Multi-objective Based Optimization Using Tap Setting Transformer, DG and Capacitor Placement in Distribution Networks

Abdolreza Sadighmanesh [1], Mehran Sabahi [2], Kazem Zare [2], and Babak Taghavi [3]
[1] Department of Electrical Engineering, Ahar Branch, Islamic Azad University, Ahar, Iran.
Email: a-sadighmanesh@iau-ahar.ac.ir (corresponding author)
[2] Faculty of Electrical and Computer Engineering, University of Tabriz, Tabriz, Iran
Email: sabahi@tabrizu.ac.ir, kazem.zare@tabrizu.ac.ir
[3] Department of Information and Communication Technology, KTH, Stockholm, Sweden
Email: btaghavi@kth.se

ABSTRACT

*In this article, a multi-objective function for p*lacement of D*istributed Generation (DG) and capacitors with the tap setting of Under Load Tap Changer (ULTC) Transformer is introduced. Most of the recent articles have paid less attention to DG, capacitor placement and ULTC effects in the distribution network simultaneously. In simulations, a comparison between different modes was carried out with, and without tap setting of ULTC. Simultaneous DG, capacitor placement, and ULTC transformer tap setting improve the voltage profile of load buses globally. In addition, they can also reduce loss and increase Available Transfer Capability (ATC). The IEEE 41-bus radial distribution network is used to illustrate the effectiveness and feasibility of the proposed approach.*

KEYWORDS: DG placement, capacitor placement, ULTC Transformer, loss reduction, voltage profile, available transfer capability, multi-objective function.

1. INTRODUCTION

The optimal placement and assignment of DG and capacitors are of the main problems in the distribution network design. The primary problem of DG and capacitors optimal placement is to study a method to reduce power loss and voltage improvement as well as increasing the ATC. There are many methods for DG and capacitor placement for different purposes. In the past decades, much attempt have been contributed to capacitor placement problem. For example, in [1], fuzzy-genetically method for optimization is used to determine the place and the size of capacitor banks in distorted distribution systems. The fitness function reduces loss, optimized power and cost of capacitors placement, considering load voltage constraints. Capacitor placement and reconfiguration for loss reduction of distribution networks are used in [2] by an ant colony search algorithm. Also a heuristic constructive algorithm for capacitor placement in distribution systems is applied in [3].

In recent decades, different kinds of DGs have been made and different methods have been introduced for DG placement. In [4] a method for placement of a single DG on the distribution network is proposed. This method is based on the determination of most sensitive buses with voltage collapse. The analysis was done to reduce losses and improve the voltage profile and increase ATC. In [5] a multi-objective optimization method for DG placement is associated. One of the main factors in that paper is the network loss. A heuristic DG optimization method for distribution network is proposed in [6]. Moreover, the search space is reduced significantly in that work. In [7] a method to select the load buses for the DG placement based on loss reduction and voltage sensitivity improvement have been presented. An analytical approach for optimal placement of distributed generation sources in power systems is aimed to reduce loss by analytical methods in [8].

Nowadays different kinds of DGs and capacitors are simultaneously used in a lot of distribution networks. In [9] placement of DG and capacitors to reduce losses and improve the voltage profile using GA has been studied. In [10] two optimization models are proposed to improve the voltage profile. First, the DG placement problem is formulated. Then capacitor placement problem is modeled and solved.

In this paper one GA is applied to the multi-objective function including: loss reduction, load voltage profiles optimization and ATC maximization. The objective of DG and capacitor placement is to determine the placement and size of DG and capacitors. DG and capacitors are placed and the tap of ULTC transformer is set, so the system loss is reduced, load voltage profiles is improved and ATC is increased. There are some constraints on the voltage magnitude at each bus and apparent power passed through each line. It should be mentioned that in other articles less attention has been paid to simultaneous tap setting of ULTC and placement of DG and capacitors. In other articles, the ULTC is fixed to a tap in which, ULTC voltage ratio is *one* and there is no attempt to set adapting taps. In simulations a comparison between different modes was carried out with and without tap setting of ULTC. To show the effectiveness of the proposed method, it is applied to IEEE 41 bus radial distribution network. Simulation results show that simultaneous determination of location and size of DG and capacitors and the tap setting of ULTC transformer lead to more favorable results. The results show that the voltages in all buses remain within the desired range, loss is reduced and ATC is increased.

