Cost-based Optimal Distributed Generation Planning with Considering Voltage Depended Loads and Power Factor of Distributed Generation

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ABSTRACT
If determination of location and size of Distributed Generation (DG) are applied accurately, the DG's ability will improve the network situation and reduce operation costs. In this paper, various market conditions are considered to maximize the benefit of DG's presence and make a trade off among advantages of DG, network situation, and Distribution Company (DISCO) owners. To determine the optimal location and size of DG, two methods of the cost minimization and the nodal pricing are combined. In addition to evaluating the impact of parameters such as variation of energy price and load on objective function, effect of these parameters on location and size of DG is considered. To confirm the results, impact of loads which are dependent on voltage and variation of the power factor of the DG units is applied and then effect of power factor on optimal location and size of DG is shown. A method is proposed for convergence of different results which is caused by different power factors. To observe long-term impact of the DG's presence in the network, a load growth for five years is considered annually. Study is carried out on IEEE30 bus test circuit.

KEYWORDS: Optimization, Voltage Depended Loads, DG Placement and Sizing, Loss Reduction, Power Factor of DG.

1. INTRODUCTION

DG presence in power market is dependent on costs, subsidization, and technology of DG. The main aims of DG are improvement of voltage profile, loss reduction, market prices changes, imbalances omission between supply and demand, power quality improvement, planning problem solution, and postponement of updating expenditure. In addition, DG minimizes expenditure such as installation, maintenance, and the purchase of energy from Transmission Company (TRANSCO). DG may be used for one or two mentioned advantages.

The rate of losses in transmission line and voltage of each bus are affected by location, size, and power factor of DG. Considering the share of line losses, time-variant loads, and time-invariant loads in each bus, cost of electrical energy in each bus is determined. Furthermore, calculation the location and size of DG is done in order to improve voltage profile [1]. The impact of line losses and distance of each bus from TRANSCO cause a contract between DG owners and DISCO owners [2]. Although DG has positive impact on improvement of voltage profile, reduction of losses, and prevention of feeder overload, other factors such as situation of market, and uncertainty of location and size estimation of DG cause many problems. Results show that DG can reduce the price when market price is high. DG can be used to improve feeders which have non-unique load distribution; in addition, DG reduces voltage drop and losses and solves power quality problems caused by non-unique load distribution [4]. When power factor of DG equals to power factor of demand in network, network losses will reach the minimum level. Injected active and reactive power of DG has effect on voltage profile [5]. DG is applied to solve problems such as load design, load growth, and decision which depend on market's structure and price. In Active Management, DG is used to increase profits to Distribution Network Operator (DNO) and DG's developer. Moreover, voltage drop, losses, and overloaded line are improved [6–9]. Through increasing the DG's share in power market, DG's parameters in designing has been considered enormously. The rings in secondary feeders - which are operated in radial form - decrease Energy Not Supplied

(ENS) and increase DG presence and reliability of the network [10]. There are several mathematical methods [11] and smart approaches to determine location and size of DG [12 – 17].

The buses which have highest node price and losses are the best candidates for DG's arrangement. In peak load, DG causes reduction in electrical cost in different markets [18]. There are methods such as losses weighting and comparison of cost functions for DG' cost [19, 20]. Considering subject mentioned above, in this paper is tried to place parameters in objective function which are more important in calculation of location and size of DG. Considering subject mentioned above; this paper is tried to place parameters in objective function which are more important in calculation of DG's location and size. Test system is fed with TRANSCO and DG units. Constraints include voltage profile of bus, lines capacity, and maximum capacity of installable DG with considering possible problem of network's operation.

The main contributions of this paper are:

1) New objective functions are considered based on the energy purchasing's cost from TRANSCO, the installation cost of DG, the operation and maintenance cost of DG, the losses cost, and costs caused by the voltage variation and the power factor variation.
2) Different situations for market and its changes are considered to obtain accurate results.

