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Simultaneous placement of distributed generation and capacitors in distribution networks considering voltage stability index

Sayyid Mohssen Sajjadi [a,*], Mahmoud-Reza Haghifam [b], Javad Salehi [b]

[a] Electrical Engineering Faculty, Sahand University of Technology, Tabriz, Iran
[b] Faculty of Electrical and Computer Engineering, Tarbiat Modares University, PO Box 14115-111, Tehran, Iran

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ABSTRACT

With regard to widespread use of distributed generation in distribution network, its technical impacts in distribution network should be thoroughly analyzed. In this paper simultaneous placement of distributed generation (DG) and capacitor is considered in radial distribution network with different load levels. The objectives of the problem are reduction of active and reactive power loss, reduction of energy loss and improvement of voltage profile. Also effect of capacitor and DG on voltage stability improvement has been considered in the objective function. Memetic algorithm is used to find optimal solutions. This algorithm is combinatorial form of local search and genetic algorithm. The performance of the proposed method is assessed on a test distribution network.

1. Introduction

Considering the widespread number of electrical network users and also increase in network load, distribution companies try to provide required power by proper designing and exploitation of network [1]. Several facilities such as DGs and capacitors are used to achieve these goals. Optimal placement and sizing of these equipments has significant effect on decreasing network loss, voltage profile enhancement and also reliability improvement. Lots of researches were provided in recent years about optimal placement and sizing of the capacitor and DGs. Analytic method is employed to solve optimal placement and sizing of DGs in [1,2] considering loss minimization as objective of the problem. In [3], genetic algorithm has been used for DG placement with purpose of increasing spinning reserve, improvement of voltage profile, decreasing load flow and also decreasing transmission loss. In [4], Bellman-zadeh algorithm and fuzzy logic are implemented for DG placement distribution network. In [5], objective function is optimized by the usage of load flow method which includes voltage profile and power loss. In this reference optimal weighting factors of objective function are calculated and then transmission loss is decreased and voltage profile is improved by optimal DG placement. Refs. [6–8] are used genetic algorithm, DPSO approach and also a hybrid approach with Fuzzy-DE and Fuzzy-MAPSO respectively to determine optimal number and size of capacitors for power loss decreasing. Fuzzy logic is used in [9] to determine optimal capacitor placement. In this reference decreasing of power loss and also peak loss are considered in objective function. In [10], a heuristic algorithm is used to optimal capacitor placement in distribution system considering power loss and also voltage drop in the optimization process. In this reference, load duration curve is modeled as multi-level curve in network busses.

In most of previous works, load of distribution network is considered as a constant parameter. This assumption provides unreliable results and it is necessary to consider multi-level load in planning process. Furthermore, effect of devices has not been considered on voltage stability and peak shaving.

In this paper a new method is presented to perform simultaneous placement of DGs and fixed capacitors in order to reduce purchased active power demand from transmission network, improvement of voltage profile, reduction of active and reactive power loss and peak loss and also reduction in energy loss of distribution network with different load levels. Equipment cost is considered in objective function. Eventually, effect of DG and capacitor on voltage stability is considered and added to objective function. Memetic algorithm is used for optimization. This algorithm is an instance of evolutionary algorithm which reduces computational time by combination of local search and genetic algorithm. IEEE 34-bus of [8] is used as case study and simulation results are reported. This paper is organized as follows:

* Corresponding author.
E-mail addresses: mohssen.sajjadi@ymail.com (S.M. Sajjadi), haghifam@modares.ac.ir (M.-R. Haghifam), j.salehi@modares.ac.ir (J. Salehi).

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Load modeling will be given in Section 2. Details of objective function are introduced in Section 3. Section 4 gives mathematical formulation of objective function and constraints. In Section 5, memetic algorithm is addressed. Case study and numerical results are reported in Section 6. Finally, the conclusion of the paper is summarized in Section 7.

2. Load modeling

In this paper, different load levels are considered and load condition is applied in three stages; light, medium and peak load. Also load growth rate is considered 1% in each year. Fig. 1 shows load duration curves in three levels in study period.

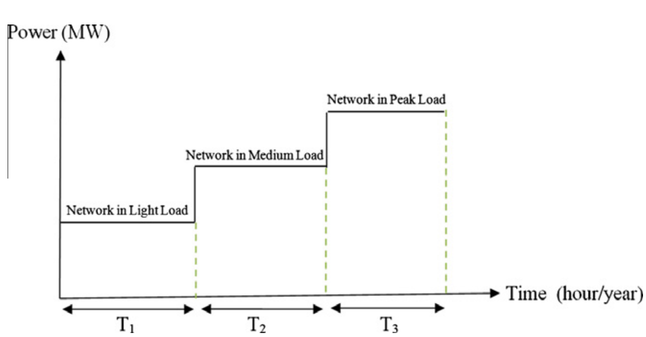

Fig. 1. Load duration curve.

3. Objective function

According to the previous sections, objective function can be presented as follows;

$$objective\_function = (BPV(B_1) + BEL + BPL + BSI + BR) - (C_1 + CM + CPV(C_2) + cost\ of\ fixed\ capacitor) \quad (1)$$

where $BPV(B_1)$ is cost reduction of purchased active power demand from transmission line, BEL is energy loss reduction benefit, BPL is power loss reduction benefit, BSI is achieved benefits from voltage stability index improvement, BR is reactive power loss reduction benefit, C_1 is DGs installation cost, CM is maintenance cost of DG and also $CPV(C_2)$ is operation cost of DG.

4. Problem formulation

In this section, objective function is presented and modeled. In this paper, distribution companies are responsible for providing customer's demand and also DG operation and distribution system management is based on cost reduction. Mathematical formulation for different terms of the objective function is presented as follows:

4.1. Installation cost

4.1.1. Capacitor installation cost

Cost of capacitor installation is presented as follows;

$$Cost\ of\ fixed\ capacitor = cost_{C_i} \times n_{C_i} \times C_i \quad (2)$$

where $cost_{C_i}$, n_{C_i} and C_i are cost, the number and capacity of ith capacitor that applied in distribution network respectively.