2. PROBLEM FORMULATION

The problem, which is formulated through a multi-objective mathematical model with three objectives, is as follows:

2.1Determining the fitness function to decrease line loss

In the power distribution network, loss depends on two factors line resistance and line current. Variations of line resistance are low and negligible. Overall line loss is related to the current and the line current depends on system topology and loads. It is usually impossible to reduce the value of loads, but line currents can be reduced with DG and capacitors proper placement. Therefore, with optimal DG and capacitors placement, line loss can be decreased. Power flow and loss can be formulated as:

$$P_i = V_i \sum_{j=1}^{n} Y_{ij} V_j \cos(\delta_i - \delta_j - \gamma_{ij}) \quad (1)$$

$$Q_i = V_i \sum_{j=1}^{n} Y_{ij} V_j \sin(\delta_i - \delta_j - \gamma_{ij}) \quad (2)$$

Where, P_i and Q_i are active and reactive power of the i'th bus, respectively. V_i is the i'th bus voltage, Y_i is the system admittance matrix element, δ is the bus voltage angle, and γ is the angle of the system admittance matrix element. The first objective fitness function (f_1) is defined as:

$$f_1 = P_{loss} = \sum_{i=1}^{n} P_{G_i} - \sum_{i=1}^{n} P_{D_i} \quad (3)$$

This fitness function shows the total line loss in the entire system (P_{loss}). P_{Gi} is the injected active power from power system to distribution network or i'th bus generated power by i'th DG. P_{Di} represents the total connected load.

2.2 Determining the fitness function to improve load bus voltages

Voltage constraint of load buses is shown as:

$$V_i^{min} \leq V_i \leq V_i^{max} \qquad i \in N_b \quad (4)$$

N_b stands for the total number of all the buses. V_i , V_i^{min} and V_i^{max} are i'th bus voltage magnitude, lower and upper boundaries of voltage magnitude of i'th bus respectively. Second fitness function is the voltage magnitude at load buses that is shown as (5). This fitness function must be decreased.

$$f_2 = \sum_{i=1}^{N_b} (V_i - V_n)^2 \quad (5)$$

V_n is the nominal voltage value that is considered one per-unit for all the buses in this article.

2.3 Determining the fitness function to increase ATC

ATC is one of the important factors in DG and capacitors placement in the distribution network. The capability of transmission lines is limited by ATC in the distribution network. ATC is increased because of active and reactive power injection by appropriate DG and capacitor placement. The third fitness function (f_3) is used to increase the available transfer capability that is defined as (6).

$$f_3 = \sum_{i=1}^{n} (S_{base} - S_{i-j}) \quad (6)$$

$$S_{i-j} = \sqrt{P_{i-j}^2 + Q_{i-j}^2} \quad (7)$$

$$S_{base} = S_{1-2} = 6.9860\ MVA \quad (8)$$

S_{i-j} is the value of apparent power flow through i'th bus to j'th bus. S_{base} is the Total Transfer Capability (TTC). S_{base} value for all lines is assumed 6.9860 MVA, which is achieved from simulation of the IEEE 41 bus system without any DG or capacitor. Maximum S_{i-j} and S_{1-2} is equal to 6.9860 MVA. Bus 1 is a substation bus. P_{i-j} and Q_{i-j} are the value of active and reactive power flow through i'th bus to j'th bus.