The rest of this paper is structured as follows: In Section 2, proposed method and mathematical modeling is presented. In Section 3, assumption of problem is provided. In Section 4, the analysis and results are presented. Finally, conclusions are drawn in the Section5.

2. METHOD DETECTION AND MATHEMATICAL MODELING

Considering the different technology of DG and its features, primary cost of installation and maintenance of DGs are various. In other hand, generation rate of active and reactive power for the different DG units are various because some technologies don't have ability to generate reactive power in wide range [5]. DISCOs have to keep the power quality delivered to customers and improve the voltage profile, and system's reliability in allowable range. Therefore, one of the most effective instruments for assisting DISCO in mentioned subject is using the DG's units. If location and size of feeders don't be determined accurately, it may have no profit and cause other problems. In this paper we have been tried to establish an accurate balance between profit of DG owners and DISCOs, considering daily variation of energy consumption, energy cost, and power factor of load. To determine optimal location and size of DG units, a cost function dependent on network losses, cost of energy purchased from TRANSCO, and installation and maintenance cost of DG are considered. In addition, to actualize the results, effect of loads dependent on voltage is applied. The reason is increase or decrease of the bus voltage changes due to change in the rate of energy consumption. This way, it is possible to put the voltage magnitude in allowable range with the annually load growth. To encourage investors to establish the DG units, it is assumed that the primary installation cost of DG units with regard to interest rate is returned to DG owners in five years. In spite of this fact, the lifespan of DG is twenty years. In the aspect of economics and security, network may be allowed to place a specified amount of DG. These constraints include allocated budget of establishment of DG units, increase of short circuit level of network, and coordination between relays. Optimization is applied in two cases: At first case, price of energy is constant and at second case, price of energy grows gradually. Cost of energy purchased from TRANSCO is modeled as twenty-four levels.

2.1. Objective function

The aim of mathematical formulation is minimizing the objective function as follows:

$$\min \quad obj(t) = C_{Inv}^{DG} + C_{O\&M}^{DG} + C_E + C_{loss} + C_V \tag{1}$$

where C_{Inv}^{DG} is the primary cost of DG investment (Eqs. 2 and 3), $C_{O\&M}^{DG}$ is cost of the DG operation and maintenance (Eq. 4), C_E is the cost of purchased energy from TRANSCO (Eq. 5), C_{loss} is cost of losses (Eqs. 6 and 7), and C_V is the benefit or loss cost caused by voltage variation of consumers (Eq. 8).

Investment cost of DG in T years and interest rate *d* is:

$$C_{Inv}^{DG} = \frac{\sum_{i=1}^{B} C_{Invi} \times P_{DGi}^{\max}}{A_{Depr} \times 8760} \tag{2}$$

where A_{Depr} is calculated as follows:

$$A_{Depr} = \left[\frac{(1+d)^T - 1}{d(1+d)^T} \right] \tag{3}$$

$$C_{O\&M}^{DG} = \sum_{i=1}^{B} C_{O\&Mi} \times S_{DGi} \tag{4}$$

Cost of purchased energy from Transmission lines is according to:

$$C_E = \sum_{i=1}^{G} C_{Pi} P_{Gi} + \sum_{i=1}^{G} C_{Qi} Q_{Gi} \quad (5)$$

$$C_{loss} = C_{pi} \times loss \quad (6)$$

To calculate losses:

$$loss = \sum_{i=1}^{n} \sum_{j=1}^{n} V_i^2 Y_{ij} \cos(\theta_{ij} + V_i V_j Y_{ij} \cos(\delta_j - \delta_i + \theta_{ij})) \quad (7)$$

$$C_V = \sum_{n=1}^{N} (1 - V_i) C_v S_{ni} \quad (8)$$

In the multi load levels mode, objective function is defined as follows:

$$\min \quad obj = \sum_{t=1}^{T} obj(t) \quad (9)$$

2.2. Constraints

The power flow equations must be satisfied in each i^{th} bus as follows [21]:

$$P_{Gi} + P_{DGi} - P_i^d = V_i \sum_{i=1}^{n} V_j (G_{ij} \cos\delta_i + B_{ij} \sin\delta_i) \quad (10)$$

$$Q_{Gi} + Q_{DGi} - Q_i^d = V_i \sum_{i=1}^{n} V_j (G_{ij} \cos\delta_i + B_{ij} \sin\delta_i) \quad (11)$$

where, P_{Gi} and Q_{Gi} are active and reactive power generated (or absorbed) in substation. V_i and δ_i show the magnitude and angle of voltage in i^{th} bus, respectively.

