minimum and maximum voltage limits at bus m.

The optimization of the objective function incorporating all constraints is done using Lagrangian method. The Lagrangian function of the optimization problem including all constraints in objective function is written as

$$\begin{aligned}\mathcal{L} = & \sum_{k=1}^{n_g} C_k(P_{G_k}) + \sum_{m=1}^{n_b} \lambda_{p_m}(P_m - P_{G_m} + P_{D_m}) \\ & + \sum_{m=1}^{n_b} \lambda_{Q_m}(Q_m - Q_{G_m} + Q_{D_m}) + \sum_{L=1}^{n_L} \mu_L(F_L - F_L^{\max}) \\ & + \sum_{k=1}^{n_g} \mu_{G_k}^{-}(P_{G_k}^{\min} - P_{G_k}) + \sum_{k=1}^{n_g} \mu_{G_k}^{+}(P_{G_k} - P_{G_k}^{\max}) \\ & + \sum_{k=1}^{n_g} \mu_{G_k}^{-}(Q_{G_k}^{\min} - Q_{G_k}) \sum_{k=1}^{n_g} \mu_{G_k}^{+}(Q_{G_k} - Q_{G_k}^{\max}) \\ & + \sum_{m=1}^{n_b} \mu_{V_m}^{-}(V_m^{\min} - V_m) + \sum_{m=1}^{n_b} \mu_{V_m}^{+}(V_m - V_m^{\max}),\end{aligned} \tag{9}$$

where λ and μ are Lagrangian multipliers vectors associated with equality constraints and inequality constraints respectively obtained by OPF solution. The interior point method is used for OPF solution in Matlab environment.

3 LMP

The LMP at a bus is defined as the marginal cost of supplying the next increment of electric energy at a specific bus while considering the generation marginal cost and the physical aspects of the transmission system [15,16]. It gives an economic signal to the electricity market and is, therefore, preferred these days in most of the electricity market to manage congestion. It consists of three components — marginal energy component which remains the same for all buses, loss component, and congestion component. Therefore, the LMP at bus m can be written as

$$\mathrm{LMP}_m = \mathrm{MEC}_m + \mathrm{LC}_m + \mathrm{CC}_m, \tag{10}$$

where MEC_m is the marginal energy component, LC_m is the loss component and CC_m is the congestion component of LMP at bus m. Since the marginal energy cost remains the same at all buses, for small loss (negligible increase in loss) the LMP difference between two buses gives the congestion cost. Hence, the LMP difference between two buses across a line gives the measure of the degree of congestion in that line and can be effectively utilized for managing congestion in deregulated electricity market. The congestion cost for an individual line is calculated by multiplying the LMP difference across a line with the power flow on that particular line and is given as

$$\mathrm{CC}_L = \mathrm{LMP}_L \cdot F_L,\ \ L = 1,2,\cdots,n_L. \tag{11}$$

The total congestion cost of the system is calculated as

$$\mathrm{TCC} = \sum_{L=1}^{n_L} \mathrm{LMP}_L \cdot F_L, \tag{12}$$

where CC_L is the congestion cost for individual line, LMP_L is the LMP difference across line L, F_L is the power flow in line L, and TCC is the total congestion cost of the system.

4 Congestion zone identification

In this paper, congestion zones for a given system are defined based on the LMP difference across a line. Congestion zones are nothing but a group of buses connected across a line, selected based on the LMP difference across that line given by Eq. (13).

$$\Delta\mathrm{LMP}_L = \mathrm{LMP}_m - \mathrm{LMP}_n,\ \ L = 1,2,\cdots,n_L, \tag{13}$$

where $\Delta\mathrm{LMP}_L$ is the LMP difference across line L, and LMP_m and LMP_n are the LMPs at bus m and bus n, respectively.

The zone having a high and non-uniform LMP difference between buses across a line has been identified as zone of type 1 and the zones having a low and uniform LMP difference between buses across a line are defined as zone of type 2 and so on. Therefore, the transactions in the congestion zone 1 have a critical and unequal impact on the LMP. The other congestion zones are farther from the interested congested line. Hence, any transaction outside the most sensitive zone 1 will have little effect on line flow and LMP. Therefore, the identification of zones of congestion will lead to the reduction of computational burden involved in congestion management schemes required for the transmission loading relief.

