Advanced in Engineering and Intelligence Systems

Journal Web Page: https://aeis.bilijipub.com

Electricity market management through optimum installation of distributed generation sources and optimum placement based on LMP and ISC

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Highlights

- Novel method based on LMP for optimum placement of DG in electricity market.
- Considers system cost index and line congestion for DG sizing and placement.
- LMP and customer payment indices used to determine desirable DG locations.
- SCI criterion utilized for selecting optimum buses based on LMP and CP ranking.
- Simulation on modified IEEE 9-bus system demonstrates cost reduction and congestion management.

Article Info

Received: 15 January 2022
Received in revised: 07 February 2022
Accepted: 24 February 2022
Available online: 07 April 2022

Keywords

Optimum generation
Local margin price
Optimum power flow
Electricity market
Congestion management

Abstract

In this paper, a novel method based on LMP with the title of system cost index is presented for optimum placement of distributed generation (DG) sources in the electricity market based on optimum power flow. Along with optimum placement, the optimum size of these sources is also calculated. Desirable locations are determined for optimum DG order based on local margin price (LMP). The LMP index is defined in the Lagrange coefficient of active power flow in each bus. Another index used to find desirable locations for DG placement is the customer payment (CP) index, which can be calculated for each bus by multiplying LMP in busload. In the presented method, in addition to considering two fundamental problems, i.e., system cost and line congestion, in the electricity market, the determination of the optimum size of DG is a criterion that is introduced as the system cost index (SCI). The optimum buses are selected based on considering the SCI criterion; two methods of bus ranking based on LMOP and CP are used. In LMP ranking, the bus with the highest LMP and the bus with the highest consumed power is chosen in the CP method. The proposed method is implemented on the modified IEEE 9-bus system. The simulation results suggest that the proposed method satisfies the engineering aspect of operation and the economic aspect of the process in the market. The optimum placement of DGs in the market environment leads to a decrease in the system cost and management of line congestion.

Nomenclature

Indices		δ_i	*Angle of voltage of ith bus*
LMP	*Local Margin Price*	v_i	*Voltage of ith bus*
DG	*Distributed Generation*		
CP	*Customer Payment*	***Variables***	
SCI	*System Cost Index*	G_{ij}	*Conductance of Line ij*
OPF	*Optimal Power Flow*	B_{ij}	*Susceptance of Line ij*
GOA	*Grasshopper Optimization Algorithm*	Q_D	*Demand Reactive power*
VSI	*voltage stability index*	Q_G	*Generator Reactive Power*

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CS	*Cuckoo Search*	a	*Price factor*
$GENCO$	*Generation Company*	b	*Price factor*
$DISCO$	*Distribution Company*	c	*Price Factor*
Parameters		S_{ji}^{max}	*Maximum mixed power limit*
C	C	v_i^{max}	*upper limit of voltage at bus i.*
B	B	v_i^{min}	*lower limit of voltage at bus i.*
P_D	P_D	λ	*energy marginal section in reference bus*
P_{DG}	P_{DG}	$\lambda_{L,i}$	*section associated with losses*
P_G	P_G	$\lambda_{C,i}$	*section associated with congestion*

1. Introduction

In peak load times, when the electricity price is high, the DG can act as a price risk coverage mechanism in the best manner [1]. In the region in which line congestion is high, which leads to higher LMP, DG is very valuable. The DG can effectively decrease the demand through line congestion management and local load supplement in such conditions. DG placement should be based on the size and location [2]. The place in which the DG is supposed to be installed must be optimal in maximization of profit point of view. To study the feasibility of placing the DG in a power system, many methods are presented [3]. Investment capacity planning of distributed generation in a competitive electricity market from the distribution company's point of view is investigated in [4], [5]. In [6], a method is presented to optimally design DGs connected to the grid whose size and type can meet the local need of the power system. In addition, many optimization tools containing artificial intelligence methods like genetic algorithms, taboo search methods, and other methods for optimum placement of DGs are used. An optimization method that uses a genetic algorithm to minimize investment costs and losses in one planning period is presented in [7]. A genetic algorithm is used in [8] to determine the extent of DG penetration to minimize the total operating costs, including variable and fixed costs. A method is introduced in [9] for optimum DG placement to reduce the active power losses in the power distribution system using the genetic algorithm. Optimum placement of DG for minimization of losses or loading the line using second-order and gradient methods are introduced in [10]. A technique based on repetition is presented in [11] for optimum DG placement to reduce losses that provide a valid approximation. Analytical method for determination of optimum place of DG to minimize power losses is studied in [12]. Optimum placement and determination of the extent of DG penetration based on a market standard design using LMP to minimize generation cost are proposed in [13]. Optimum placement of DG using a method based on the Lagrangian approach and traditional OPF and OPF with voltage stability limit is introduced in [14]. The mentioned methods in the papers above merely study the system technically and do not consider present conditions in the electricity market, such as congestion management and local pricing.