2.4 Multi-objective fitness function analyses using a genetic algorithm

GA invented by Holland in the early 1970's. It is a stochastic global search technique to optimization algorithms based on the principles of natural selection and genetic recombination. A possible solution to this problem is called an individual. An individual is represented by a computational data structure called a chromosome, which is composed of genes. The real value of a control parameter is encoded in a gene. The fitness of each individual is determined by running the GA, and examining the time required for convergence.

GAs can make possible simultaneous convergences to more than one optimum solution with a multimodal search. It is possible to adapt the genetic algorithm for determination of the global or near global optimum solution [11]. In this article, GA is applied to DG and capacitors placement and tap settings of ULTC. In addition, GA is used to determine active and reactive power values of DG and capacitors.

By proper choice of all variables using GA, multi-objective fitness function is optimized. In this paper, the multi-objective function is described as:

$$F = f_1 + f_2 - f_3 \qquad (9)$$

Where, F, f_1, f_2 and f_3 are multi objective fitness function, loss reduction, load voltage profiles optimization and ATC maximization, respectively. f_1 and f_2 should be minimized but f_3 should be maximized.

3. SIMULATION RESULTS

The proposed method is applied to the IEEE 41 bus radial distribution network. The structure of the system is shown in Fig. 1. Bus 1 is a substation bus and distribution network has one ULTC transformer at the first bus. This network has 41 load buses and 40 transmission lines. Total active and reactive loads are 4.635 MW and 3.250 MVar, respectively. The parameters of the network are given in the appendix A.

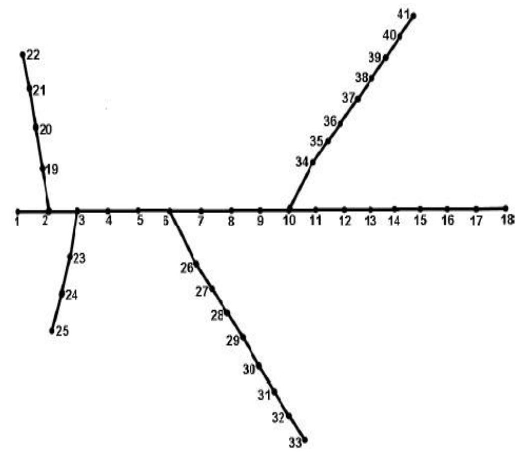

Fig. 1. Structure of the IEEE 41 bus distribution network

In this paper, one DG and four capacitors are assumed to add in the network. DG and capacitor characteristics are given in the Table 1. ULTC characteristics are given in the Table 2.

Table 1. DG and Capacitor Characteristics

	Number	Max. Active Power (MW)	Max. Reactive Power (MVar)
DG	1	4.0	2.0
Capacitor	4	-	0.4

Table 2. ULTC characteristics

	Tap Numbers	Min. (V_i /V_o)	Max. (V_i /V_o)
ULTC	6	1.00	1.05

At first stage, load flow was performed on the IEEE 41 bus distribution network. The voltage conversion ratio of the ULTC was set to *one* in this simulation. Power consumptions in distribution network are supplied only by the power system. At this stage, the distribution network has no DG and capacitor. Numerical values of three fitness functions are shown in Table 3.

Table 3. Numerical values of three fitness functions without DG and capacitor and ULTC tap setting

f_1	1.0075
f_2	1.8238
f_3	228.7923
$S_{1\text{-}2\ MVA}$	6.9860
$V_{trans\text{-}pu}$	1.00

