Distributed Generation Site and Size Allocation Through a Techno Economical Multi-objective Differential Evolution Algorithm

Hosein A. Hejazi
Dept. of Electrical Eng.
Amirkabir Uni. of Tech.
Tehran, Iran
hejazi.hossein@gmail.com

Maryam A. Hejazi
Dept. of Electrical Eng.
Amirkabir Uni. of Tech.
Tehran, Iran
akhavanhejazi@aut.ac.ir

Gevork B. Gharehpetian
Dept. of Electrical Eng.
Amirkabir Uni. of Tech.
Tehran, Iran
grptian@aut.ac.ir

Mehrdad Abedi
Dept. of Electrical Eng.
Amirkabir Uni. of Tech.
Tehran, Iran
abedi@aut.ac.ir

Abstract— **The evaluation of technical effects of connecting distributed generation to distribution networks is a complicated activity requiring a wide range of network operational and security characteristics to be qualified and quantified.** ***This paper presents a Differential Evolution Algorithm for optimal allocation of distributed generation in distribution networks considering various technical and economical aspects of the problem. The optimization*** **considers different technical issues like stability of systems voltage profile, capacity release of distribution system, voltage dependency of loads and different modes of DG operation as PV or PQ modes. Multi objective function that is to be minimized also consists of the costs associated with energy purchase from the grid and the DGs according to feed in tariffs and the cost of network upgrading.**

Index Terms— **Energy market, distribution network,** ***DG sitting and sizing, Feed-in Tariffs, stability analysis , evolutionary algorithms, differential evolution algorithm***

I. INTRODUCTION

IN a liberalized energy market, the engineering attributes of planning should be redefined even though for the most parts, the aims remain the same. Various objectives should be simultaneously fulfilled to reach a distribution system with optimal development and operation. Nowadays, there are still some barriers restricting an increased market penetration of Distributed Generation (DG). The high costs and unreliable performances of many DG technologies, the lack of established standards, the architecture of the distribution system, possible degradation of power quality, reliability and control of the system are impediments to the DGs break through [1]. DG installation, apart from its operation, needs a careful attention for the interaction with existing power network concerning to stability, reliability, power quality and protection issues [2-5]. The location of DG and its size is one of main problems. Many efforts have been dedicated to determine the optimal size and location of distributed generation. [6] presents an analytical algorithm to define the proper site and size for a single DG in order to minimize the electrical network losses.

Several works have been done for the selection of optimal locations and sizes of distributed generators to improve different factors such as: total power loss, the total voltage deviation and the total expansion cost, including substation expansion, DG installation and feeders upgrade, active and reactive losses [7, 8, 9, 10, 11, 12, and 13].

[14] studies the effect of voltage dependency of loads in multi-objective approach that stated in [13]. The optimal size and place for a unity power factor DG is obtained through an exhaustive method; however [14] has not considered the expenses related to installation of DGs and eventually the optimum obtained and maximum allowable values are very close. Investigating the aforementioned studies shows that consideration of various, different technical issues leads to different solutions that many of those may not agree with others. Therefore optimizing all the technical aspects in the objective function is not reasonable.

In this paper, a novel approach for the determination of the site and size of DGs is presented that accounts for reliable operation of distribution system. To be more specific, optimal location, size and power factor of multiple DGs are determined so that probable faults have the least effect on DG operation and therefore the probability of DGs outage is minimized. The proposed algorithm also considers other different technical issues like voltage profile, capacity release of distribution system, voltage dependency of loads and different modes of DG operation. Multi-objective function which should be minimized also consists of costs associated with energy purchase from the grid and the DGs according to feed in tariffs and the cost of network upgrading. A Differential Evolution Algorithm (DEA) is applied to solve this problem and the implementation issues are discussed.

This paper is organized as follows: section II describes problem formulation. Section III presents implementation of DEA on optimization of energy and reserve. The case studies and the comparison of the results are given in Section IV and Section V concludes the paper.