In [15], the costs of transmission and production of DGs unit are considered as the objective function to achieve the optimal place and size of distributed generations. In this paper, the benefit maximizing of DGs owners is the main important factor to solve this problem. A novel analytical model as zero bus flow to the placement of DGs in distributions networks is proposed in [16]. The various load modeling in two different distribution networks is considered in this paper. The main factors of the objective function are containing; power loss, economic factors, and benefits. In [17], a hybrid intelligence algorithm is used to reduce the power loss by solving the optimal site and size of the DGs problem. This method used Grasshopper Optimization Algorithm (GOA) and Cuckoo Search (CS) technique. Here, the GOA optimization behavior is upgraded by utilizing the CS technique. Ref [18] is proposed a new model with some objective function factors such as; Loss Sensitivity, Power Stability Index (PSI), and proposed voltage stability index (VSI) for optimal location and sizing of distributed generation (DG) in the radial distribution network. Power Loss Sensitivity and PSI methods, voltage stability index, and load growth are the main contributions of this paper. A novel fuzzy-based model for optimal size and site DGs is proposed in [19]. Minimizing total electrical energy losses, total electrical energy cost, and total pollutant emissions produced are the objective functions of this problem.

In this paper, DG placement in a whole electricity sale based on investment and having concentrated dispatching is studied in which DG is considered as a negative load. The DG placement problem is stated to minimize system cost, reducing and managing system line congestion. The proposed method places the DG in the system is based on the local price of busses. In order to apply the power market factors, this paper considers both local margin price and customer payments factors for the increase of the performance of the proposed model. Also, this paper considers the economic parameters besides the operation factors to achieve the optimal point for both factors. The

IEEE standards system is used to study the proposed method to confirm the achieved results of the paper.

To sum up, the main contributions of this paper could be written as follows;

- Considering optimal placement and sizing of distributed generations in power market-based systems with using optimal power flow
- Considering local margin price as a factor of power market factor besides customer payment factor
- Applying the fast optimization method to find the optimal place and size of distributed generations
- Considering operation and economic factors in the optimal model to achieve the best point
- Analysis of both operation and economic factors after placement to illustrate the method's robustness.

2. Problem statement

In this paper, the traditional OPF algorithm for minimization of costs is changed in such a way that it includes demand-side offers in addition to generation-side offers. LMP is defined as the Lagrange coefficient in the OPF load balance equation. The basic OPF is based on system cost minimization and evaluates each grid bus's generation, demand, and price dispatching. Node prices that are obtained this way are determining indices of chosen busses for DG placement. Through changing generation dispatching, the placement makes it possible for the demand to be supplied at the least price. In order to make it possible for the DG owners to have more profit from the provided power to the grid, the size and location of the DG should be chosen so that LMP is decreased and profit is maximized. As LMP is increased, the profit is reduced, and the profit might be negative.

2.1.Minimizing the system cost

The objective function of the problem has defined the difference between the profit vector, which is presented by the purchaser (DISCO), the offer vector, presented by the seller (GENCO), and the cost function, which the DG owner presents. The introduced SCI index in this paper minimizes the objective function.

$$\text{SCI} = \min \sum_{i=1}^{N} (C_i(P_{Gi}) - B_i(P_{Di})) + C(P_{DGi}) \tag{1}$$

As it can be seen, minimization of the system cost is composed of two multi-layer. The inner block is used by the independent operator (ISO) of the system. In this state, the owner of DG is one of the market participants located outside of this block and presents its layer size. Next, the independent system operator executes the OPF considering the grid limits. The purpose of this OPF is to minimize the overall cost of the system. This block allows for general control and coordination between generation and transmission. The limits considered for the above objective function include equality constraint and inequality limits that will be studied in the following.

2.2. Equality constraints

The electrical energy transmission grid is modeled using the power equilibrium equation in each group. The sum of input active and reactive powers should equal the sum of active and reactive powers.

$$P_i = P_{Gi} + P_{DGi} - P_{Di} = v_i \sum_{j=1}^{N} [v_j\{G_{ij} \cos(\delta_i - \delta_j) + B_{ij} \sin(\delta_i - \delta_j)\}] \tag{2}$$

$$Q_i = Q_{Gi} - Q_{Di} = v_i \sum_{j=1}^{N} [v_j\{G_{ij} \sin(\delta_i - \delta_j) - B_{ij} \cos(\delta_i - \delta_j)\}] \tag{3}$$

2.3. Equality constraints

Generation constraints: there is a maximum and minimum generation capacity for power plants, and because of technical and economic reasons, the power plants cannot exceed these values.

Generation constraints for active and reactive powers are defined as upper and lower limits:

$$P_{Gi}^{\min} \le P_{Gi} \le P_{Gi}^{\max} \tag{4}$$

$$Q_{Gi}^{\min} \le Q_{Gi} \le Q_{Gi}^{\max} \tag{5}$$

Transmission line capacity constraint: this constraint shows the maximum power passing through a transmission line in a given condition. This constraint can be based on thermal and stability considerations. Thermal constraints are usually considered for short lines. The constraint below investigates the power in both ends of the transmission line to not exceed the allowed range.

$$S_{ij} \le S_{ij}^{\max} \tag{6}$$

$$S_{ji} \le S_{ji}^{\max} \tag{7}$$

Bus voltage constraint: these constraints guarantees that bus voltage stays within the allowed limit.

$$v_i^{\min} \le v_i \le v_i^{\max} \tag{8}$$

Where;

N: the number of system buses.

PGi: active power generation at bus i.

PDi: active power demand at bus i.

PDGi: active power generation by DG at bus i.

Bi(PDi): the buyer's profit function at bus i:

$$B_i(P_{Di}) = a_{Di} + b_{Di}P_{Di} + c_{Di}(P_{Di})^2 \quad (9)$$

Ci(PGi): the seller's proposed price at bus i:

$$C_i(P_{Gi}) = a_{Gi} + b_{Gi}P_{Gi} + c_{Gi}(P_{Gi})^2 \quad (10)$$

C(PDGi): DG cost function at bus i:

$$C(P_{DGi}) = a_{DGi} + b_{DGi}P_{DGi} + c_{Gi}(P_{DGi})^2 \quad (11)$$

Vi: voltage at bus i.