The voltage of each bus and its angle should be kept in the safe operating limits.

$$V_i^{\min} \le V_i \le V_i^{\max} \quad (12)$$

$$\delta_i^{\min} \le \delta_i \le \delta_i^{\max} \quad (13)$$

where, $V_i^{\max}$ and $V_i^{\min}$ are the maximum and minimum limits of voltage magnitudes at bus *i*, respectively.

The active and reactive power limits of the substation are proportional to its capacity and can be formulated as follows:

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

$$Q_{Gi}^{\min} \le Q_{Gi} \le Q_{Gi}^{\max} \quad (15)$$

Operating limits of DG units: The DG units should be operated with considering the limits of their maximum installed capacity:

$$P_{DG}^{\min} \le P^{DG} \le P_{DG}^{\max} \quad (16)$$

$$Q_{DG}^{\min} \le Q^{DG} \le Q_{DG}^{\max} \quad (17)$$

The thermal constraint of the line connected between nodes *i* and *j* should be satisfied as follows:

$$S_{ij} \le S_{ij}^{\max} \quad (18)$$

In this paper, there will be problems such as voltage drop and overload of feeders, due to load growth in coming years. DG must be localized in a way to achieve maximum profit, furthermore, the price is considered for two cases - constant price and gradually growth price. DG can be concentrated or comprised of small DGs.

3. ASSUMPTIOPNS

Test system is the modified circuit of IEEE-30bus which has approximately 300 MVA load capacity with power factor 0.92 lag. The Network is fed by buses 1 and 2 with two transmission lines. It is assumed that establishment cost of each DG unit (MW) is 0.5 million $/MW. In concentrated DG, generation price of DG is 45 $/MWh and in multi small DGs is 50 $/MWh due to few output of small DG. Price of each unit of active and reactive power is 70 and 30 $/MWh respectively. Price of purchased energy from TRANSCO for each MW is varied between 42 and 75 $/MWh. Maximum load is 140% of nominal load and minimum load is 70% of nominal load. Interest rate is 10 percentages. It is also assumed that losses cost is paid by DISCO.

4. ANALYSIS AND RESULTS

Results are investigated for four cases of market. Impact of concentrated DG or multi small DGs on determination of location and size of them is assessed. Then the network costs with and without DG is comprised. The load growth for constant load for five years is considered and role of DG is analyzed.

4.1. Evaluation of market condition and consumption during a day

4.1.1. Constant load and constant price

It is assumed that the load of network and price of energy for consumers are constant during a day. The results of determination of location and size of DG and loss calculation are shown in Table 1. Comparison among three modes: without DG, with DG in first year, and with DG in third year is carried out. Optimal amount of DG in two mentioned years are shown in Figures 1 and 2. In addition, in this case, all losses costs of active power for installed DG in first year have 52.97% reduction in comparison to without DG case.

Table 1. Comparison between results of with and without DG at a constant load and constant price

	Without DG	Year #1	Year #3
Optimal DG size	-	1MVA	1.5 MVA
DG size and location	-	1MW @bus 1	0.5MW@ bus 1 1 MW@ bus 8
Loss (MW)	10.6873	5.0262	10.6291
Benefit Due voltage profile (Average in $)	-	280.797	245.256
MW rise Cost (Average in $)	55.5296	55.3225	60.8549
Objective functions (Average in $)	2.7738×10^5	2.7729×10^5	4.0486×10^5