4.1.2. DGs installation cost

The cost of DG installation is included in purchased DGs cost with specified capacity. This cost can be formulated as following equation:

$$C_1 = \sum_{i=1}^{N_{DG}} \sum_{k=1}^{k_{DG}} cost_{installation,ik} \quad (3)$$

where N_{DG}, k_{DG}, and $cost_{installation,ik}$ are number of DG units installed in the network, capacity of DG units, and installation cost of ith DG source ($/MW) respectively.

4.2. Maintenance cost of DG

This term consists of DG units maintenance cost which is proportional to the number of applied DG units in network. Maintenance cost is formulated as follow:

$$CM_1 = \sum_{i=1}^{N_{DG}} \sum_{K=1}^{K_{DG}} cost_{main,ik} \quad (4)$$

CM_1 is maintenance cost for 1 year. During of the planning period maintenance cost is calculated as below:

$$CM = CM_1 \times \sum_{t=1}^{T} \left(\frac{1 + InfR}{1 + IntR} \right)^t \quad (5)$$

where $InfR$, $IntR$, and T are inflation rate, interest rate, and planning period respectively. Also CM is maintenance cost along of the planning period ($/MW h).

4.3. Operation cost of DG

This cost is equal to cost of active power generation and can be evaluated by:

$$C_2 = \sum_{i=1}^{N_{DG}} \sum_{k=1}^{k_{DG}} T_j \times DG_{j \cdot ik} \times CG_{ik} \quad (6)$$

$$CPV(C_2) = C_2 \times \sum_{t=1}^{T} \left(\frac{1 + InfR}{1 + IntR} \right)^t \quad (7)$$

where N_{DG} is number of DG units installed in the network; k_{DG} is capacity of DG units; $DG_{j,ik}$ is generated power by ith DG source in jth load level (MW); CG_{ik} is operation cost of DG sources ($/MW h); CPV($C_2$) is cost of present worth; T_j is duration of jth load level (h/year) and also T is planning period (year) respectively.

4.4. Reduction of purchased active power demand from transmission line and benefit of network loss reduction due to installation of DG sources

The distribution company purchases its power demand from transmission grid. Portion of this power demand is for distribution system customers and another one is spent in line and equipment loss. This power demand is evaluated by [11]:

$$PT_{N_{DG},j} = PD_j + Loss_{NDG,j} \quad (8)$$

where $PT_{N_{DG},j}$ is purchased active power from transmission line in jth load level without DG sources in distribution network, PD_j is customers demand and $Loss_{NDG,j}$ is distribution network loss in jth load level without DG sources in the network.

Using DGs, the distribution company can provide portion of its power demand from these resources. In this case, electric power demand is calculated as below:

$$PT_{DG_j} = PD_j + Loss_{DG,j} - \sum_{i=1}^{N_{DG}} \sum_{k=1}^{k_{DG}} DG_{j,ik} \quad (9)$$

where PT_{DG_j} is purchased active power from transmission line in jth load level with DG sources installed in distribution network and

$Loss_{DG,j}$ is distribution network loss in jth load level with DG sources installed in the network.

Reduction of active power demand can be formulated as following equation:

$$\Delta PT = PT_{N_{DG},j} - PT_{DG,j} = Loss_{NDG,j} - Loss_{DG,j} + \sum_{i=1}^{N_{DG}}\sum_{k=1}^{k_{DG}} DG_{j,ik} \quad (10)$$

And loss reduction based on presence of DG can be evaluated by:

$$\Delta Loss_j = Loss_{NDG,j} - Loss_{DG,j} \quad (11)$$

Therefore Eq. (10) can be formulated as following equation:

$$\Delta PT = PT_{N_{DG},j} - PT_{DG,j} = \sum_{i=1}^{N_{DG}}\sum_{k=1}^{k_{DG}} DG_{j,ik} + \Delta Loss_j \quad (12)$$

Based on mentioned notes, active power reduction benefit for each year follows:

$$B_1 = \sum_{j=1}^{n} C_{Mwh,j} \times \Delta PT \times T_j \quad (13)$$

Present worth value of (13) is calculated as below:

$$BPV(B_1) = B_1 \times \sum_{t=1}^{T}\left(\frac{1+InfR}{1+IntR}\right)^t \quad (14)$$

where $BPV()$ is benefit present worth; $C_{Mwh,j}$ is energy market price in jth load level ($/MW h) and n is the number of load levels. Daily energy curve in different hours can be modeled as Fig. 2. In this paper multi-level electricity price proportional to receiving active power from transmission grid is used. Fig. 3 shows the proposed electric price.

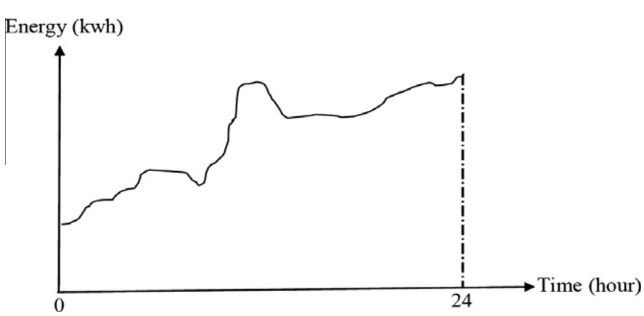

Fig. 2. Daily energy curve.

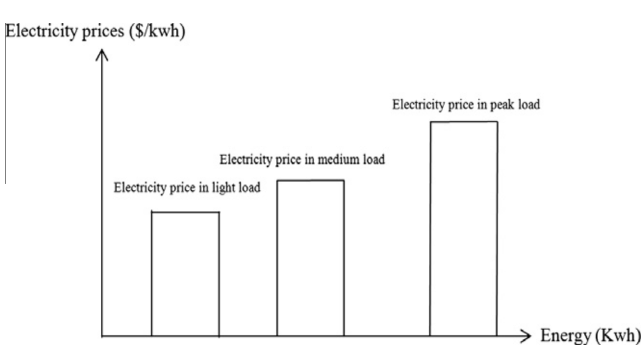

Fig. 3. Electricity prices at different levels of energy consumption.