II. OBJECTIVE FUNCTION OF DG SITTING AND SIZING

The main objective of the proposed planning algorithm is to determine proper locations for new generators and their optimal size and power factor by minimizing different functions related to the cost of energy losses (C_L), interruptions, the cost of network upgrading (C_U) and the cost of energy purchased (C_E). Such objectives should be met subject to the network power flow equations, the limits on the bus voltages and the technical constraints. A mathematical expression of the problem is, as follows:

$$\min \; C(x(u)) = \min[C_U, C_L, C_E] \tag{1}$$

Where, $x(u)$ is a power flow solution calculated as a function of vector u , which stores data about the position and the size of generators. In the following, the objective function is described in detail.

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A. *Cost of Network Upgrading* (C_U)

The cost of network upgrading takes into account investments that can be necessary to upgrade a distribution network to face with the natural growth of the energy demand. The general expression is, as follows:

$$C_U = \sum_{j=1}^{n_t} C_{0,j} \tag{2}$$

where n_t is the number of network nodes and $C_{0,j}$ is the present cost of the *j*th branch.

B. *Cost of Purchased Energy* (C_E)

In order to allow assessing the more convenient penetration level of DG in a given distribution network, the cost of purchasing energy from the transmission grid, $(C_{kWh})_{TR}$ and from DG $(C_{kWh})_{DG}$,has been considered.

. By calculating the amount of energy generated per year by each generator on the basis of its power capacity, it is possible to assess the energy that a DISCO may buy from both the transmissions system and the DG installed in its network during the study period. By resorting to an average value of energy rate in the planning period, it is easy to calculate the term $(C_{kWh})_{TR}$ and $(C_{kWh})_{DG}$, opportunely transferred to the cash value at the beginning of the planning period, so that they can be comparable with the other costs of the objective function. Equation (3) allows assessing the impact of DG on MV distribution networks and the more convenient penetration level. This limit will be reached when the benefits, achievable by adding new DG, no longer compensate their relative costs:

$$C_E = (C_{kWh})_{TR} + (C_{kWh})_{DG} \tag{3}$$

C. *Cost of Energy Losses* (C_L)

The real power losses in a system, which is popularly referred to as "exact loss formula", is given as follows:

$$C_L = c_L \cdot \sum_{i=1}^{N} \sum_{j=1}^{N} [\alpha_{ij}(P_i P_j + Q_i Q_j) + \beta_{ij}(Q_i P_j - P_i Q_j)] \tag{4}$$

$$\alpha_{ij} = \frac{r_{ij}}{V_i V_j} \cos(\delta_i - \delta_j) \tag{5}$$

$$\beta_{ij} = \frac{r_{ij}}{V_i V_j} \sin(\delta_i - \delta_j) \tag{6}$$

where $P_i$and Q_i are the net active and reactive power injections to *ith* bus. c_L is the coefficient of annual power losses cost.

D. *Total Voltage Deviation (TVD)*

By introducing DG into existing system, voltage can be improved because DG can provide a portion of the real and reactive power to the load and reduce the losses in the feeders; consequently the voltage deviation is improved.

$$TVD = \sum_{i=1}^{N_{pq}} K_v \left|V_{ref} - V_i\right| + \sum_{i=1}^{N_{pq}} K'_v \max(0, V_i - V_i^{\max}, V_i^{\min} - V_i) \tag{7}$$

Where V_i *is the voltage in per unit at the system PQ buses.* K_V *and* K'_V *are the corresponding coefficients related to deviations from the reference and boundary values of the voltage at ith bus.*

E. *Total Capacity Release (TCR)*

The summation of total power delivered by the substation transformers to the network must be within the substation capacity limit. *The power flowing through existing line sections should also be within their limits.* The index (TCR) gives important information about the level of MVA flow/currents through the substation and the network regarding the maximum capacity of facilities.

$$TCR = \sum_{j=1}^{N_t} K_{t,j}(S_j - S_j^{\max})/S_j^{\max} + \sum_{i=1}^{N_l} K_{l,i}(S_i - S_i^{\max})/S_i^{\max} \tag{8}$$

where, $K_{t,j}$ is the weighting factor of *jth* transformer and $K_{l,i}$ is the weighting factor of *ith* line section. $K_{t,j}$ and $K_{l,I}$ are proportional with initial cost of transformers and line segments whith are transformed to the operating cost considering a 0.3 rate of return for investment .