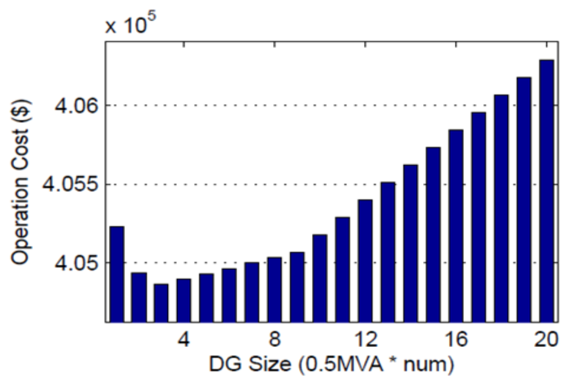

Fig. 1. Optimal measure of DG for constant load and constant price in the first year.

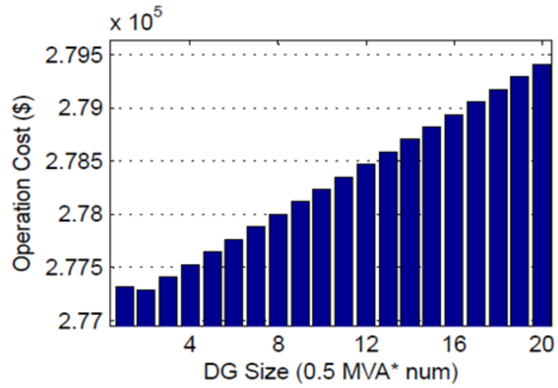

Fig. 2. Optimal measure of DG for constant load and constant price in the third year.

4.1.2. Constant load with variable price

It is assumed that the rate of demand is constant and price varies during a day. Results can be different due to an amount of price growth and duration of each time step. Results for this case are shown in Table 2. Results indicate that all loss costs of active power for installed DG have 52.74% reduction in comparison to without DG case. Optimal amount of DG is shown in figure 3.

Table 2. Comparison between results of with and without DG at a constant load and variable price

	Without DG	Year #1	Year #3
Optimal DG size	-	1MVA	4.5 MVA
DG size and location	-	1MW @bus 1	0.5MW@ bus 1 3 MW@ bus 2 1 MW@ bus 8
Loss (MW)	10.6342	5.0262	10.4654
Benefit Due voltage profile (Average in $)	-	224.6376	245.469
MW rise Cost (Average in $)	58.8647	58.7995	64.7042
Objective functions (Average in $)	2.9664×10^5	2.9652×10^5	4.3009×10^5

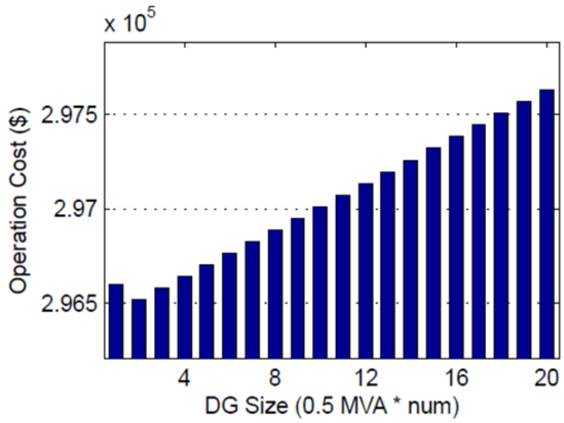

Fig. 3. Optimal measure of DG for constant load and gradually price growth

4.1.3. Variable load and constant price

For systems which their loads vary but their price energy sold to consumers is constant, following results are achieved. In this case, all loss costs for installed DG have 76.46% reduction in comparison to without DG case. Optimal amount of DG is shown in figure 4.