4.5. Benefit from reduction of reactive power loss

Capacitors and distributed power resources have considerable effect in reactive power loss reduction of distribution networks. Reduction of reactive power loss benefit can be calculated from the following equation:

$$BR_1 = C_R(Q_0 - Q_1) \quad (15)$$

where Q_0, Q_1, and C_R, are reactive power loss before installation of equipment (kVar), reactive power loss after installation of equipment (kVar), and worth of reactive power ($/kVar) respectively. BR_1 is reduction of reactive power loss benefit for 1 year. During of the planning period reduction of reactive power loss benefit is calculated as below:

$$BR = BR_1 \times \sum_{t=1}^{T}\left(\frac{1+InfR}{1+IntR}\right)^t \quad (16)$$

where $InfR$, $IntR$, and T are inflation rate, interest rate, and planning period respectively. Also BR is reduction of reactive power loss benefit during planning period.

4.6. Energy loss reduction benefit

Energy loss in section-i in T_j is given by:

$$EL_{i,j} = T_{i,j} \times R_i \times I_i^2 \quad (17)$$

where $EL_{i,j}$ is energy loss of section-i in T_j; R_i is resistance of section-i; and I_i is the current of section-i in T_j. Energy loss of a feeder with n sections in T_j can be evaluated by:

$$EL_{i,j} = T_{i,j} \times R_i \times I_i^2 \quad (18)$$

If there are n time intervals in the planning period, total feeder energy loss of the planning period is:

$$EL = \sum_{j=1}^{n} E_j \quad (19)$$

Energy loss cost in the planning period can be achieved by multiplying 19 by the energy rate (C_e).

$$CEL = C_e \times EL \quad (20)$$

Total benefit for energy loss saving is:

$$BEL_1 = CEL_0 - CEL_1 \quad (21)$$

In this equation, BEL_1 is benefit of energy loss reduction for 1 year, CEL_0 and CEL_1 are cost of energy loss before and after capacitor installation, respectively. During of the planning period, benefit from energy loss reduction is calculated as below:

$$BEL = BEL_1 \times \sum_{t=1}^{T}\left(\frac{1+InfR}{1+IntR}\right)^t \quad (22)$$

where BEL is energy loss reduction benefit during the planning period.

4.7. Peak power loss reduction benefit

Peak power loss reduction is one of the most important effects of capacitor placements in distribution network and can be computed as,

$$PL = P_{Loss,0} - P_{Loss,1} \quad (23)$$

where $P_{Loss,0}$ is the peak power loss in feeder before capacitor installation (kW) and $P_{Loss,1}$ is the peak power loss in feeder after capacitor installation (kW). The benefit of capacitor installation for 1 year is as follows;

$$BPL_1 = C_d \times PL \quad (24)$$

where C_d is demand reduction benefit rate ($/MW). During of the planning period, peak power loss reduction benefit is calculated as below:

$$BPL = BPL_1 \times \sum_{t=1}^{T} \left(\frac{1+InfR}{1+IntR}\right)^t \quad (25)$$

where *BPL* is peak power loss reduction benefit along of the planning period.

4.8. Voltage stability index improvement

Voltage stability is the ability of a system to maintain voltage in acceptable level so that when system nominal load is increased, the active power delivered to the load by the system will increase and both power and voltage are controllable [12]. To ensure voltage stability of network busses, we have considered monetary value of voltage stability in the objective function. Monetary value of voltage stability is calculated using Eqs. (26) and (27) and also Fig. 5. Considering this index in the objective function leads to allocation of DGs and capacitors in places which increase voltage stability of network busses. To determine node voltage stability index, *P–V* curve of a certain bus is used and is shown as Fig. 4.

In Fig. 4, V_0 and P_0 are operation point of bus before installation of equipment. When DGs and capacitor are applied in distribution network, the node voltage will increase and voltage security will enhance. Therefore voltage stability margin increases from m_0 to m_1. This means that DG and capacitors improve voltage stability index. To calculate voltage stability, the curve of Fig. 5 is presented.

As Fig. 5 shows, considering importance of voltage stability for the distribution company planners, we can consider appropriate curve. For example curve 5 of this figure can be used if the voltage stability importance is high and curve 1 can be used if the voltage stability importance is low. In other words, with using different importance curves we can change weighting factor of voltage stability in the objective function. It should be mentioned that quadratic functions can be used for modeling of these curves. For example curve 5 can be formulated as $f(x) = -ax^2 + b$ and curve 1 can be formulated as $f(x) = (ax - b)^2$ which the shape of curves can be changed by *a* and *b* coefficients. After selection of appropriate curve for each bus of network, to calculate monetary value of voltage stability of objective function, voltage stability index (VSI) is determined for each bus using Eq. (27) and the bus with minimum VSI is determined. VSI of each bus is a number between 0 and 1. After determination of the bus with minimum VSI, monetary value of voltage stability index is calculated for this bus considering its appropriate curve which is selected based on the importance of the bus. It should be mentioned that maximum voltage stability index cost (C_{max}) for each curve is obtained by Eq. (26). Considering this equation, C_{max} is obtained when the load point is disconnected from the network due to voltage collapse.

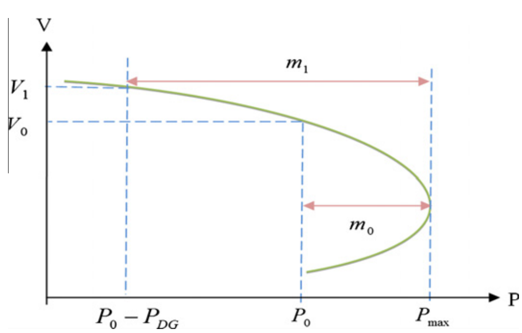

Fig. 4. *P–V* curves of a certain bus to investigate voltage stability.

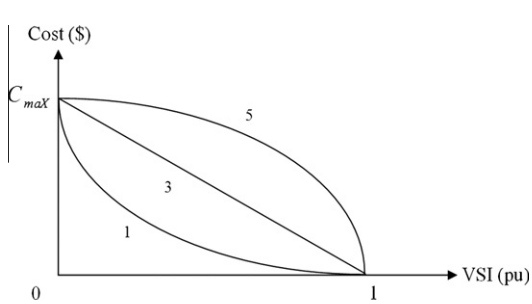

Fig. 5. Different cost curves based on importance of VSI.