III. DEA FOR CO-OPTIMIZATION PROBLEM

Like nearly all evolutionary algorithms, DEA is a population based optimizer that attacks the starting point problem by evaluating the objective function at multiple random initial points. A population composed of N_P individuals evolves over several generations to reach an optimal solution. DEA includes several steps that are explained with more details in [15]. This section discusses the application of DEA for the proposed problem.

A. *Initial Population*

The first generation in DEA algorithm consists of a population of N_P vector with D dimension, where D is the number of control variables. The control variables in this problem are the number of DG units, the location of each DG, the capacity to be placed, and the power factor or voltage magnitude each unit should operate at. However how to implement these into the DEA so that a robust algorithm shall be attained is another problem. Since the number of places that a unit can be located are limited compared to the amounts that DG capacity can take and each position can significantly change the outcome of the objective function, we must make sure that the program examines all the places that a DG may be sited. So a problem specific approach was uses in this work.

In this problem, each vector will contain the active power generation in each node of distribution system P_i. Either of each unit power factor or voltage magnitude can be set as the other control variable for each DG unit since the meters normally calculate the price that should be paid to a DG unit according to their operating power factor, here the DG power factors have been set as control variables. It should be noted that even though we place the DG units in arbitrary positions, quite a few of them will remain in the successive generations until the optimum solution with the desired number of DGs is selected. This is due to the special fitness function that is developed for this purpose. Therefore the population individuals will be in this form:

$$x_{i,G} = [P_2, \ldots, P_N, PF_2, \ldots, PF_N] \tag{9}$$

where, N is the number of buses. The population size NP normally considered as 3.D to 5.D while D is equal with the number of control variables.

A random number generator assigns each parameter of every vector a value from within the prescribed range. For example, the initial value of the j^{th} parameter of the i^{th} vector is, as follows:

$$x_{j,i,0} = rand(0,1).(b_{j,u} - b_{j,L}) + b_{j,L} \tag{10}$$

Where $b_{j,l}$ and $b_{j,u}$ are the lower and upper bounds for each control variable of each vector of population.

The control variables of all the vectors which are P_i and PF_i therefore will lay within their limits but since the control variables are not completely independent it is required to set additional constraints in initialization step to replace some of infeasible solutions.

Parts of these constraints are related to the satisfaction of the slack bus or the substation active power constraints. The total amount of active load is known and is equal with P_L. Suppose that system total loss is predefined as P_{loss} respectively; the maximum capacity of the substation bus should not be violated which will result in the following constraint:

$$P_{SS} = P_{loss} + \sum_{i=2}^{N} (P_{D,i} - P_{G,i}) \tag{11}$$

$$P_{SS}^{\min} < P_{SS} < P_{SS}^{\max}$$

P_{SS} is the power that has been dispatched to the substation bus. Note that initially a rough amount of 2 percent for P_{loss}.

B. Unbalanced Load Flow, Short Circuit Calculation and Fitness Evaluation

Because of unbalanced nature of many distribution systems, a three phase unbalanced load flow, designed for distribution systems, is applied to this work. More discussions about the utilized load flow algorithm are in [16]. Load flow was performed for each individual in steady state. The three phase load flow considers voltage dependency of loads and different modes of DG operation as PV or PQ.