5 Zonal congestion management using optimal placement of distributed generation (DG)

In the new era of competitive electricity market, the demand side approach for congestion management is getting more attention as it mitigates congestion more effectively and efficiently, thereby, improving the reliability and security of the power system [17]. Since DGs can be generally located in load pockets as negative power demand and can also respond quickly to the changing conditions of competitive electricity market, they are attracting an augmented interest in restructured power system operation and planning. Their strategical location and operation in system reduce losses, improve voltage profile, defer system upgrades and improve reliability of the system. In addition, they are easy to install and simple to operate. With all these benefits, DGs are extensively used for congestion management in restructured power system and hence are considered in this paper, too.

After the identification of the most sensitive congestion zone 1, the congestion is alleviated using optimal placement of DG in that zone. Due to the congestion of a line, the LMP at the buses is high and non-uniform throughout the system, thereby, increasing the system generation and congestion cost. With the implementation of DG for congestion management, the LMP of the buses becomes more uniform throughout the system so that the LMP difference across a line decreases, thereby, decreasing the system generation cost as well as the system congestion cost. Hence, LMP can be effectively used to identify the optimal location for DG placement in order to alleviate congestion efficiently. A simple method that can be employed to place DG optimally for congestion alleviation is the highest LMP method [10]. But it may give rise to a situation that the congestion increases in the network. Therefore, this method cannot be reliably used for DG placement. Another method which is based on the difference of LMPs of two buses across a line, known as the "LMP difference method," can be utilized more efficiently and reliably to place a DG optimally in order to mitigate congestion.

Therefore, in this paper, the DG location is also identified based on the LMP difference across a line. The buses across a line having the highest LMP difference in the most sensitive congested zone 1 are the potential locations for DG placement. Since the buses having the more generation capacity than their demand have low LMPs, in order to reduce the search space for DG placement, the bus having the generation greater than the demand is not considered for an optimal location of DG. Once the search space for DG placement is reduced, their potential locations are identified among the remaining buses in a congestion zone based on LMP difference. The bus connecting a line having the highest LMP difference among them is identified as the optimal location for DG. Hence, the optimal location of DG placement is identified based on LMP difference while satisfying Eq. (14).

$$P_{G_k} \leqslant P_{D_k},\ k = 1,2,\cdots,n_{\mathrm{b}}. \quad (14)$$

Utilizing Eq. (13) as well as Eq. (14), the best possible location for DG placement in order to alleviate congestion is obtained.

6 Results and discussion

The robustness of the proposed methodology is analysed on IEEE 14-bus system and IEEE 57-bus system. The load and network data for both the systems are taken from the footnote 1). The generator data for the IEEE 14-bus system is taken from Ref. [9] while the generator data for the IEEE 57-bus system is taken from Ref. [18]. Since a number of DG technologies with varying operating characteristics are nowadays available in the market, assumptions are made for cost characteristics of DG in order to accommodate this variation [19]. The cost characteristic for DG is taken from Ref. [20] and is considered to inject only real power of 5 MW.

6.1 Results for IEEE 14-bus system

Tables 1 to 4 show the results for the IEEE 14-bus system. Table 1 shows the LMP difference across different lines obtained from the OPF solution. It shows that the LMP difference across line 1 to line 7 is high and non-uniform as compared to other lines. Therefore, these lines are more prone to congestion as compared to other lines. Hence, line 1 to line 7 being the most congestion sensitive lines, the buses connecting them are considered to be grouped in zone 1 (the most congestion sensitive zone) while the buses connecting remaining lines are grouped in zone 2 as their LMP difference is low and uniform as listed in Table 2. The identification of zones based on LMP difference is also illustrated in Fig. 1.

A load flow analysis of the IEEE 14-bus system indicates that lines 1 (connected between bus 1 and 2) and line 3 (connected between bus 2 and 3) are congested. The power flow in line 1 is 64.09 MW while that in line 3 is 67.97 MW, which are above their transfer limit. Both these lines lie in the most sensitive congestion zone.