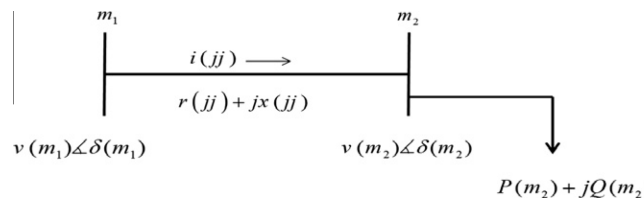

Fig. 6. Simple two node system.

$$Cost_{\max,i} = k \times P_{load,i} \times T \quad (26)$$

where *T* and *k* are duration of peak load (hour) and the average cost of a blackout ($/$MW_{peak}$), and $P_{load,i}$ is active power of the bus-*i* in peak load level. The other point in Fig. 5 is that when the bus voltage stability index is greater than 1, the cost of the voltage stability index will not be calculated. Voltage stability index is calculated by the relationship [13];

$$VSI(m_2) = |V(m_1)|^4 - \{4[P(m_2) \times x(jj) - Q(m_2) \times r(jj)]^2\} - \{4 \times |V(m_1)|^2 \times [P(m_2) \times r(jj) + Q(m_2) \times x(jj)]\} \quad (27)$$

where $SI(m_2)$ is voltage stability index of node m_2 ($m_2 = 2,3,4,\ldots,N$) *N* is the number of nodes. *jj* is the number of branch, $r(jj)$ and $x(jj)$ are resistance and reactance of the *jj* branch respectively. $V(m_1)$ is node m_1 voltage. $P(m_2)$ and $Q(m_2)$ are total real power load fed through node m_2 and total reactive power load fed through node m_2. The above equation is true for a system with two buses equivalent system shown in Fig. 6 and can be generalized as follows.$P(m_2)$ is sum of the real power loads of all the nodes beyond node m_2 plus the real power load of node m_2 itself plus the sum of the real power losses of all the branches beyond node m_2. $Q(m_2)$ is sum of the reactive power loads of all the nodes beyond node m_2 plus the reactive power load of node m_2 itself plus the reactive power losses of all the branches beyond node m_2. According to the above relation benefits from improved voltage stability index can be written as follows.

$$BSI_1 = (SI_0 - SI_1) \quad (28)$$

where SI_0 is the cost of voltage stability for bus which has lower voltage stability index value than other buses before equipment installation. SI_1 is the cost of voltage stability for bus which has lower voltage stability index value than other buses after equipment installation.

In Eq. (28), BSI_1 is voltage stability index benefit for 1 year. During of the planning period benefit from voltage stability index is calculated as below:

$$BSI = BSI_1 \times \sum_{t=1}^{T} \left(\frac{1+InfR}{1+IntR}\right)^t \quad (29)$$

where *BSI* is voltage stability index benefit along of the planning period.

- constrains

Constrains include, voltage, thermal capacity and the capacity of distributed generation source that can be demonstrated as follows:

$$V_i^{\min} < V_i < V_i^{\max}$$

$$S < S^{\max}$$

$$\sum_{i=1}^{N_{DG}} \sum_{k=1}^{k_{DG}} DG_{ik} < DG_{\max}$$

where $V_i^{\min}$ and $V_i^{\max}$ are minimum and maximum voltage of node *i*. $S^{\max}$ is feeders thermal capacity and $DG_{\max}$ is maximum capacity of distributed generation units.

5. Memetic algorithm

Genetic algorithms based on Darwin's evolutionary theory are one of the most popular and widely Meta heuristics, which are applied in optimization [14–17]. Genetic algorithm like other Meta heuristics such as particles swarm optimizing in the first steps well identified the implementation of algorithm in the areas of state space which global and local optimal are located, but it acts very slowly toward the global optimum [14,15]. The second major problem is the lack of stability of these algorithms which Meta heuristics such as genetic algorithms are faced with them. This means that the quality of responses which is driven from different performances of the algorithm may have many differences and may be unreliable.

Among the various strategies, which are presented for resolving Meta heuristic problems, the combination Strategy has special place [18] .The combination strategy derived from applying various techniques in the process of problem solving. Memetic algorithms considered as the most famous member of this family. This algorithm is an instance of evolutionary algorithms which is combination of local initiative search with genetic algorithm to solve an optimization problem in order to reduce achievement time of optimal responds.

Genetic algorithms are established to explore the search space while local search examines the neighborhood area of any found respond by the genetic to reach more appropriate responses.

Choice of reproduction operators in a genetic part of a memetic algorithm and the type of local search methods which are used, leads to very different performance results. Optimization in the form of memetic algorithm includes following steps:

- initial population formation,
- crossover operator,
- mutation operator,
- local search.

A local search algorithm has started from initial state and enters into a loop to navigate the search space, which is the same neighborhood area of a chromosome. Search in each stage estimates the quality of each state by competence functions and it continues to find the best chromosome in the neighborhood of current chromosomes.

Then the competence of new chromosome is calculated, if the competence is improved, the result chromosome of local search will be replaced to initial chromosome, otherwise the same initial chromosome will be considered as the best solution in his neighborhood and will be remained unchanged.

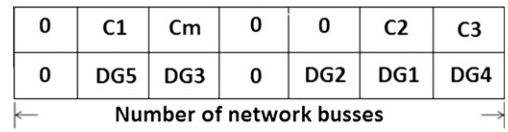

Fig. 7. Chromosome encoding scheme.

The main stages of MA search method used in this paper are described in next sections.

5.1. Chromosome encoding

Chromosomes of initial population have a structure similar to Fig. 7.

Number of columns of chromosomes are equal to number of network busses. First row of chromosomes defines capacity and location of capacitors in the network busses and contains random discreet variables between 0 to *m* (number of available capacitor types from capacity point of view). 0 means there is no capacitor in the related bus and m means there is capacitor of type m in the related bus. For example, if value of 7th gene of first row is equal to 3, it means capacitor type 3 is installed in 7th bus of the network.