δi: power angle at bus i.

Bij: susceptance of line ij.

Gij: conductance of line ij

QGi: reactive power generation at bus i.

P_{Gi}^{max} and P_{Gi}^{min}: upper and lower limits of active power of generator at bus i.

Q_{Gi}^{max} and Q_{Gi}^{min}: upper and lower limits of reactive power of generator at bus i.

v_i^{max} and v_i^{min}: upper and lower limits of voltage at bus i.

S_{ij} and S_{ji}: transmitted mixed power from bus i to bus j and vice versa

S_{ji}^{max} and S_{ij}^{max}: mixed power limit associated with lines ij and ji.

Note that in the basic OPF PDGi = 0, for the buses with load PGi = 0, and for the buses with generator PDi = PDGi = 0 are assumed.

3. Method

To integrate the generation and demand offer vectors, the basic OPF calculates the different electricity prices for the other nodes of the grid. Node prices are obtained through the Lagrange coefficient of equality constraints. Incremental functions for generation company's offers and decremental functions for consumer's offers are considered marginal cost or offeror's profit. The existing difference between prices is due to practical constraints of line and losses in the system. There are two types of ranking to determine the chosen node for placement of DG, including the order based on LMP and the scale based on the consumer's payment.

3.1.Ranking based on LMP

LMP is the Lagrange coefficients that are related to the active power flow equations in each system bus. [20]. In general, LMP has three sections: the energy marginal section, which is the same for all buses, the losses marginal section, and a section associated with congestion. Concerning the node price of active power at bus i, LMP can be obtained using the equation below:

$$\mathrm{LMP}_i = \lambda + \lambda \frac{\partial P_L}{\partial P_i} + \sum_{ij=1}^{N_L} \mu L_{ij} \frac{\partial P_{ij}}{\partial P} \quad (12)$$

$$\mathrm{LMP}_i = \lambda + \lambda_{L,i} + \lambda_{C,i} \quad (13)$$

Where:

λ: energy marginal section in reference bus, which is the same for the of the buses.

λL,i: section associated with losses.

λC,i: section associated with congestion.

Hence, node prices at each bus are a function of location and vary with losses marginal section and congestion section. Higher LMP at a bus suggests that the active power flow of that node has higher effects on the SCI index of the system. In other words, it shows how much generation is affected by load. Hence, it is clear that to minimize the SCI index of the system, injecting active power to the associated bus will lead to a reduction in the overall costs of the system. Hence it is assumed that the DG injects active power to the associated bus; buses with larger LMP have higher priority for installation of the DG. Therefore, buses with loads are sorted in descending order of LMP size, and as a result, the first node in this sorting is the best choice for DG placement.

$$\mathrm{LMP} = \begin{bmatrix} LMP_1 \\ LMP_2 \\ LMP_3 \\ \vdots \\ LMP_n \end{bmatrix} \quad (14)$$

Where n is the number of buses with a load.

3.2. Ranking based on CP

Consumer's payment index (CP) is defined as the multiplication of LMP and size of the load and used as another criterion in the determination of chosen buses for placement of DG.

$$\mathrm{CP} = \mathrm{LMP}_i \times \mathrm{Load}_i = \begin{bmatrix} \mathrm{CP}_1 \\ \mathrm{CP}_2 \\ \mathrm{CP}_3 \\ \vdots \\ \mathrm{CP}_n \end{bmatrix} \quad (15)$$

Where suggests an amount that the consumer of the bus I should pay to receive electricity. This ranking is derived from the fact that DG placement can be studied from two points of view. One is when the price is high, and the load is relatively low, and the other is when the price is relatively low, but the load is high. Ranking based on consumer's payment (CP) is based on the second state in which the overall payment in the associated buses has more priority than a high price. Using this index for placement of DG, LMP is reduced, which leads to the increased strength of large-scale consumers because the amount they pay in the presence of DG is less than that in the absence of the DG. Placement is done using several cost functions that are considered for the DG. DG placement decreases LMP, and DGs with higher operating costs than LMP does not have a chance to be present in the system. It is expected that the DGs with less operation cost than the generation company's operation cost will have more penetration in the market, and the DGs with higher operating costs will have less penetration.

4. Simulation results

In this section, the impact of the presence of DG on the system is studied, and in the following, applying SCI objective function and its minimization in two separate scenarios, we explain the resulted outcomes. It should be noted that to achieve optimum results from DG placement in the electricity market; there is a procedure conducted in three steps:

First step: choosing the type of DG. Second step: determining the suitable bus for placement of the DG, wherein this paper is conducted through the two LMP and CP criteria. Third step: choosing the optimum power of DG for managing line congestion and reducing the system cost, wherein this paper, it is realized through minimization of SCI index.

4.1.DGs used in the electricity market

Extensive use of DG in the electricity market has led to an increase in DG technology level and variety. Popular DGs in the electricity market are diesel turbines with a generation capacity of under 10 MW, gas turbines with 10- MW, and microturbines with 30-200 kW. With respect to the required power range in the studied market, we chose the gas turbine in this paper [21]. Each DG has unique characteristics with respect to its specific cost function; hence, to utilize each DG, its cost function should be analyzed first. In Table 1, the data associated with seven different gas turbine DGs can be seen, and in the following, the cost curve and incremental cost of each DG are plotted. Optimum DG for utilization in the electricity market is chosen accordingly.