$$F_i = C_{E_i} + C_{U_i} + C_{L_i} + TVD_i + TCR_i \tag{12}$$

After evaluation of the fitness of individuals, the stability index should be computed. The stability index for the distribution system with a defined amounts of DGs located in certain places is obtained by calculating the short circuit power injection of DGs during the fault. Since this analysis may take quite some time, we have tried to avoid these calculations as much as possible. Therefore the stability is not included into the fitness function as in (12), since transient stability here is a condition to be met, not an objective to optimize. Therefore, we assign each individual an index as "stability" to show if this individual can maintain the stability of the system or not after the contingency and this index will take effect in the selection procedure during evolution. Since the searching space is very large in optimization problems, it is necessary to improve the efficiency for the practical use. Two measures are proposed to improve the selection procedure of DE iteration:

Strategy 1: After fitness evaluation of a generation, the whole population will be sorted by the fitness from the best to the worst. It aims at finding out the elite part of the whole individuals, stable ones among these elite can help to lead the converge direction.

Strategy 2: Instead of all individuals in the population, only certain percentages of the population with better fitness will undergo the Short circuit calculation to find out some stable "seeds" used to push the population converging to a feasible and stable space. This can help to release the computational burden without deteriorating the reproduction characteristics of the evolution.

C. DEA Operators

- *Mutation*

In DEA a mutant vector is produced from each individual. The DE mutation scheme that has been chosen among the several ways stated in references [17, 18, and 19] for mutation is the one as follows:

$$v_{i,G} = x_{i,G} + \lambda(x_{best} - x_{i,G}) + F(x_{r1,G} - x_{r2,G}) \tag{13}$$

This form of mutation uses the best found vector to push mutant vectors toward it. The algorithm eventually converges with less iteration, so it provides the best choice for smooth search spaces. The integers *r1* and *r2* are chosen randomly from the interval [1, NP] and are different from the running index *i.*

- *Cross Over*

DEA also employs a uniform crossover. Crossover builds trial vectors out of parameter values that have been copied from two different vectors. In particular DEA mixes each vector with a mutant.

$$u_{i,G} = u_{j,i,G} = \begin{cases} v_{j,i,G} & if \ \text{rand}_j(0,1) \le C_r \ \text{ or j=rn}_i \\ x_{j,i,G} & \text{otherwise} \end{cases} \tag{14}$$

Cr is a user defined value between 0 and 1 that controls the fraction of parameters that copied from the mutant. $rand_j$ is a random number in [0,1) interval and rn_i is a randomly chosen index between *1,…,D* that ensures at least one of the control variables change during cross over.

- *Selection*

Each u_{iG} vector produced in crossover is compared with associated x_{iG}. The selected vector between a trial vector and its parent in presence of constraints moves to the next generation.

- *Global Best Individual*

For the first generation, the global best individual is the best one in the initial population. To obtain the x_{best} in the successive generations the individuals need to compete with each other. The rules of competition are as stated above. For each generation $x_{best,G}$ is obtained and is compared with the global best individual x_{best}. If the $x_{best,G}$ is better than x_{best}, it takes x_{best} place; otherwise x_{best} remains unchanged.

IV. CASE STUDY

The IEEE 37-bus distribution system is used to demonstrate the effectiveness of the proposed method for various cases [20].

This feeder is an actual feeder located in California. The characteristics of the feeder are, as follows:

- Three-wire delta operating at a nominal voltage of 4.8 kV
- All line segments are underground
- Substation voltage regulator consisting of two single phase units connected in open delta
- All loads are "spot" loads and consist of constant PQ, constant current and constant impedance and
- The loading is very unbalanced.

Although there are very few three-wire delta systems in use, this feeder has been chosen to test the software to assure that it can handle any unbalanced type of feeder. The total active power of loads is 2.63 MW and the total reactive power of loads is 1.55 Mvar. The characteristics of cable types used in different line segments and their rough price per meter is shown in Table I. The feed-in tariff prices for different buses and their fault occurrence ratio are summarized in Table II. The loading of the line segments, their maximum allowable currents is depicted in Table III.