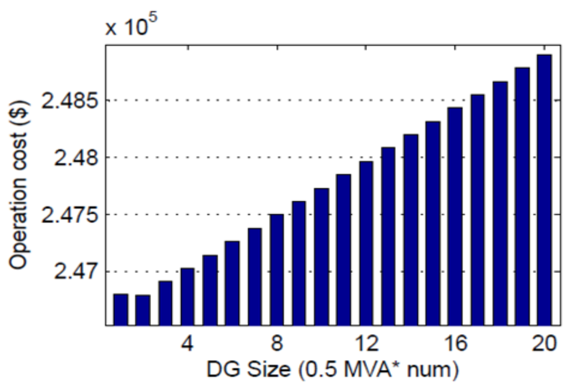

Fig. 4. Optimal measure of DG for variable load and constant price

Table 3. Comparison between results of with and without DG at a variable load and constant price

	Without DG	Year #1	Year #3
Optimal DG size	-	1MVA	1.5 MVA
DG size and location	-	1MW @bus 1	0.5MW@ bus 1 1 MW@ bus 8
Loss (MW)	10.6873	2.5159	10.6291
Benefit Due voltage profile (Average in $)	-	275.511	242.256
MW rise Cost (Average in $)	55.5296	55.3342	60.8514×1 0^5
Objective functions (Average in $)	2.4685×10^5	2.4679×10^5	4.0486×10^5

4.1.4. Variable load and variable price

This case is more realistic rather than previous cases because load varies during a day, in the other hand, distribution utilities are interested in calculation of variable price for their consumers. In this market situation, results of prices and periods of time are shown in table 4. In this case, all loss costs of active power for installed DG have 76.25% reduction in comparison to without DG case. Optimal amount of DG is shown in figure 5.

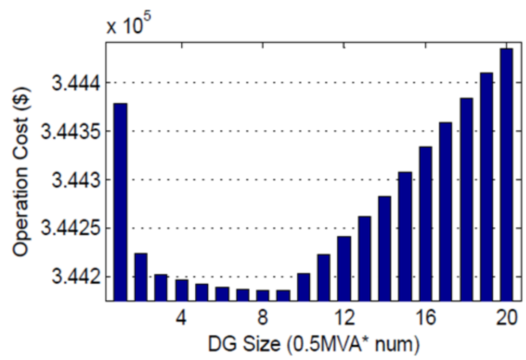

Fig. 5. Optimal measure of DG for variable load and variable price

Table 4. Comparison between results of with and without DG at a variable load and variable price

	Without DG	Year #1	Year #3
Optimal DG size	-	1MVA	4.5 MVA
DG size and location	-	1MW @bus 1	0.5MW@ bus 1 3 MW@ bus 2 1 MW@ bus 8
Loss (MW)	10.6337	2.5259	10.4654
Benefit Due voltage profile (Average in $)	-	224.6376	245.469
MW rise Cost (Average in $)	58.8651	58.7995	64.7042
Objective functions (Average in $)	2.7616×10^5	2.7607×10^5	4.3009×10^5

4.2. Annual load growth

In this paper, it is assumed that consumed electrical energy and energy price vary per annum. Load growth of network and energy price increase 5% and increment price at TRANSCO is 4%. At annual load growth, it is tried to investigate the network's situation with DG and without DG during a day. Furthermore, situation of transmitted power and bus voltage are assessed annually.

According to figures 6 and 7 when network hasn't DG, load growth causes that bus voltage becomes lower than allowable range and DISCO is obliged to place a capacitor or change cross-section of conductors. In figure 8, network doesn't have DG and through the load growth, transmitted power of feeders exceed allowable range and therefore DISCO is obliged to establish new lines or change the situation of network completely.