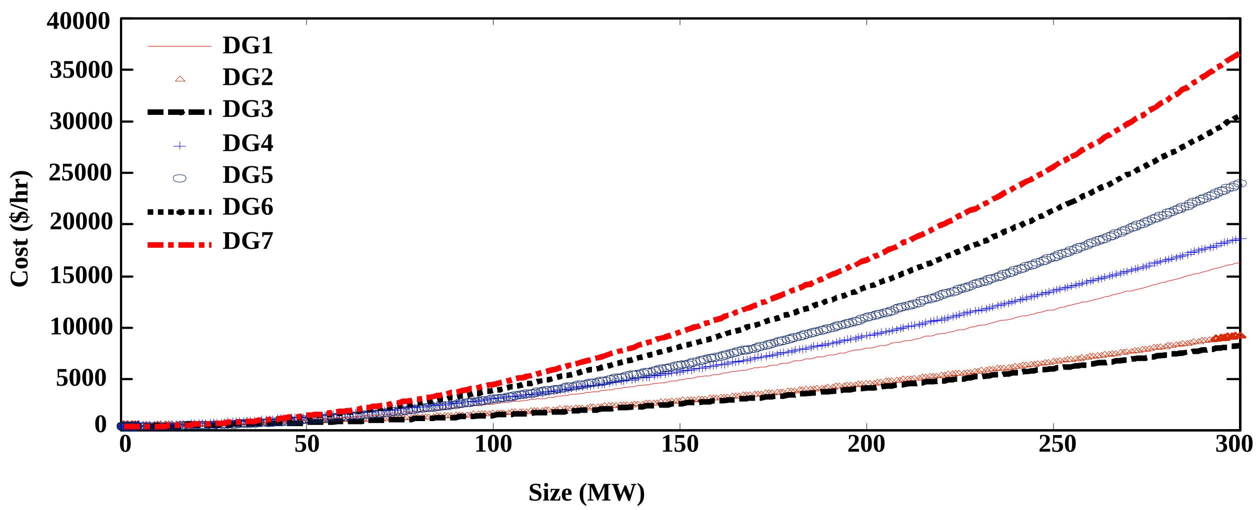

Fig. 1. DG curve functions in terms of their nominal power.

The cost function of each DG is defined using $C(P_{DG}) = a_{DG} + b_{DG} \times P_{DG} + c_{DG} \times (P_{DG})^2$. The DG curve functions in terms of their nominal power are shown in Fig. 1.

Table 1. Specification of studied DGs.

DG ID	c_{DG}	b_{DG}	a_{DG}
DG1	0.150	9.0	100
DG2	0.090	1.9	550
DG3	0.075	3.8	300
DG4	0.170	10	340
DG5	0.260	0.9	295
DG6	0.330	1.5	350
DG7	0.400	1.1	305

The incremental cost curve of DGs in terms of their nominal power is shown in Fig. 2. With respect to these two figures, it can be seen that their costs saturate faster than other DGs because of the smallest parameters in DG2 and DG3. Since parameter is close in DG1 and DG4, their incremental cost has a linear and fixed slope, and since incremental costs in DG5, DG6, and DG7 have steep and incremental slop, DG1 and DG2 are chosen as optimum DGs. The impact of each one is investigated in two separate scenarios on a modified IEEE 9-bus grid.

4.2. *modified IEEE 9-bus grid*

The total power that the system should provide is 400 MW. The basic state's system cost index state is SCI=7718.23 $/hr, and since buses 4 and 9 do not have generators, all of them can replace DGs. The results of minimizing the studied index in the absence of DG in the system and the LMP of each bus are provided in Table 2. The generated power in generators are P(G1)=145MVA, P(G2)=140MVA, and P(G3)=121MVA, whereas their flow in the system, according to Figure 3, leads to stability of congestion and overload in lines 1-4 and 4-9. As can be seen, the overload in lines 1-4 is approximately 90%.