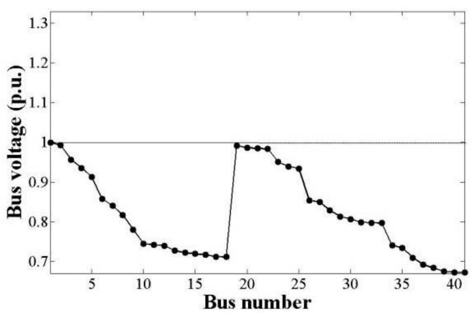

Fig. 2. Bus voltage magnitudes without DG and capacitor and ULTC tap setting

In Table 3, the network has relatively high losses. Load bus voltages are not desirable. In addition, relatively high power passes through the first lines of the network. Therefore, active and reactive power generators are needed to improve network. At second, third and fourth stages load flow was run again in two modes by adding a DG and four capacitors in the network. In the first mode, tap of ULTC was set, however in the second mode tap of ULTC was fixed to have the voltage ratio equals to one. In the all stages and modes, the GA attempts to minimize the values of f_1 (Eq. 3) and f_2 (Eq. 5) and maximize the value of f_3 (Eq. 6). In the second stage, although this fitness function has reduced loss, but there is no effort to improve either the bus voltage profile or to increase the ATC. Also at third and fourth stages, only one of voltage profiles or ATC is considered as a fitness function. The results are shown in Tables 4 to 5.

Table 4. Numerical values of three fitness functions with loss reduction function

$F = f_1$	with ULTC tap setting	without ULTC tap setting
F	0.143	0.152
f_1	0.143	0.152
f_2	0.058	0.020
f_3	252.936	253.538
$S_{1\text{-}2\ MVA}$	2.386	2.310
$V_{trans\text{-}pu}$	1.05	1.00
$P_{DG\ MW}$	2.4	2.6
$Q_{DG\ Mvar}$	1.3	0.9
DG_{Place}	10	10
$C_{1\ Place}$	27	29
$C_{2\ Place}$	29	32
$C_{3\ Place}$	31	38
$C_{4\ Place}$	38	41

Table 5. Numerical values of three fitness functions with improving voltage profiles function

$F = f_2$	with ULTC tap setting	without ULTC tap setting
F	0.006	0.007
f_1	0.212	0.250
f_2	0.006	0.007
f_3	251.444	249.511
$S_{1\text{-}2\ MVA}$	1.794	2.049
$V_{trans\text{-}pu}$	1.01	1.00
$P_{DG\ MW}$	3.4	3.7
$Q_{DG\ Mvar}$	1.1	1.1
DG_{Place}	9	9
$C_{1\ Place}$	30	32
$C_{2\ Place}$	32	32
$C_{3\ Place}$	33	33
$C_{4\ Place}$	41	41

Main fitness functions of each stage are highlighted with gray color in tables. By comparing second columns of Tables 4 and 5, it is clear that in Table 4, losses are lower but bus voltage profiles are undesirable. Conversely, in Table 5, losses are higher and bus voltage profiles are more favorable. By adding DG and capacitors and comparing Table 6 with two previous tables, it can be seen that with any fitness function selection, ATC is improved. In fitness function with only the ATC, the ATC is considerably improved, but loss is still considerable and the bus voltage profiles are more unfavorable. Comparison of the apparent power flow through bus 1 to bus 2, $S_{1\text{-}2}$ from all tables with Table 3, show that line current in the distribution network with DG and a capacitor is reduced significantly. Therefore, according to the mentioned results, using a mono-objective function cannot improve the network status.

Comparing second and third columns of Tables 4 to 6 indicate that approximately the similar results are obtained. Also by the same comparison, it is evident that all fitness functions with ULTC tap setting have better values without ULTC tap setting.

Table 6. Numerical values of three fitness functions with increasing ATC function

$F = f_3$	with ULTC tap setting	without ULTC tap setting
F	254.459	254.471
f_1	0.167	0.172
f_2	0.015	0.021
f_3	254.459	254.471
$S_{1\text{-}2\ MVA}$	1.870	1.874
$V_{trans\text{-}pu}$	1.03	1.00
$P_{DG\ MW}$	3.1	3.1
$Q_{DG\ Mvar}$	0.9	0.9
DG_{Place}	9	10
$C_{1\ Place}$	30	30
$C_{2\ Place}$	31	31
$C_{3\ Place}$	38	38
$C_{4\ Place}$	39	39