TABLE I
UNDERGROUND CABLE LINE CONFIGURATION DATA

Config.	Cable (AWG)	Conductor size **(mm^2)**	Ampacity (A)	Price ($/m)
721	1000 AA, CN	3×500	550	213
722	500 AA, CN	3×240	385	161
723	2/0 AA, CN	3×70	200	64
724	2# AA, CN	3×35	135	41

TABLE II
FEED-IN TARIFF PRICES FOR DIFFERENT BUSES AND THEIR FAULT OCCURRENCE RATIO

Node	CHP FIT rates (¢)/kWh	Fault occurrence ratio		Node	CHP FIT rates (¢)/kWh	Fault occurrence ratio	
		two phase	three phase			two phase	three phase
701	6.89	0	0	711	7.05	0.025	0.007
702	7.05	0.002	0	740	7.05	0.032	0.01
703	7.05	0.005	0.002	741	7.05	0.018	0.005
727	6.89	0.03	0.002	731	7.15	0.025	0.008
744	6.89	0.01	0	775	7.23	0.025	0.01
728	6.89	0.025	0.005	705	6.89	0.027	0.007
729	6.89	0.03	0.008	712	6.89	0.032	0.01
730	7.15	0.008	0	742	6.89	0.017	0.007
709	7.23	0.005	0	713	7.05	0.015	0.002
708	7.23	0.005	0	704	7.05	0.025	0.007
732	7.05	0.02	0.005	714	6.89	0.031	0.01
733	7.23	0.015	0.002	718	6.89	0.029	0.01
734	7.23	0.015	0.002	720	7.05	0.023	0.007
710	7.05	0.028	0.007	706	6.89	0.039	0.012
735	7.05	0.02	0.005	725	6.89	0.027	0.007
736	7.05	0.035	0.01	707	6.89	0.041	0.013
737	7.15	0.015	0.007	722	6.89	0.024	0.007
738	7.15	0.028	0.007	724	6.89	0.038	0.01

It is assumed that the demand increases about 50 percent of the current value. Then for the new configuration the optimum solution including the network expansion and installation of DGs is proposed. The average price of energy purchase from the whole sale market is considered to be *4¢* /kWh. The Feed-In Tariff prices for distributed generation were considered in two different ways. At the first case a uniform price of 7 ¢/kWh for all CHP units has been considered.

It should be highlighted that, in the presence of a liberalized electricity market, different retail sales rate of the energy produced by a DG unit should be considered. These retail sales depend on the technology adopted (mini gas turbine, CHP, wind turbine, etc.), the regulatory actions and the willingness to harness the renewables. So in the second case different prices is considered for different buses. These prices may reflect the installation cost in different areas or the willingness of the distribution network for DG installation in particular area.

TABLE III
LOADING INFORMATION OF LINE SEGMENTS IN STARTING CONFIGURATION

Node A	Node B	Length (m.)	Config.	Maximum line flow(A) 100%loading	Loading (%)	Maximum line flow(A) 150%loading	Loading (%)
701	702	292.6	722	267.66	69	405.83	105
702	705	121.92	724	20.46	15	33.23	25
702	713	109.72	723	59.47	30	92.36	46
702	703	402.3	722	189.70	49	288.79	75
703	727	73.1	724	42.39	31	65.96	49
703	730	182.8	723	147.60	74	224.31	112
704	714	24.3	724	26.67	20	42.82	31
704	720	243.8	723	66.86	33	103.67	52
705	742	97.5	724	20.70	15	33.76	25
705	712	73.15	724	19.41	14	31.29	23
706	725	85.3	724	9.78	7	15.13	11
707	724	231.6	724	9.74	7	15.02	11
707	722	36.5	724	35.11	26	54.96	40
708	733	97.5	723	122.58	61	186.82	93
708	732	97.5	724	9.84	7	15.55	11
709	731	182.88	723	19.58	15	32.33	16
709	708	97.53	723	130.67	65	199.87	100
710	735	60.9	724	19.82	15	31.07	23
710	736	390.1	724	9.74	7	15.08	11
711	741	121.9	723	9.78	5	15.14	8
711	740	60.9	724	19.88	15	32.55	24
713	704	158.5	723	72.40	36	111.37	56
714	718	1585 6	724	19.97	15	32.88	24
720	707	280.4	724	44.75	33	69.15	51
720	706	182.9	723	9.78	5	15.10	8
727	744	85.3	723	35.00	17	55.62	28
730	709	60.9	723	130.66	65	198.37	99
733	734	170.6	723	105.25	53	160.59	80
734	737	195.1	723	81.06	41	125.42	63
734	710	158.5	724	25.85	19	40.70	30
737	738	121.9	723	51.10	26	78.72	40
738	711	121.9	723	29.63	15	46.95	23
744	728	60.96	724	16.82	12	26.83	20
744	729	85.3	724	9.78	7	15.15	11
775	709	0	XFM-1	0	0	0	0
799	701	563.88	721	366.20	67	554.22	101