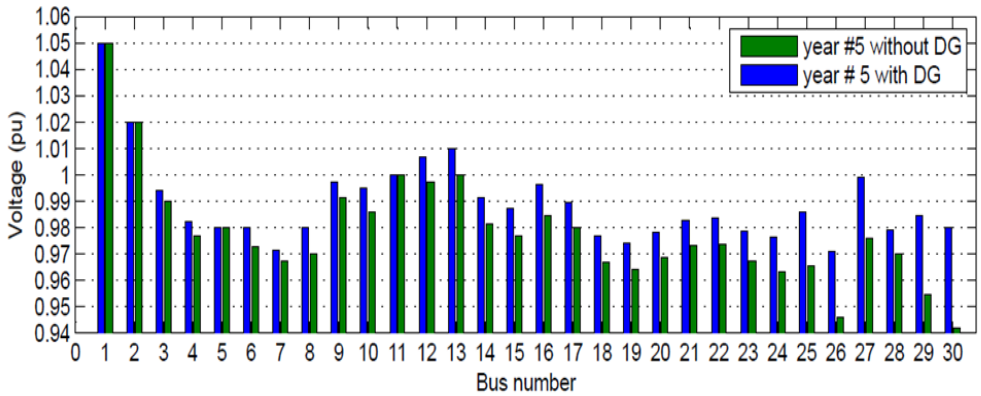

Fig. 6. The voltage profiles with DG and without DG in the fifth year.

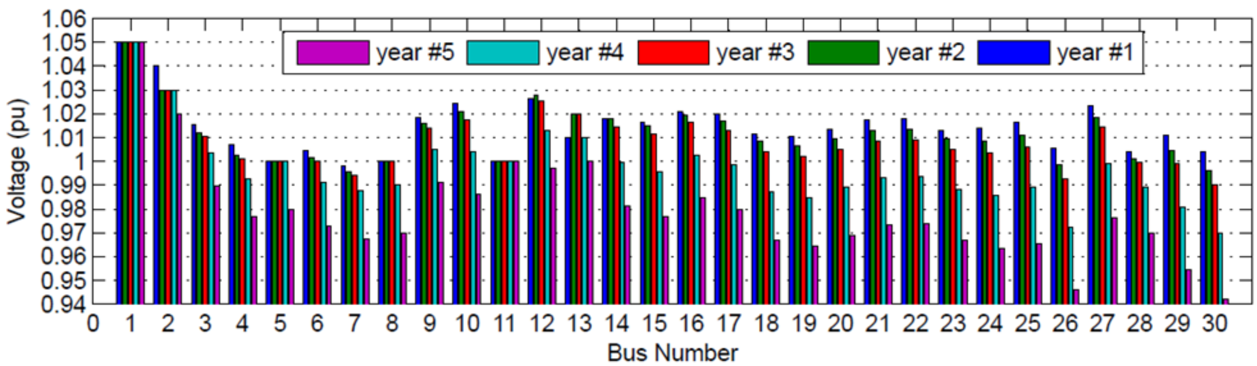

Fig. 7. The voltage profiles without DG in five years.