Second row defines capacity and location of DG sources in the network busses and contains continues variables. Each gene of second row is calculated as below:

$$DG_j = DG_{\max} \times \alpha_j$$

where $DG_{\max}$ is the maximum capacity of available DG sources in the distribution company and α_j is a stochastic number between 0 and 1 respectively.

5.2. Crossover

This operator uses one chromosome as parent and one child is produced. Number of crossover operation is determined by crossover possibility factor. For more details consider Fig. 8.

As this figure shows, a column is selected randomly and two parts of parent chromosome are replaced to produce child chromosome.

5.3. Mutation

In the mutation mechanism, for each gene, a uniform random number is generated between the interval [0,1]. If this number is lower than the mutation rate, the respective value of the current gene is swapped for another random value within a specific interval.

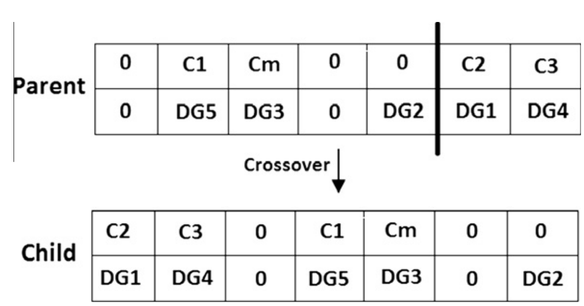

Fig. 8. A simple structure of the crossover mechanism.

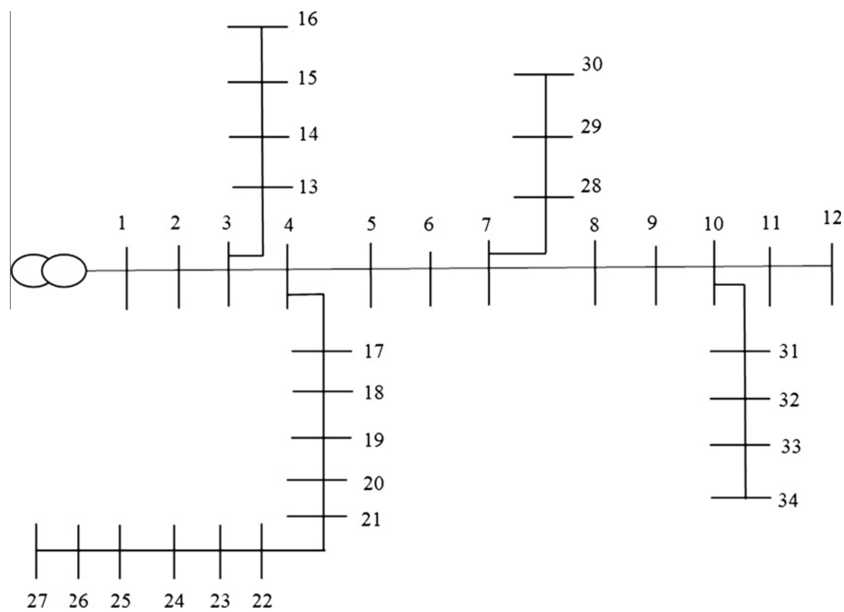

Fig. 9. 34-Bus test system.

5.4. Local search

In memetic algorithm by a local search, the best chromosome is obtained after several mutation. It means that after each mutation, local search is done and the best solution is compared with the best solution of the previous mutation and best answer is selected among them.

6. Case study and numerical results

6.1. Case study

The test 11 kv distribution network and its data are shown in Fig. 9 and Tables A1 and A2 of appendix respectively. In this study

Table 1
Technical and commercial information of load and electricity market price.

Load level	Network condition	Time duration (h/year)	Market price ($/MW h)
1	Light load	2190	35
2	Medium load	4745	49
3	Peak load	1825	70

Table 2
Commercial information of DG and capacitor.

Parameter	Unit	Value
DG installation cost	$/MW	318,000
DG operation cost	$/MW h	29
DG maintenance cost	$/MW h	7
Capacitor cost		
100 kVar	$	400
300 kVar		1100
500 kVar		1700
Active power purchased price	$/MW	120,000
Reactive power purchased price	$/MVar	30,000
The average of 1-h interruption costs	$/$MW_{peak}$	19,100
Annual load growth rate	%	10
Inflation rate	%	9
Interest rate	%	12.5
Planning period	Year	4

Table 3
Overall results obtained from the proposed method.

Benefit of loss reduction	4,369,200 $
Benefit of voltage stability	616,580 $
Total benefit	4,653,500 $

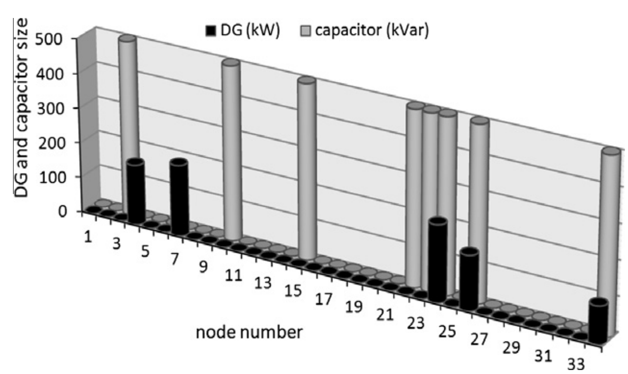

Fig. 10. Location and size of installed devices in the network.

Table 4
Parts of objective function in different load levels.

Economical cost	Network condition	Costs ($)
Capacitor installation cost	Light load	16,400
DG installation cost		445,200
Maintenance		48,873
Operation		202,470
Total		712,943
Capacitor installation cost	Medium load	16,400
DG installation cost		445,200
Maintenance		105,890
Operation		438,690
Total		1,006,180
Capacitor installation cost	Peak load	16,400
DG installation cost		445,200
Maintenance		40,727
Operation		168,730
Total		671,057

Table 5
Benefits of energy procurement reduction from the electricity market.