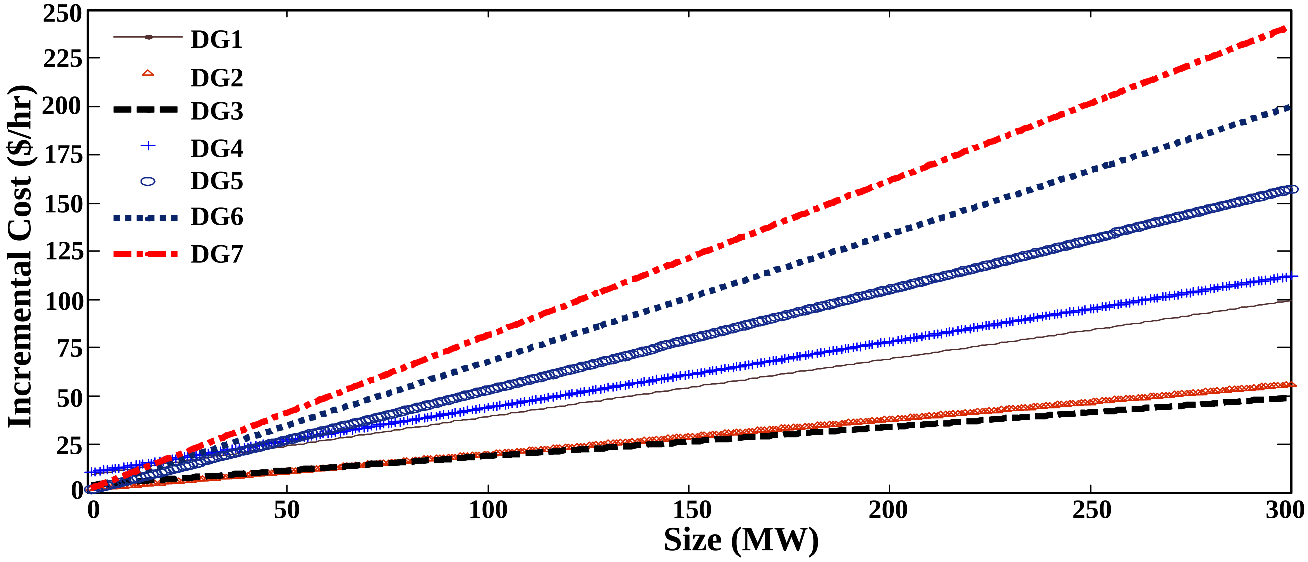

Fig. 2. DG incremental cost curve in term of nominal power.

Table 2. Simulation results of a basic system.

Bus	PD(MW)	QD(MVAR)	LMP($/MVA)
1	0	0	33.632
2	40	0	24.994
3	0	0	33.484
4	10	0	33.632
5	90	30	34.231
6	25	0	33.484
7	100	35	34.074
8	10	0	34.004
9	125	50	35.291

If no fault occurs, this system can tolerate this congestion. But congestion of 137% has put lines 4-9 in critical condition. One of the reasons for this condition is the end bus of lines 4-9, i.e., bus 9.

4.3. *selecting proper bus for placement of DG*

According to Table 3, the maximum consumed power of the system is at bus 9, which is P_D=125MW. As can be seen, the maximum LMP of the system is associated with bus 9, which is 35.291$/MVA.

CP criterion in this bus is 4411.375$/h. Hence, bus 9 meets the requirements of both CP and LMP, which was detailed in the previous section. As a result, compared to other buses without generation in the system, it is more suitable for the placement of DG.

Table 3. selecting proper bus based on CP and LMP criteria.

Rank	Bus	P_D(MW)	LMP($/MWh)	CP($/h)
1	9	125	35.291	4411.375
2	5	90	34.231	3080.79
3	7	100	34.074	3407.4
4	8	10	34.004	340.04
5	4	10	33.632	336.32
6	6	25	33.484	837.1

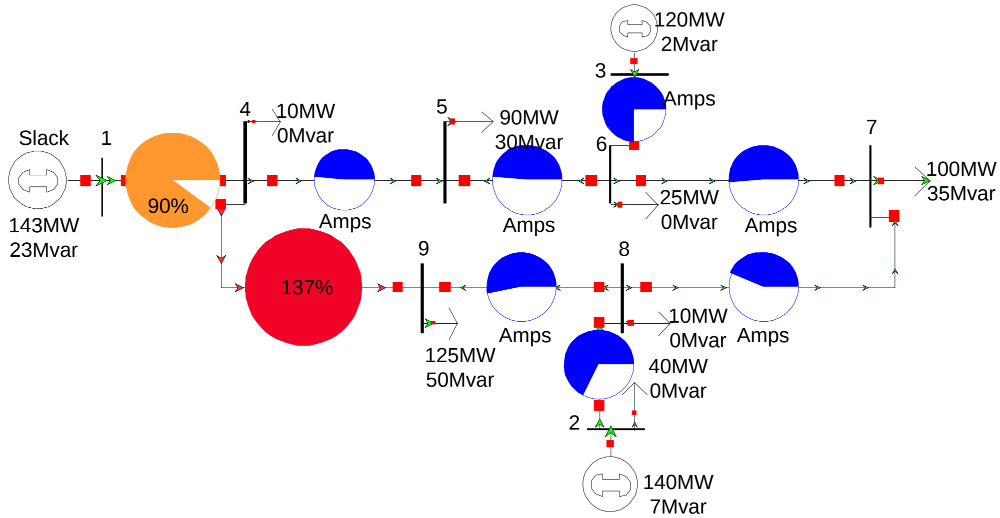

Fig. 3. system line congestion in basic state.

Therefore, DG1 and DG4, which were chosen as optimum DGs in the previous section, are placed at bus 9 in two separate scenarios. Their effect on the system is analyzed, and the optimum size of each DG is obtained through congestion reduction of lines 4-9 and minimization of SCI index criterion. Finally, optimum DGs and their sizes are chosen by comparing the results of the two scenarios.

4.4. DG1 placement

As mentioned before, the cost function of DG1 is $C(P_{DG1}) = 0.15 + 9 * P_{DG1} + 100 * (P_{DG1})^2$, hence, DG1 is placed at bus 9 first, and its size is determined based on the minimization of SCI index. Since the chosen type for DG is a gas turbine, its nominal power variation is defined in a range of 10-100MW. SCI index variation in terms of nominal power is shown in Fig. 4.