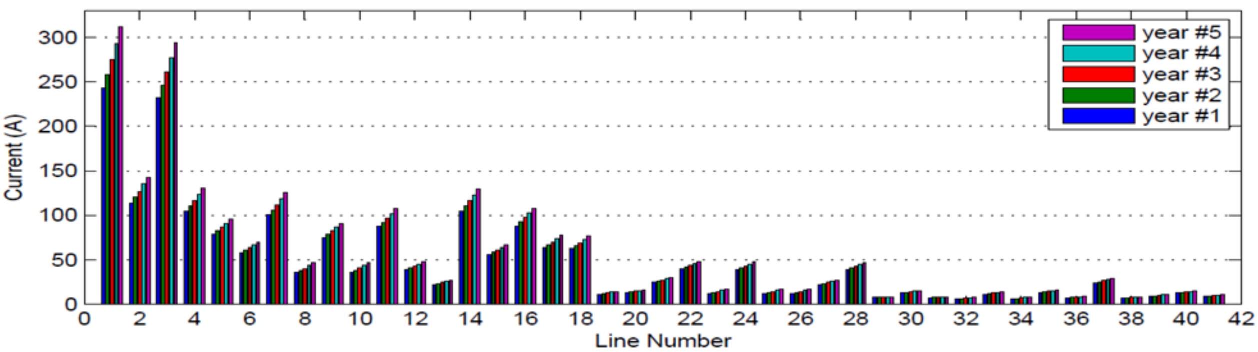

Fig. 8. The condition of transition power of feeders without DG

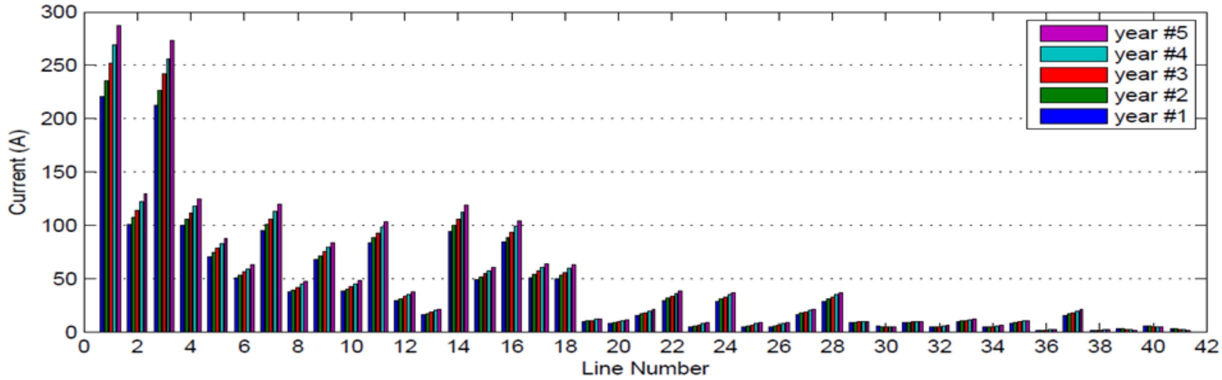

Fig. 9. The condition of transition power of feeders with DG

4.3. Impact of DG on energy price

Energy price generated by DG is technically constant during a day, but energy price purchased from TRANSCO changes every hour. Moreover, when generated electricity of DG is more expensive than electricity of TRANSCO, DG causes increase of market price; otherwise DG causes decrease of market price (figure 10). The rate of these variations is dependent on the share of DG in electrical market.

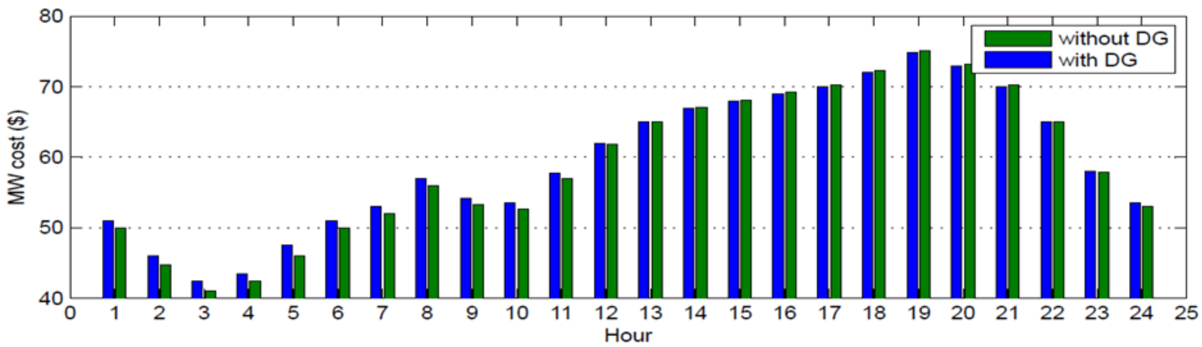

Fig. 10. Impact of DG on price of electrical market

4.4. Optimal location for DG based on node price

In aspect of DG owners, optimal bus which is appropriate to establish DG is that energy cost becomes expensive for DISCO. On the other hand, in aspect of DISCO, appropriate bus to establish DG is which operation cost has more reduction. Power transmission causes energy losses and the losses rate of power transmission for each bus will be different. DG owners are interested in delivering their energy in busses which total cost of transmission power is high for DISCO. Results of choice sequence of busses for DG owners and DISCO are shown in Table 5.