Network condition	Benefits of reduction in purchase energy ($)
Light load	1,010,300
Medium load	3,064,700
Peak load	1,683,900
Total	5,759,000

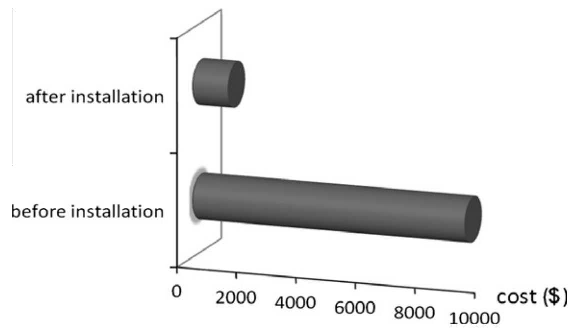

Fig. 11. Comparing reactive loss cost, before and after installation of equipment.

we have used five distributed generation units with capacity of 250 kW and 0.9 power factor. All nodes are candidate for DG installation.

Information for network load during 24 h of the day has been modeled. In other hand, these curves indicate daily loading of the system during whole year. For modeling of annual load change, these curves have been repeated 365 times. Network technical and commercial information are presented in Table 1. Commercial information of DG and capacitor can be seen in Table 2 and are derived from [19,20].

6.2. Numerical results and analysis (base case: considering loss and voltage stability index in the objective function)

Overall results of application of the proposed method can be seen in Table 3 and Fig. 10. According to Fig. 10, DGs values are determined as 173 kW, 204 kW, 220 kW, 157 kW and 108 kW. These DGs are placed in nodes 4, 7, 24, 26 and 34 respectively. Also one capacitor of 300 kVar, and nine capacitor of 500 kVar are placed in nodes 7, 3, 10, 15, 22, 23, 24, 26, 31, and 34 respectively. These results show that, benefit of devices installation is noticeable

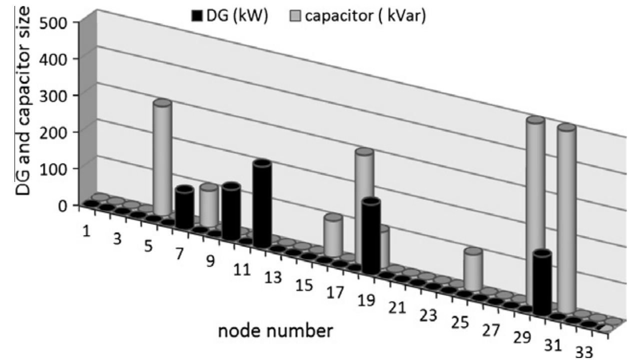

Fig. 13. Optimal location and size of the DGs and capacitors.

value and is equal to 4,653,500 $. 616,580 $ of this benefit is due to voltage stability improvement. It should be mentioned that curve 3 of Fig. 5 is used to calculate monetary value of voltage stability index and another curves (1 and 5) will be investigated in Section 6.4.

In order to more illustration, Table 4 can be studied. In this table parts of objective function in different load levels is given. One of DGs installation purpose is reduction of energy procurement from up-stream network. In Table 5 the benefits of energy procurement reduction from the electricity market at different load levels is shown. Comparison of network reactive loss cost before and after devices installation can be seen in Fig. 11.

Fig. 12 is presented for investigation of voltage stability index in two cases of before and after device installations. As these figure shows, after optimal allocation of DG and capacitors voltage stability index is improved considerably in node 3. Also VSI of node 28 (The node with minimum voltage stability index) is changed from 0.64 pu to 0.93 pu before and after installation of equipment.

6.3. Illustrative case 1: considering loss in the objective function (without considering voltage stability index)

In this part, we have considered loss in the objective function without considering voltage stability index. In other words, voltage stability index is eliminated from objective function to investigation of its effect. In Fig. 13 optimal location and size of the DGs and capacitors in this case are shown. The voltage stability index of buses before and after placement of devices is shown in Fig. 14. As Fig. 14 shows, voltage stability of node 28 is changed

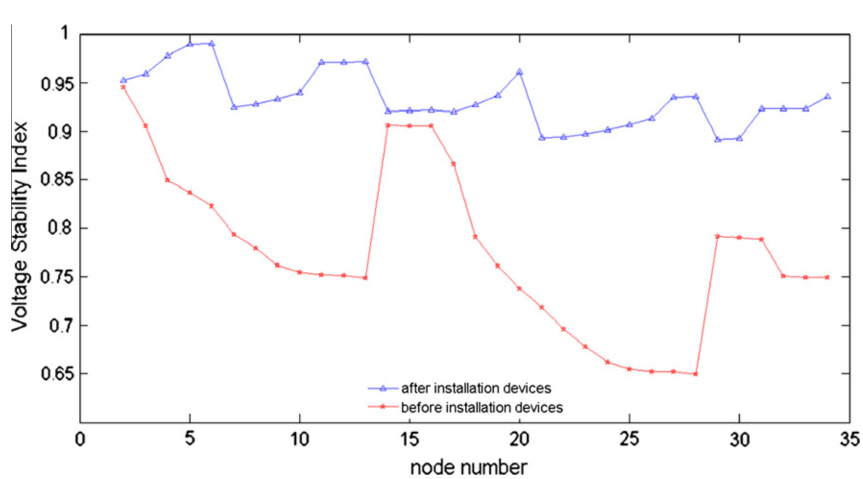

Fig. 12. Voltage stability index curves before and after installation devices.