After the identification of the most sensitive congestion zone 1, the congestion is managed by optimally placing the DG on the bus of that particular zone. The buses across lines in congestion zone 1, having a high LMP difference, are the potential locations for DG placement with the condition that the generation at that bus is less than their demand, thereby, satisfying Eq. (14). Tables 1 and 2 show that lines 1, 2, 3 and 6 in zone 1 have high LMP differences and are more prone to congestion. Therefore, the busses connecting these lines are the potential locations for DG placement in order to alleviate congestion. But, since buses 1, 2, and 3 do not satisfy Eq. (14), these buses cannot be considered for DG placement. Only buses 4 and 5 in the most sensitive congestion zone 1 are considered for DG placement. DG can be allocated to these buses separately and the best location for congestion management can be found. But in a larger system, it would be difficult and time consuming to separately place the DG at all potential bus locations and find the optimal location. Therefore, a method for the optimal location of DG based on LMP difference is adopted such that it could be found in no time. From the potential locations for DG placement, the line connecting bus 4 (line 6) has the highest LMP difference. Therefore, DG is placed at bus 4 for congestion management and the results are presented in Table 3, which depicts that both the system generation cost and the system congestion cost decrease when DG is implemented in the most sensitive congestion zone.

1) Power system test case archives. 2004, http://www.ee.wasington.edu/research/pstca

Table 1 LMP difference across lines for IEEE 14-bus system

Line No.	From bus to bus	LMP difference/($\$\cdot MWh^{-1}$)	Line No.	From bus to bus	LMP difference/($\$\cdot MWh^{-1}$)
1	1–2	11.5	11	6–11	1.0
2	1–5	12.5	12	6–12	0.6
3	2–3	16.7	13	6–13	0.9
4	2–4	3.7	14	7–8	0.0
5	2–5	1.0	15	7–9	0.1
6	3–4	13.0	16	9–10	0.1
7	4–5	2.6	17	9–14	0.3
8	4–7	0.2	18	10–11	0.8
9	4–9	0.3	19	12–13	0.3
10	5–6	0.4	20	13–14	1.3

Table 2 Congestion zone identification based on LMP difference for IEEE 14-bus system

Congestion zones	Bus No.
Zone 1	1, 2, 3, 4, and 5
Zone 2	6, 7, 8, 9, 10, 11, 12, 13, and 14

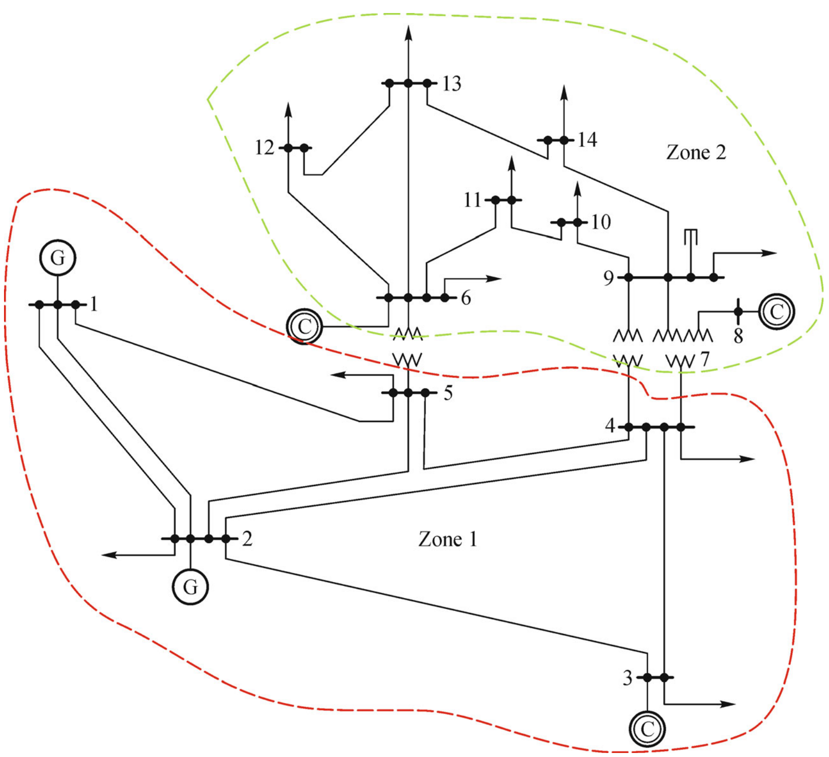

Fig. 1 Congestion zone identification based on LMP difference for IEEE 14-bus system

Table 3 Results for IEEE 14-bus system

DG location	System generation cost /($\$\cdot h^{-1}$)	System congestion cost /($\$\cdot h^{-1}$)
Without DG	6353.65	2116.84
Bus 4	6193.58	2071.95