Table 5. Comparison of the bus selection

Bus number (operation Cost method)	30	30	30	30	30	30	30	30	19	26	19	30	19	19	19	30
Bus number (Node Price method)	30	30	30	30	30	30	30	30	26	19	30	19	19	26	19	30

4.5. Impact of power factor on optimal location and size of DG

To achieve realistic results, in addition to variation of loads in the rate of consumed energy, different power factors have been considered. Results show that probably optimal power factor of DISCO is different from optimal power factor of DG owners. In other words, increase in profit of DG owners causes increase in operation cost of DISCO, also generation of reactive power increase network losses. Optimal power factor of the DISCO equals to power factor of loads. Furthermore, variation in optimal power factor of DG is dependent on variation in prices of active and reactive power.

In this paper, a method is proposed to establish a balance between power factors based on cost of DISCO and DG owners. According to Table 6, optimal location and size of DGs are various for different power factors. To solve this problem and establish an accurate balance between DG and DISCO, profit of DG owners and DISCO is divided between them and therefore location and size of DG can be convergent (Table 7).

Table 6. Optimal DG's location and size in different power factors

	Cos θ						
DG's P.F.	1.000	0.975	0.950	0.925	0.900	0.875	0.850
Optimal location and size of DG	2.5MVA @2 6MVA @ 5 0.5MVA @7 1MVA @ 8 0.5MVA-@26 4MVA @30 14.5MVA	3MVA @ 2 0.5MVA @4 5.5MVA @5 0.5MVA @7 0.5MVA @8 1MVA @26 4MVA @30 15 MVA	2.5MVA@ 2 0.5MVA@ 4 5.5MVA@ 5 1MVA @ 7 0.5MVA @8 1MVA @ 26 4MVA @ 30 15 MVA	3MVA @ 2 0.5MVA@ 4 5MVA @ 5 1MVA @ 7 0.5MVA@ 8 0.5MVA@ 19 1MVA @ 26 4MVA @ 30 15.5MVA	2.5MVA @2 0.5 MVA@4 5MVA @ 5 1.5MVA@ 7 0.5MVA @8 0.5MVA@19 1 MVA @26 4MVA @30 15.5MVA	2.5MVA@ 2 1MVA @ 4 5.5MVA @5 1MVA @ 7 0.5MVA @8 0.5MVA @19 1.5MVA @26 3.5MVA@ 30 16MVA	2.5MVA @2 1.5MVA @4 5MVA @ 5 1.5MVA @7 1MVA @ 19 1.5MVA @26 3.5MVA@ 30 16.5MVA
Cost ($)	469250	496260	469260	492260	496310	496320	496280

Table 7. Optimal measure for convergence of DG's location and size (for all power factors)

Optimal size and location
3.5 MVA @ bus 19
0.5 MVA @ bus 24
1.5 MVA @ bus 26
4.5 MVA @ bus 30

5. CONCLUSION

In this paper, it is tried to emphasize the capability of DG to reduce operation costs and increase profit. The solutions of the problems related to network design and load rise are presented. DG removes or postpones upgrade cost of network. In this study, the network losses and impact of loads dependent on voltage is transformed to the money units. It is possible to add two mentioned factors to the energy cost purchased from TRANSCO, costs of construction, operation, and maintenance of DG units in order that optimization results become more reliable and realistic.

Selection of busses based on the node price is very similar to selection of busses based on operation cost of DISCOs and sometimes have identical results.

According to continuous changes in the load power factors and also in desirable power factors of DISCO and DG owners, a method is proposed to solve the difference in the selection of optimal location and size of DG. In proposed method, various conditions of market prices, load growth, and energy consumption during the day are considered. Furthermore, the impact of energy prices on market price is investigated. Regarding load growth, DG increases lifespan of feeders and solves problems caused by overload of feeders and voltage drop considerably. In addition, DG causes reduction in the operation cost of DISCO.

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