The DG units is considered to be among the CHP technologies including micro turbines, reciprocating engines, mini gas turbines which make up for most of the capacities installed up to now. These units usually have a synchronous or induction type generator which can normally operate at a maximum power factor of 0.85 due to the limitation of their prime movers. The price paid to distributed generators also depends on their power factor which is measured by the meters at the generating facility.

The optimum place, DG size, and DG power factor is computed in several steps. In this way the effect of each assumption can clearly be demonstrated. the results in each step has be obtained for installation of one and two DG units.

Step 1:

In the first step, the difference of energy purchase from the network and from DG unit has been ignored. so the optimization has been performed for technical objectives except the stability index. It can be seen that the optimal amount of DG is defined to be the maximum allowable value considered for DG penetration (64%). also the optimum place obtained for placement of one DG is necessarily not one of the optimal places for two DGs as can be seen in Table IV. Also as it can be expected the TVD and TCR factors are lower in two DGs case.

Step 2:

In the second step, a uniform Feed-In Tariff price is considered for all the installation locations. In this case the amount allocated to the DG units decreases considerably. Also the optimal location changes due to improvement of TVD and TCR.

Step 3:

In the third step, different price for installation points has been considered.

It is obvious that the total cost increases in this case but the total voltage deviation decrease in this case and thus shows the regulatory enforcement impact of the network decisions. it should be noted that the optimum power factor for the DG units is not necessarily equal with unity but depending to the case different optimum power factors can be attained.

Step 4:

In the final step, the effect of considering the Stability index is investigated. The optimum location without considering the difference of DG price is shown in Table VII. It can be seen that the optimum location changes with considering the Stability index and with all other parameters kept constant. The unit power factor also changes since the stability index of synchronous generator changes significantly with respect to the power factor and that is because of initial rotor angle dependency to the power factor.

Fig.1 shows the voltage profile diagram of the distribution system with considering different prices for each node and for the installation of one and two DG units. It also shows the voltage profile in the starting configuration. It is seen that installation of DG significantly improves the voltage profile, also considering the stability index has changed the DG location and variation of voltage profile. So considering the stability changes the optimum place and increase the voltage deviation and the total objective function but decreases the stability index of the system.

TABLE IV

OPTIMAL DG LOCATION, SIZE AND POWER FACTOR FOR INSTALLING ONE AND TWO DGS AND COMPARISON OF DIFFERENT OBJECTIVES IN STEP 1

DG units	Location	Size (kW)	P_{net}(kW)	P. F	Fitness	TVD	TCR	C_{DG} (\$/kWh)	C_{net} (\$/kWh)	C_{total} (\$/kWh)
one	708	2400	1337	0.87	217.48	20.63	10.73	124.58	66.85	191.43
two	720,711	1804,1473	451	0.98,0.94	210.29	15.25	9.97	163.91	22.55	186.46

TABLE V

OPTIMAL DG LOCATION, SIZE AND POWER FACTOR FOR INSTALLING ONE AND TWO DGS AND COMPARISON OF DIFFERENT OBJECTIVES IN STEP 2