Table 4 Generation cost for IEEE 14-bus system in different zones

Congestion zones	DG location	System generation cost/($\$\cdot h^{-1}$)
Zone 1	Bus 4	6173.58
Zone 1	Bus 5	6192.82
Zone 2	Bus 14	6197.10

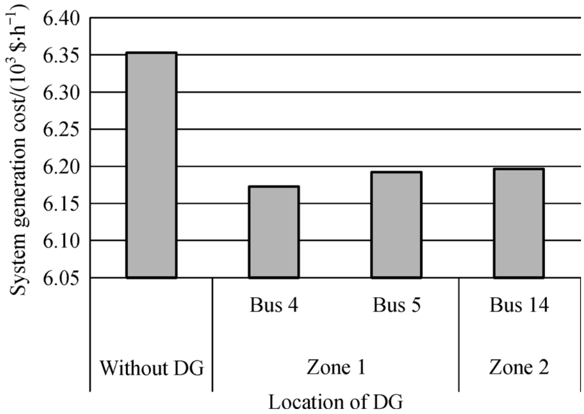

Fig. 2 Generation cost for IEEE 14-bus system

After optimally placing DG in the most sensitive congestion zone 1, the load flow analysis indicates that the power flow on congested lines 1 and 3 reduces to 48.93 MW and 34.72 MW respectively which are well within their respective transfer limits. Thus the congestion is effectively alleviated with the optimal placement of DG in the most sensitive congestion zone.

Besides, to analyse the effectiveness of zonal based congestion management using LMP difference, the DG is placed to other potential location of congestion zone 1, i.e., bus 5 as well as the buses of congestion zone 2 which are considered less prone to congestion as compared to congestion zone 1 and the results are tabulated in Table 4. The minimum generation cost due to placement of DG at different buses in congestion zone 2 is obtained for bus 14. Therefore, only bus 14 is considered in this paper for analysing the effectiveness of the proposed methodology.

Table 4 reveals that the DG allocation at bus 4 in congestion zone 1 has less generation cost as compared to when it is placed at bus 5. It also reveals that the DG allocation in congestion zone 1 has low system generation cost for both the potential locations of DG placement as compared to when it is placed at any bus locations of congestion zone 2. Hence, the identification of congestion zones and placement of DG based on LMP difference provides management of congestion in a better and easier manner, as illustrated in Fig. 2.

6.2 Results for IEEE 57-bus system

Tables 5 to 8 demonstrate the results for the IEEE 57-bus system. Table 5 shows the LMP difference obtained across each line of the IEEE 57-bus system based on which congestion zones are identified. The LMP difference across lines connecting bus 17 is high. Therefore, the lines connecting nearby buses also have high and non-uniform LMP. Hence, bus 17 and nearby buses are grouped in congestion zone 1 in which the lines connecting these buses are most sensitive to congestion, as listed in Table 6.

The other zones have buses connecting the lines of less LMP difference across them. Zone 2 also has buses connecting lines of high LMP difference, but these lines have more uniform LMP difference. Therefore, zone 2 is considered to be less sensitive to congestion. The remaining zones have buses connected to line with low and uniform LMP difference across them and, hence, are less sensitive to congestion as compared to congestion zone 1 and 2. The different congestion zone is illustrated in Fig. 3.

A load flow analysis of IEEE 57-bus system indicates that line 17 (connected between buses 1 and 17) is congested. The power flow on line 17 is 79.19 MW which is above its transfer limit.

After the identification of congestion zones, the optimal location for DG placement is identified based on the LMP difference in congestion zone 1. Since bus 1 and bus 12 do not satisfy Eq. (14), the remaining buses in congestion zone 1 are potential locations for DG placement. But the lines connecting buses 1 and 17 have the highest LMP difference, and the bus is also among the potential locations. Therefore, bus 17 is selected as an optimal location for DG placement in order to manage congestion. The results are given in Table 7, which shows that both the system generation cost and the system congestion cost decrease significantly when DG is implemented in the most sensitive congestion zone.

After optimally placing DG in the most sensitive congestion zone 1, the load flow analysis shows that the power flow on congested line 17 reduces 39.23 MW which is well within its transfer limit. Thus, the congestion is effectively alleviated with the optimal placement of DG.