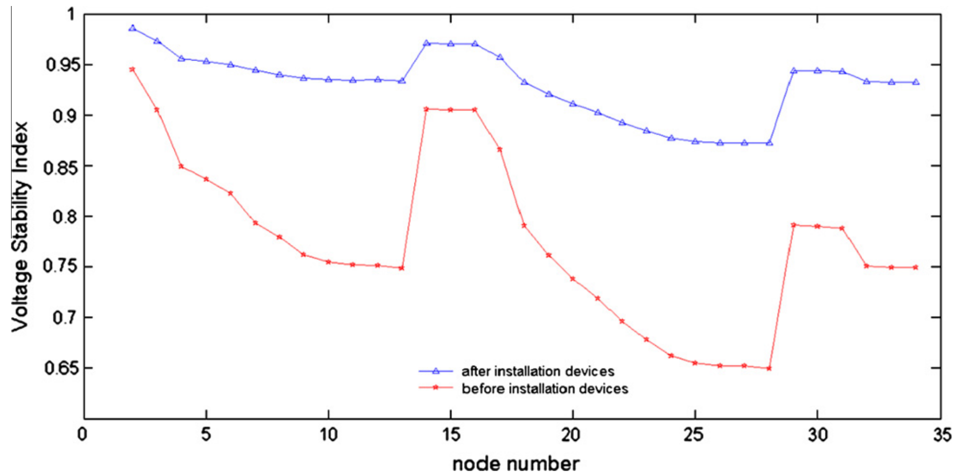

Fig. 14. Voltage stability index curves before and after installation of devices.

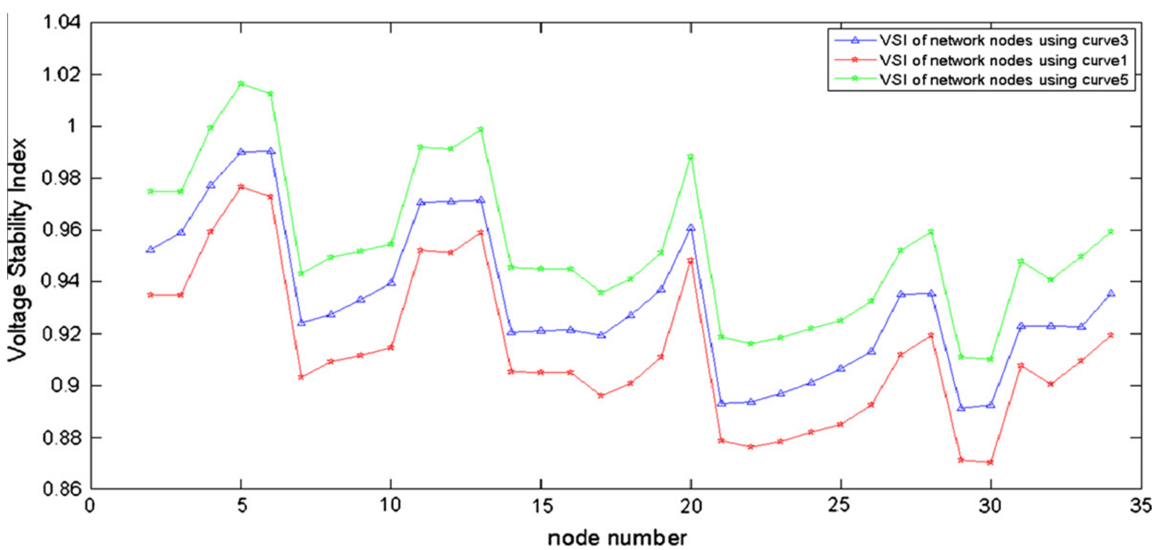

Fig. 15. Comparing voltage stability index of network nodes using different importance curve.

from 0.64 pu to 0.87 pu before and after installation of equipment. This means, ignoring voltage stability index from objective function leads to less improvement of voltage stability in the network nodes. This results show the importance of the proposed method which proposes the consideration of monetary value of voltage stability index in the objective function. In other words, if we consider voltage stability index in the objective function we can assure further voltage stability in the network.

6.4. Illustrative case 2: investigation of the effect of different VSI importance curve

In this section impact of different curves of Fig. 5 is investigated on the obtained solutions. We investigate voltage stability curves corresponding to curve 1, 3, and 5. As mentioned in previous sections, curve-1 of Fig. 5 is used when the voltage stability is not a critical objective in the allocation problem and curve-5 of Fig. 5 is used when the voltage stability index is important. In other words, choosing different type of importance curves we can change weighting factor of voltage stability index in the objective function. For example, if the voltage stability index of the network nodes which is obtained by Eq. (27) is low, network planner can choose curve five of Fig. 5 to more improvement of the voltage stability index in the obtained solution. But if obtained voltage stability index of network nodes by Eq. (27) are not low, the planners can choose curves 1 or 3 of Fig. 5. Fig. 15 is presented to compare the effect of different importance curves on the obtained solutions. As expected, voltage stability of network nodes using curve 5 is more than when curve 3 is used and voltage stability of network nodes using curve 3 is more than when curve 1 is used. This result shows the effect of different importance curves on the voltage stability of network nodes.

7. Conclusion

In this paper, simultaneous placement of distributed generation (DG) and fixed capacitor in radial distribution network with time varying load in order to decrease reactive power loss, energy and power loss reduction, improvement of voltage profile and voltage stability has been studied. For calculating the cost of voltage stability, the maximum cost occurs when connected load to bus is disconnected. In this case voltage stability index will be minimum value and when voltage stability index was equal to 1^{pu}, the cost of voltage stability is supposed to zero. For validation of method,

Table A1
Network data.

From bus	To bus	R (Ω)	X (Ω)
1	2	0.117	0.048
2	3	0.10725	0.044
3	4	0.16445	0.04565
4	5	0.1495	0.0415
5	6	0.1495	0.0415
6	7	0.3144	0.054
7	8	0.2096	0.036
8	9	0.3144	0.054
9	10	0.2096	0.036
10	11	0.131	0.0225
11	12	0.1048	0.018
3	13	0.1572	0.027
13	14	0.2096	0.036
14	15	0.1048	0.018
15	16	0.0524	0.009
6	17	0.1794	0.0498
17	18	0.16445	0.04565
18	19	0.2079	0.0473
19	20	0.189	0.043
20	21	0.189	0.043
21	22	0.262	0.045
22	23	0.262	0.045
23	24	0.3144	0.054
24	25	0.2096	0.036
25	26	0.131	0.0225
26	27	0.1048	0.018
7	28	0.1572	0.027
28	29	0.1572	0.027
29	30	0.1572	0.027
10	31	0.1572	0.027
31	32	0.2096	0.036
32	33	0.1572	0.027
33	34	0.1048	0.018

different scenarios are considered and the results indicate significant reduction of network loss and also voltage stability improvement. The results show the importance of considering monetary value of voltage stability index in the objective function.