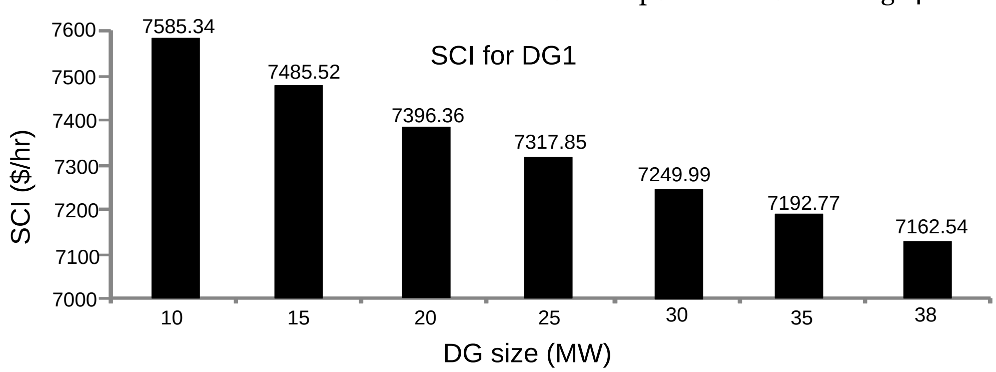

Fig. 4. SCI index variation in term of nominal power

As shown in Fig. 4, in power generation of P_{DG1}=38MW, SCI has a minimum value of 7163$/h, which is far less than that of the basic state (in the basic state, SCI is 7718.23 $/hr). Hence, it can be concluded that the placement of DG1 at bus 9 reduces system cost. Fig. 5 shows the congestion of lines 4-9 with the placement of DG1 at bus 9.

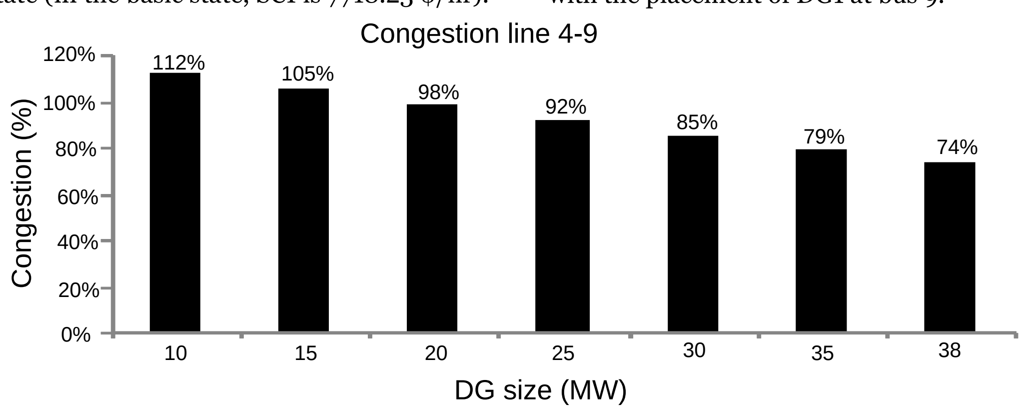

Fig. 5. Congestion of lines 4-9 in terms of the nominal power of DG1

As can be seen, as the nominal power of the DG increases, congestion of this line decreases, and with nominal power of 38MW, based on the mentioned criterion, line congestion will be 74 percent which is less than 80. According to Fig. 5, placement of the DG at bus 9 will reduce congestion of lines 4-9, and consequently, congestion of lines in the presence of the DG will be as shown in Fig. 6.

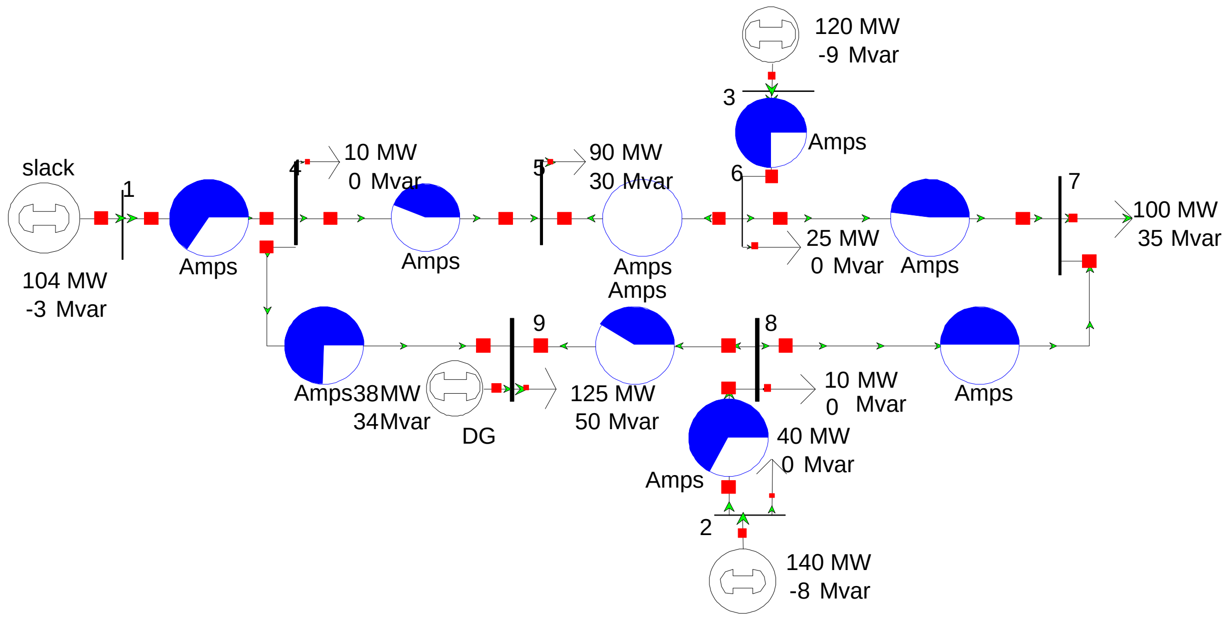

Fig. 6. Congestion of the system lines in the presence of the DG.