In the next stage, the relative improvement fitness function is described for all three previous functions. The multi-objective function presented in (Eq. 9) is used. In Tables 4, 5 and 6 minimum f_1 and f_2 and maximum f_3 are highlighted with gray color. Following equations represent minimization and maximization results:

$$Min(f_1) = 0.143 \quad (10)$$
$$Min(f_2) = 0.006 \quad (11)$$
$$Max(f_3) = 254.459 \quad (12)$$

Considering the optimized numerical values, the differences between three mono-objective function values (equations 10 to 12) are considerable. Therefore, per-unit system is required. Equations (13 to 15) show base values of each function.

$$f_{1\text{-}base} = 0.143 \quad (13)$$
$$f_{2\text{-}base} = 0.006 \quad (14)$$
$$f_{3\text{-}base} = 254.459 \quad (15)$$

Thus, a multi-objective function using a combination of three mono-objective functions is made. Placement results by using this fitness function are presented in Table 7. This table shows that the results in the second column are considerably better than the third column in 2^{nd} to 6^{th} rows. Comparing Tables 8 and 9 show the normalized values of Table 7.

By comparing the gray area of Table 4 to Table 9, it can be shown that using the multi-objective function causes to improve each of three functions to acceptable values. In the other words, it is possible to improve the overall network status by using an intelligent optimization algorithm with a multi-objective function.

Fig. 3 and Fig. 4 shows that using the proposed method, bus voltage magnitudes with ULTC tap setting are more favorable than without ULTC tap setting. Fig. 5 shows the flowchart of proposed method.

Table 7. Per unit values of three fitness functions with multi-objective function

$F_{pu} = f_{1pu} + f_{2pu} - f_{3pu}$	with ULTC tap setting	without ULTC tap setting
F	1.109 p.u.	1.872
f_{1pu}	1.087 p.u.	1.707
f_{2pu}	1.014 p.u.	1.150
f_{3pu}	0.993 p.u.	0.985
$S_{1\text{-}2\ MVA}$	2.468	2.140
$V_{trans\text{-}pu}$	1.02	1.00
$P_{DG\ MW}$	2.4	3.8
$Q_{DG\ Mvar}$	1.0	1.0
DG_{Place}	10	9
$C_{1\ Place}$	30	30
$C_{2\ Place}$	31	31
$C_{3\ Place}$	33	32
$C_{4\ Place}$	40	40

Table 8. Normalize values of three fitness functions with multi-objective function and ULTC tap setting

with ULTC tap setting	p.u.	normal
f_1	1.087 p.u.	0.155
f_2	1.014 p.u.	0.006
f_3	0.993 p.u.	252.678

Table 9. Normalize values of three fitness functions with multi-objective function and without ULTC tap setting

without ULTC tap setting	p.u.	normal
f_1	1.707	0.244
f_2	1.150	0.006
f_3	0.985	250.642

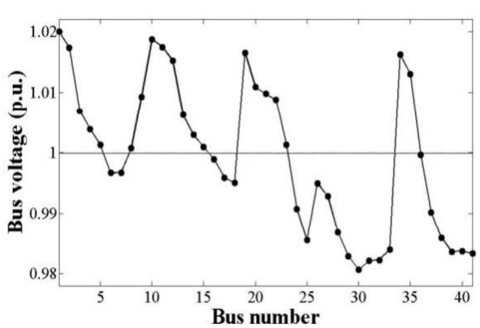

Fig. 3. Bus voltage magnitudes using the proposed method with ULTC tap setting

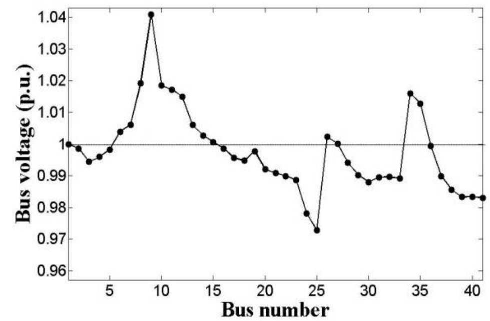

Fig. 4. Bus voltage magnitudes using the proposed method without ULTC tap setting