DG units	Location	Size (kW)	P_{net} (kW)	P. F	Fitness	TVD	TCR	C_{DG} (\$/kWh)	C_{net} (\$/kWh)	C_{total} (\$/kWh)
one	737	1617	2108	0.85	262.25	33.75	11.35	117.54	105.4	222.94
Two	732,741	597.92,1203	1927	0.87,0.86	263.3	30.81	11.45	129.38	96.35	225.73

TABLE VI

OPTIMAL DG LOCATION, SIZE AND POWER FACTOR FOR INSTALLING ONE AND TWO DGS AND COMPARISON OF DIFFERENT OBJECTIVES IN STEP 3

DG units	Location	Size (kW)	P_{net} (kW)	P. F	Fitness	TVD	TCR	C_{DG} (\$/kWh)	C_{net} (\$/kWh)	C_{total} (\$/kWh)
one	737	1823	1937	0.85	265.83	29.94	11.73	133.49	96.85	230.34
two	707,737	541,1376	1814	0.98,0.8	265.6	27.7	10.27	141.92	90.7	232.62

TABLE VII

OPTIMAL DG LOACATION AND SIZE WITH SND WITHOUT INCLUDING STABILITY INDEX

Objective	Location	Size (kW)	P_{net} (kW)	P. F	Fitness	TVD	TCR	F_S	C_{DG} (\$/kWh)	C_{net} (\$/kWh)	C_{total} (\$/kWh)
DG cost	737	1823	1937	0.85	265.83	29.94	11.73	12.79	133.49	96.85	230.34
Stability	733	2567	1173	0.89	270.71	21.92	8.47	11.53	179.69	58.65	238.34
Both	738	1633	2097	0.85	277.17	33.78	7.47	11.74	116.8	104.85	221.65

Fig 2 shows the fitness diagram of the proposed DE algorithm for the final case. The fitness value decreases smoothly over the generations and represents the continuous advance of the algorithm toward the optimum solution. The average generations for convergence in 50 times running the algorithm are about 130 generations.

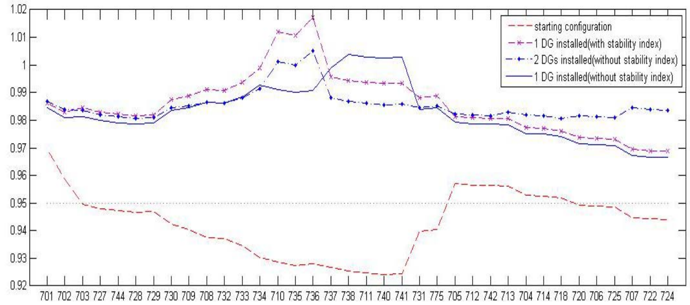

Fig.1: voltage profile in step 3 and effect of including stability index

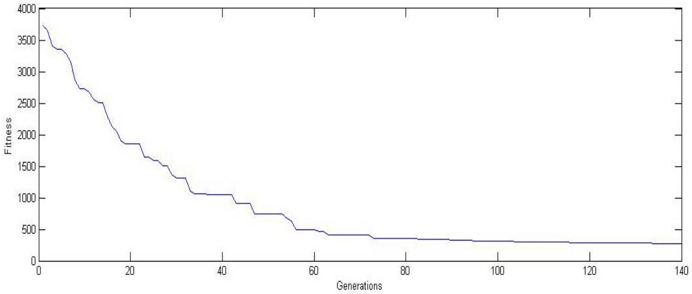

Fig.2: Best fitness curve vs. generation in step 4

V. CONCLUSION

In this paper, the application of DEA for a techno-economical multi-objective allocation for distributed generation has been proposed and discussed. The optimal location, size and power factor of multiple DGs have been determined, so that probable faults have the minimum effect on DG operation. The effect of different assumptions regard to the DG price and technical aspects are demonstrated. It is shown that considering the difference of energy purchase price significantly decreases the amount of DG installed compared to solely considering the technical issues. Also, the optimal power factor can be other that unity, and considering the technical constraints changes the optimal solution of the problem.

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