Comparing the LMP of system buses according to Figure 7, it can be seen that in addition to a reduction of system SCI index and line 4-9 congestion, the presence of DG1 leads to reduction of LMP of system buses and their closeness to each other, which shows increased competition in the market and reduction of system cost in the presence of DG. As can be seen, using DG1, LMP of bus 9 has decreased from 35.291$/MWh to 29.507$/MWh.

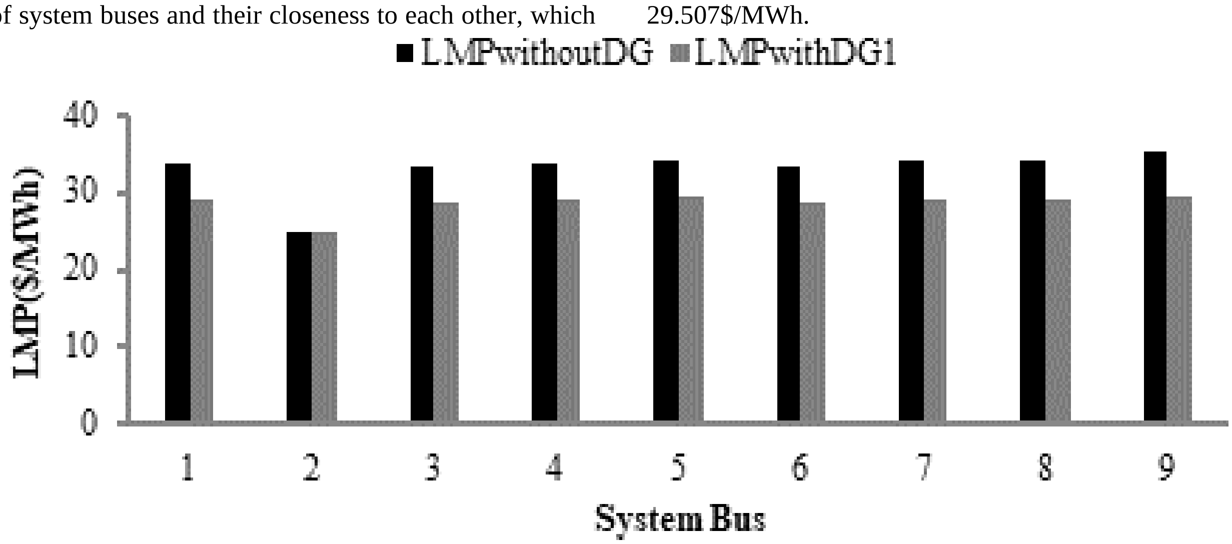

Fig. 7. system LMP comparison in basic state and presence of DG1.

4.5. DG4 placement

In this section, the placement of DG4 with cost function is conducted at bus 9, and like in the previous section, the effect of DG4 on the system is analyzed. SCI index variation in terms of the nominal power of DG4 is shown in Fig. 8.

$$C(P_{DG4}) = 0.17 + 10 * P_{DG4} + 340 * (P_{DG4})^2 \qquad (16)$$

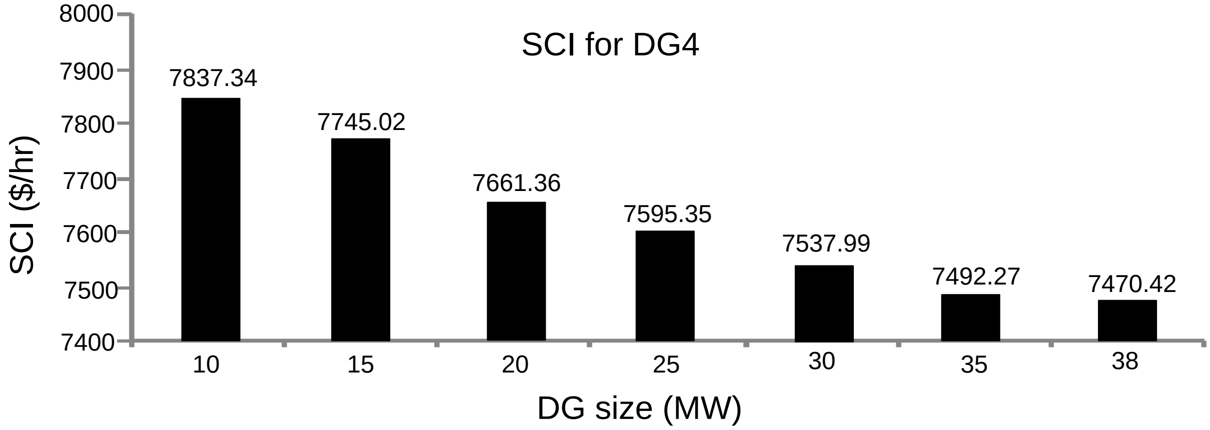

Fig. 8. SCI index variation in terms of the nominal power of DG4.

As can be seen, at the power of PDG4=38MW, SCI index has a minimum value of 7470.42$/h, which is lower than that of the basic state (in basic state SCI= 7718.23$/hr).