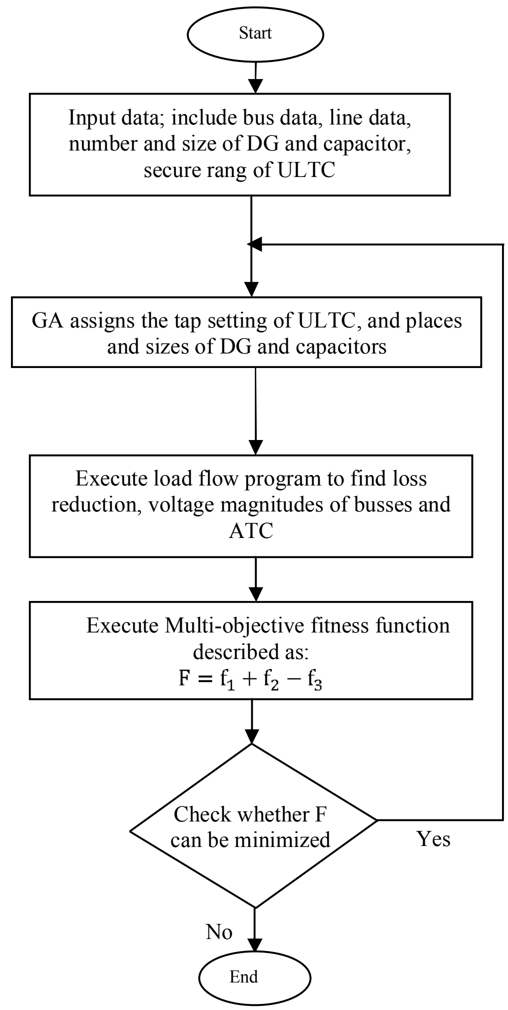

Fig. 5. shows the flowchart of the proposed method.

4. Conclusions

In this paper, an improved GA based method for proper placement of a DG and capacitors and the tap setting of ULTC transformers has been proposed. The proposed algorithm is based on a new multi-objective function, which is matched with three mono-objective functions to reduce losses, improve the bus voltage profiles and to increase ATC. A multi-objective function of several per-unit Objects is created. To verify the proposed method, simulations are used based on the IEEE 41 bus distribution network. In simulations, a comparison between different modes with and without tap setting of ULTC has been shown. The capability of this method has been well shown by the results. The simulation results using multi-objective fitness function has validated the effectiveness of the proposed approach.

APPENDIX

A. Parameters of the IEEE 41-bus distribution systems

Table 8. Parameters of the IEEE 41 bus radial distribution network

Line Index	To Bus Index	From Bus Index	R(ohm)	X(ohm)	bus load P(KW)	bus load Q(KVar)
1	1	2	0.0992	0.0470	100	60
2	2	3	0.4930	0.2511	90	40
3	3	4	0.3660	0.1864	120	80
4	4	5	0.3811	0.1941	60	30
5	5	6	0.8190	0.7070	60	20
6	6	7	0.1872	0.6188	200	100
7	7	8	0.7114	0.2351	200	100
8	8	9	1.0300	0.7400	60	20
9	9	10	1.0440	0.7400	60	20
10	10	11	0.1966	0.0650	45	30
11	11	12	0.3744	0.1238	60	35
12	12	13	1.4680	1.1550	60	35
13	13	14	0.5416	0.7129	120	80
14	14	15	0.5910	0.5260	60	10
15	15	16	0.7463	0.5450	60	20
16	16	17	1.2890	1.7210	60	20
17	17	18	0.7320	0.5470	90	40
18	2	19	0.1640	0.1565	90	40
19	19	20	1.5042	1.3554	90	40
20	20	21	0.4095	0.4784	90	40
21	21	22	0.7089	0.9373	90	40
22	3	23	0.4512	0.3083	90	50
23	23	24	0.8980	0.7091	420	200
24	24	25	0.8960	0.7011	420	200
25	6	26	0.2030	0.1034	60	25
26	26	27	0.2842	0.1447	60	25
27	27	28	1.0590	0.9337	60	20
28	28	29	0.8042	0.7006	120	70
29	29	30	0.5075	0.2585	200	600
30	30	31	0.9744	0.9630	150	70
31	31	32	0.3105	0.3619	210	100
32	32	33	0.3410	0.5302	60	40
33	10	34	0.2030	0.1034	60	25
34	34	35	0.2842	0.1447	60	25
35	35	36	1.0590	0.9337	60	20
36	36	37	0.8042	0.7006	120	70
37	37	38	0.5075	0.2585	200	600
38	38	39	0.9744	0.9630	150	70
39	39	40	0.3105	0.3619	210	100
40	40	41	0.3410	0.5302	60	40