Appendix A

Network data including resistance and reactance of branch and active and reactive power buses in Tables A1 and A2 are specified.

References

[1] Gözel T, Hocaoglu MH. An analytical method for the sizing and siting of distributed generators in radial systems. Electr Power Syst Res 2009;79:912–8.

[2] Wang C, Nehrir MH. Analytical approaches for optimal placement of distributed generation sources in power systems. IEEE Trans Power Syst 2004;19:2068–76.

[3] Abou El-Ela AA, Allam SM, Shatla MM. Maximal optimal benefits of distributed generation using genetic algorithms. Electr Power Syst Res 2010;80:869–77.

[4] Barin A, Pozzatti LF, Canha LN, MacHado RQ, Abaide AR, Arend G. Multi-objective analysis of impacts of distributed generation placement on the operational characteristics of networks for distribution system planning. Int J Electr Power Energy Syst 2010;32:1157–64.

[5] Ghosh S, Ghoshal SP. Optimal sizing and placement of distributed generation in a network system. Int J Electr Power Energy Syst 2010.

[6] Park JY, Sohn JM, Park JK. Optimal capacitor allocation in a distribution system considering operation costs. IEEE Trans Power Syst 2009;24:462–8.

[7] Ziari I, Ledwich G, Ghosh A, Cornforth D, Wishart M. Optimal allocation and sizing of capacitors to minimize the transmission line loss and to improve the voltage profile. Comput Math Applic 2010;60:1003–13.

[8] Kannan SM, Renuga P, Kalyani S, Muthukumaran E. Optimal capacitor placement and sizing using fuzzy-DE and fuzzy-MAPSO methods. Appl Soft Comput J 2011;11:4997–5005.

[9] Tabatabaei SM, Vahidi B. Bacterial foraging solution based fuzzy logic decision for optimal capacitor allocation in radial distribution system. Electr Power Syst Res 2011;81:1045–50.

Table A2
Different load levels of network buses.

Bus number	$P_{level\ 1}$ (kW)	$Q_{level\ 1}$ (kVar)	$P_{level\ 2}$ (kW)	$Q_{level\ 2}$ (kVar)	$P_{level\ 3}$ (kW)	$Q_{level\ 3}$ (kVar)
2	126.5	78.375	161	99.75	149.5	92.625
3	0	0	0	0	0	0
4	126.5	78.375	161	99.75	149.5	92.625
5	126.5	78.375	161	99.75	149.5	92.625
6	0	0	0	0	0	0
7	0	0	0	0	0	0
8	126.5	78.375	161	99.75	149.5	92.625
9	126.5	78.375	161	99.75	149.5	92.625
10	0	0	0	0	0	0
11	126.5	78.375	161	99.75	149.5	92.625
12	68.5	42	82.2	50.4	75.35	46.2
13	32.4	20.25	46.8	29.25	43.2	27
14	32.4	20.25	46.8	29.25	43.2	27
15	32.4	20.25	46.8	29.25	43.2	27
16	8.1	4.5	9.45	5.25	8.775	4.875
17	126.5	78.375	161	99.75	149.5	92.625
18	126.5	78.375	161	99.75	149.5	92.625
19	126.5	78.375	161	99.75	149.5	92.625
20	126.5	78.375	161	99.75	149.5	92.625
21	126.5	78.375	161	99.75	149.5	92.625
22	126.5	78.375	161	99.75	149.5	92.625
23	126.5	78.375	161	99.75	149.5	92.625
24	126.5	78.375	161	99.75	149.5	92.625
25	126.5	78.375	161	99.75	149.5	92.625
26	126.5	78.375	161	99.75	149.5	92.625
27	68.5	42.5	82.2	51	76.35	76.75
28	41.25	26.4	56.25	36	52.5	33.6
29	41.25	26.4	56.25	36	52.5	33.6
30	41.25	26.4	56.25	36	52.5	33.6
31	32.49	19.665	35.91	21.735	33.06	20.01
32	32.49	19.665	35.91	21.735	33.06	20.01
33	32.49	19.665	35.91	21.735	33.06	20.01
34	32.49	19.665	35.91	21.735	33.06	20.01

[10] Silvio S, Ruben R, Marcos J. Efficient heuristic algorithm used for optimal capacitor placement in distribution systems. Int J Electr Power Energy Syst 2010;32:71–8.
[11] Khalesi N, Rezaei N, Haghifam M-R. DG allocation with application of dynamic programming for loss reduction and reliability improvement. Int J Electr Power Energy Syst 2011;33:288–95.
[12] Parizad A, Khazali A, Kalantar M. Optimal placement of distributed generation with sensitivity factors considering voltage stability and losses indices. In: 18th Iranian conference on electrical engineering, ICEE 2010. Isfahan; 2010. p. 848–55.
[13] Sedighizadeh M, Jahangir M, Gandomkar M, Esfandeh S. Distributed generation location and capacity effect on voltage stability of distribution network. In: 12th WSEAS international conference on mathematical methods and computational techniques in electrical engineering, MMACTEE'10; 2010. p. 89–94.
[14] Eiben AE, Smith JE. Introduction to evolutionary computing. Springer; 2003.
[15] Engelbrecht AP. Fundamentals of computational swarm intelligence. John Wiley& Sons; 2005.
[16] Guimarães FG, Campelo F, Igarashi H, Lowther DA, Ramírez JA. Optimization of cost functions using evolutionary algorithms with local learning and local search. IEEE Trans Magn 2007;43:1641–4.
[17] Mitchell M. An introduction to genetic algorithms. MIT Press; 2002.
[18] Ong YS, Lim MH, Zhu N, Wong KW. Classification of adaptive memetic algorithms: a comparative study. IEEE Trans Syst, Man, Cyber, Part B: Cyber 2006;36:141–52.
[19] Belman R, Dreyfus S. Applied dynamic programming. Princeton University Press; 1962.
[20] Haghifam MR, Falaghi H, Malik OP. Risk-based distributed generation placement. IET Gener, Transm Distrib 2008;2:252–60.