Also, to analyze the effectiveness of the proposed methodology in larger systems, the DG is placed in other congestion zones and the results for its location of minimum system generation cost in a particular zone are shown in Table 8. Table 8 reveals that the placement of DG in the most sensitive congestion zone 1 has less system generation cost as compared to when it is placed in other congestion zones. Hence, the allocation of DG in the most sensitive congestion zone 1 with the proposed methodol-

Table 5 LMP difference across lines for IEEE 57-bus system

Line No.	From bus to bus	LMP difference /($·MWh^{-1})	Line No.	From bus to bus	LMP difference /($·MWh^{-1})	Line No.	From bus to bus	LMP difference /($·MWh^{-1})
1	1–2	0.55	28	14–15	1.08	55	41–42	2.63
2	2–3	3.04	29	18–19	2.32	56	41–43	0.3
3	3–4	1.16	30	19–20	0.56	57	38–44	0.75
4	4–5	1.35	31	21–20	0.2	58	15–45	0.46
5	4–6	1.63	32	21–22	0.03	59	14–46	0.21
6	6–7	8.09	33	22–23	0.27	60	46–47	1.11
7	6–8	8.79	34	23–24	3.5	61	47–48	0.33
8	8–9	4.36	35	24–25	0.39	62	48–49	0.41
9	9–10	3.26	36	24–25	0.39	63	49–50	0.59
10	9–11	2	37	24–26	0.64	64	50–51	1.62
11	9–12	4.83	38	26–27	1.29	65	10–51	0.09
12	9–13	3.1	39	27–28	0.14	66	13–49	1.09
13	13–14	0.15	40	28–29	0.35	67	29–52	0.16
14	13–15	1.23	41	7–29	1.42	68	52–53	0.3
15	1–15	3.83	42	25–30	1.03	69	53–54	4.78
16	1–16	5.37	43	30–31	1.22	70	54–55	4.98
17	1–17	21.58	44	31–32	1.87	71	11–43	0.1
18	3–15	0.25	45	32–33	0.18	72	44–45	2.28
19	4–18	0.06	46	33–32	1.35	73	40–56	0.9
20	4–18	0.06	47	32–35	0.52	74	56–41	3.78
21	5–6	0.29	48	35–36	0.7	75	56–42	1.15
22	7–8	16.88	49	36–37	0.48	76	39–57	0.27
23	10–12	1.57	50	37–38	1.24	77	57–56	0.75
24	11–13	1.1	51	37–39	0.07	78	38–49	1.18
25	12–13	1.73	52	36–40	0.01	79	38–48	0.77
26	12–16	1.42	53	22–38	0.53	80	9–55	1.19
27	12–17	14.8	54	11–41	0.41			

Table 6 Congestion zone identification based on LMP difference for IEEE 57-bus system

Congestion zones	Bus No.
Zone 1	1, 12, 13,14, 15, 16, 17, 44, and 45
Zone 2	6, 7, 8, 9, 52, 53, 54, and 55
Zone 3	2, 3, 4, 5, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, and 29
Zone 4	10, 11, 30,31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 46, 47, 48, 49, 50, 51, 56, and 57

ogy manages congestion more effectively and efficiently as compared to its allocation in other congestion zones, as illustrated in Fig. 4.

7 Conclusions

In this paper, a novel approach to zonal congestion management in pool market is proposed. The identification of different congestion zones is based on the LMP difference between buses connecting a line. The most sensitive congestion zone is one which groups the buses connecting lines of high and non-uniform LMP difference across them. The congestion is managed by optimally allocating the DG in the most sensitive congestion zone. The optimal allocation of DG is also based on LMP difference. To analyze the effectiveness of zonal based congestion management, the DG is also allocated to other