REFERENCES

[1] M. Ladjavardi and M. A. S. Masoum "Genetically Optimized Fuzzy Placement and Sizing of Capacitor Banks in Distorted Distribution Networks," *IEEE Transactions on Power Delivery,* Vol. 23, No. 1, Jan 2008.

[2] Ch. Chang "Reconfiguration and Capacitor Placement for Loss Reduction of Distribution Systems by Ant Colony Search Algorithm," *IEEE Transactions on Power Systems,* Vol. 23, No. 4, Nov 2008.

[3] I. C. Silva, S. Carneiro, E. J. Oliveira, J. S. Costa, J. L. Pereira and P. A. Garcia "A Heuristic Constructive Algorithm for Capacitor Placement on Distribution Systems," *IEEE Transactions on Power Systems,* Vol. 23, No. 4, Nov 2008.

[4] H. Hedayati, S. A. Nabaviniaki and A. Akbarimajd "A Method for Placement of DG Units in Distribution Networks," *IEEE Transactions on Power Delivery,* Vol. 23, No. 3, Jul 2008.

[5] M. Moeini-Aghtaie, P. Dehghanian and S. H. Hosseini "Optimal Distributed Generation Placement in a Restructured Environment via a Multi-Objective Optimization Approach," *16th Conf. on Electrical Power Distribution Networks (EPDC),* Bandar abbas, Iran, 19-20 April 2011.

[6] O. Aliman1, I. Musirin, M. M. Othman and M. H. Sulaiman," *5th International Power Engineering and Optimization Conference (PEOCO),* Shah Alam, Selangor, Malaysia, 6-7 Jun 2011.

[7] A. K. Singh and S. K. Parida "Selection of Load Buses for DG placement Based on Loss Reduction and Voltage Improvement Sensitivity," *IEEE International Conf. on Power Eng., Energy and Electric Drives,* p.p. 1-6 May 2011.

[8] C. Wang and M. H. Nehrir "Analytical Approaches for Optimal Placement of Distributed Generation Sources in Power Systems" *IEEE Transactions on Power Systems,* Vol. 19, No. 4, Nov 2004.

[9] M. Kalantari and A. Kazemi "Placement of Distributed Generation unit and Capacitor Allocation in Distribution Systems using Genetic Algorithm," *10th International Conf. on Environment and Electrical Eng., EEEIC* p.p. 1-5, 2011.

[10] M. Wang, and J. Zhong "A Novel Method for Distributed Generation and Capacitor Optimal Placement considering Voltage Profiles," *IEEE power and Energy Society General Meeting,* p.p. 1-6 Jul 2011.

[11] M. Tarafdarhagh, A. Sadighmanesh, and M. R. Hesamzadeh "Improvement of Load Bus Voltages Considering the Optimal Dispatch of Active and Reactive Powers," *43rd International Universities Power Engineering Conf. (UPEC),* Padova, Italy, (on CD) 1-4 Sep 2008.