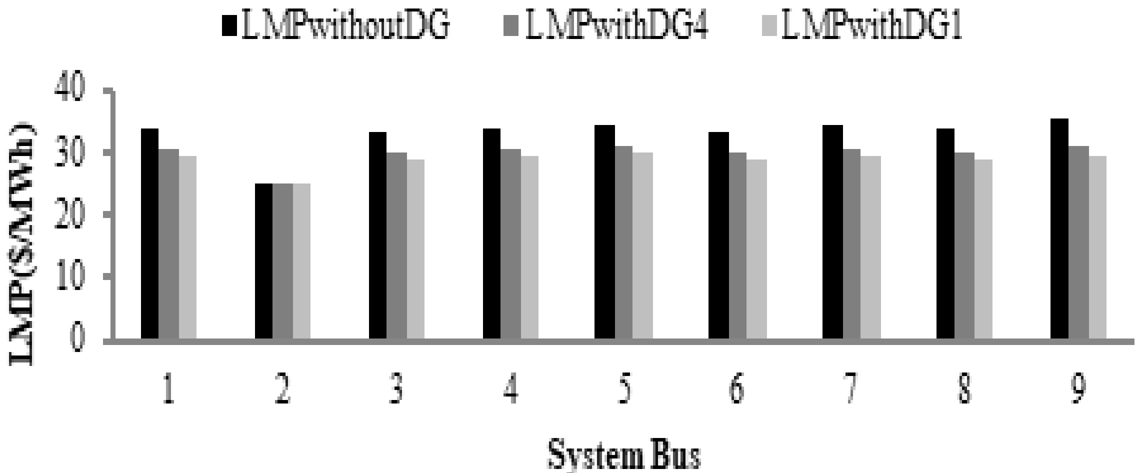

Fig. 9. system LMP comparison in basic state and in the presence of DG1 and DG4.

Hence, it can be said that DG4 placement at bus 9 leads to congestion reduction in line 4-9 (similar to figures 5 and 6) and, consequently, reduction of the system cost. Also, the LMP of system buses will be as shown in Fig 9.

As can be seen, placing DG4 at bus 9, its LMP has decreased from 35.291$/MWh to 30.771$/MWh. Placement of DG4 at bus 9 leads to congestion reduction in lines 4-9 (similar to Figs. 5 and 6) and, consequently, reduction of system cost and LPM of system buses, as shown in Fig. 9. It also should be noted that the effect of DG1 on the system LMP is higher than DG4. If the system SCI index is compared in the presence of both DGs, similar to what is done in Fig. 10, it can be seen that DG1 had a higher impact on the reduction of system costs. Hence, DG1 is chosen as the optimal option for placement in the system.

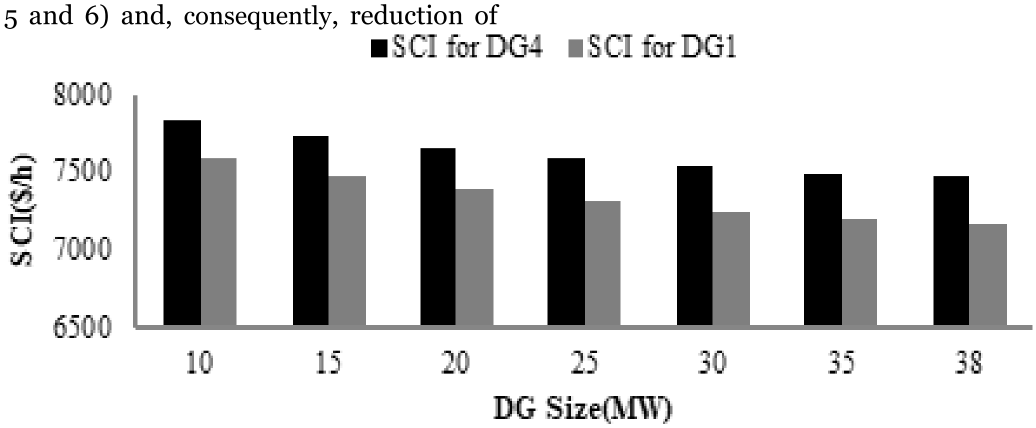

Fig. 10. SCI index variation in terms of power in DG1 and DG4.

5. Conclusions

In this paper, a new method based on OPF is presented for the optimum placement of DG in the electricity market. In the optimum placement of DG, the size and cost function of DG are considered. The type of DG is determined based on the cost function and incremental cost of DG. Studies suggest that a DG with the lowest cost function will be saturated faster than other DGs and cannot supply the required power by the grid. A DG with the highest incremental cost will increase system cost in supplying the consumed power. In the presented method, in addition to considering two fundamental problems, i.e., system cost and line congestion, in the electricity market, the determination of the optimum size of DG is a criterion that is introduced as the system cost index (SCI). The DG size optimization problem is solved by minimizing this index as the objective function, leading to system cost reduction and line congestion management. In choosing the optimum bus of a system for placement of DG, considering the SCI criterion, two methods of bus ranking based on LMOP and CP are used. In LMP ranking, the bus with the highest LMP and the bus with the highest consumed power is chosen in the CP method. Simulation results suggest that utilization of the two indexes above can decrease the price of all buses with load and increase the consumers' profit. In order to apply the power market factors, this paper considered both local margin price and customer payments factors for the increase of the performance of the proposed model. The IEEE standards system is used to study the proposed method to confirm the achieved results of the paper.

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