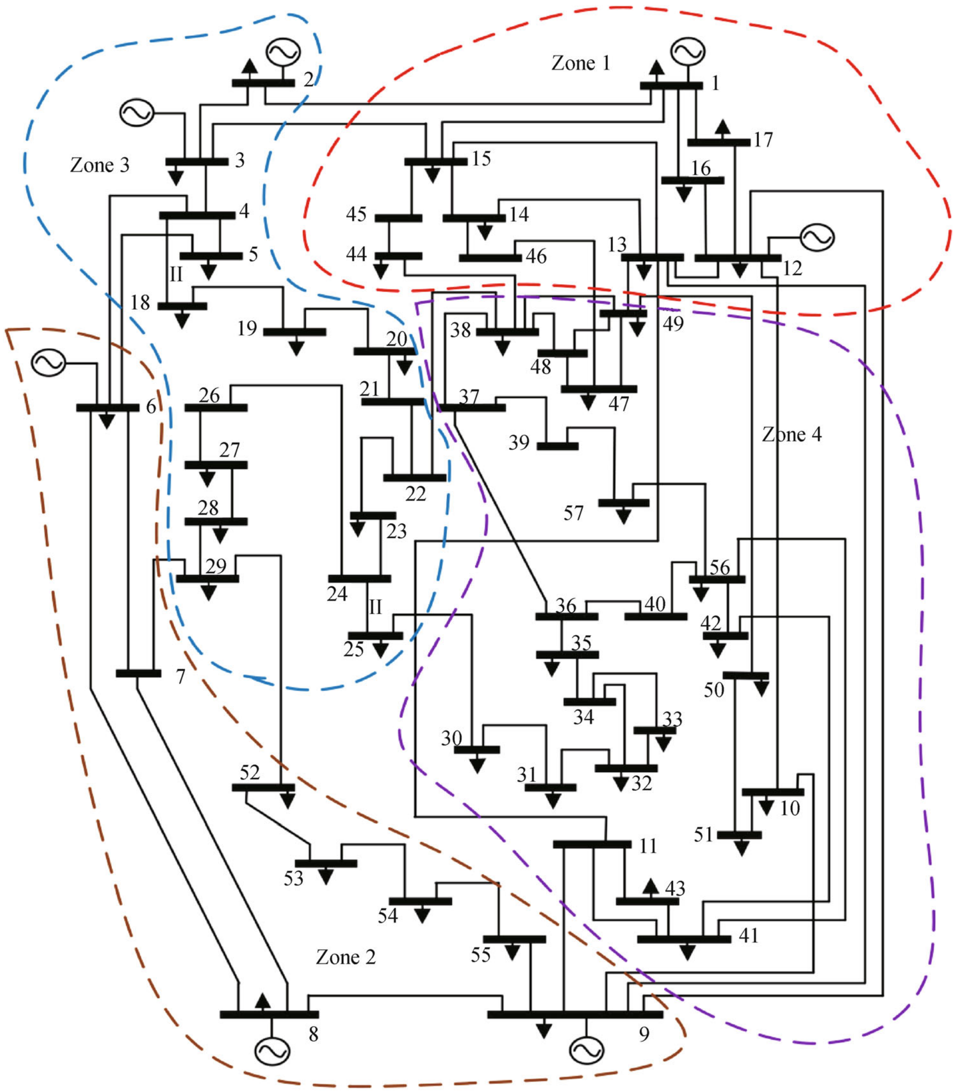

Fig. 3 Congestion zones identification based on LMP difference for IEEE 57-bus system

Table 7 Results for IEEE 57-bus system

DG location	System generation cost /($·h^{-1})	System congestion cost /($·h^{-1})
Without DG	41920.8	4610.11
Bus 17	41638.6	3584.39

Table 8 Generation cost for IEEE 57-bus system in different zones

Congestion zones	DG location	System generation cost /($·h^{-1})
Zone 1	Bus 17	41638.56
Zone 2	Bus 7	41665.97
Zone 3	Bus 23	41670.85
Zone 4	Bus 56	41671.9

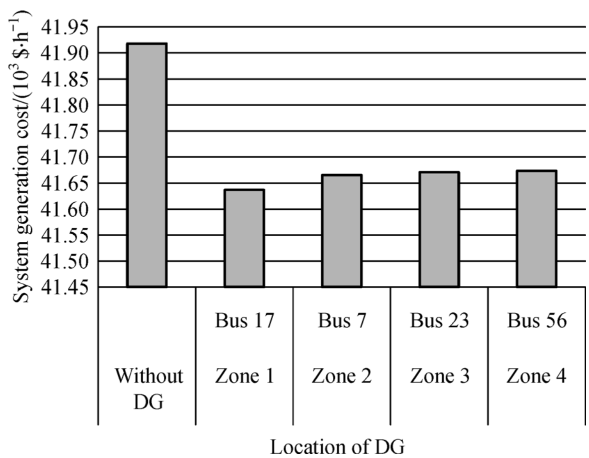

Fig. 4 Generation cost for IEEE 57-bus system

zones which are considered as less sensitive to congestion. The robustness of the proposed methodology is tested on IEEE 14-bus system and IEEE 57-bus system and it is found to be efficient for both small and large power systems.

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