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Clean and Polluting DG Types Planning in Stochastic Price Conditions and DG Unit Uncertainties

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ABSTRACT

This study presents a dynamic way in a DG planning problem instead of the last static or pseudo-dynamic planning point of views. A new way in modeling the DG units' output power and the load uncertainties based on the probability rules is proposed in this paper. A sensitivity analysis on the stochastic nature of the electricity price and global fuel price is carried out through a proposed model. Six types of clean and conventional DG units are included in the planning process. The presented dynamic planning problem is solved considering encouraging and punishment functions. The imperialist competitive algorithm (ICA) as a strong evolutionary strategy is employed to solve the DG planning problem. The proposed models and the proposed problem are applied on the 9-bus and 33-bus test distribution systems. The results show a significant improvement in the total revenue of the distribution system in all of the defined scenarios.

KEYWORDS: Distributed generation, Investment time, Dynamic programming, Uncertainty, Monte carlo simulation, ICA.

1. INTRODUCTION

The DG sizing, allocation and planning issues have attracted a lot of interests in the field of distribution system studies. Fig. 1 shows a brief classification of the DG sitting, sizing and planning studies. As seen in this figure, the planning problems are divided into single-objective and multi-objective problems. The objective function in single-objective planning problems consists of the technical, economic and environmental functions. The researches in Refs. [1, 2] focused on improving the power quality issues such as harmonic levels, voltage stability and voltage profile of the distribution system. Reducing the power loss and improving the reliability of the distribution system were presented in [3, 4]. In some of the planning studies [5, 6], the short circuit level and loadability of the feeders were considered as the final objective function. The authors in these studies did not consider a planning problem in a period of time. The economic functions have not considered by the authors. Also, all of the important technical functions were not considered in these papers.

The economic functions as the objective function of the DG planning studies include the energy loss cost [7], purchased energy cost [8], reliability [9, 10], grant subsidies [8] and the investment and operation cost of the DG units [11]. The reliability in these studies is modeled with energy not supplied cost. In recent years, a new parameter as an objective function is introduced in planning studies beside the economic or technical issues called environmental function [12]. The environmental function includes the amount of polluting gases produced by the power generating units. In this point of view, some of the DG units such as wind turbines (WTs) or PV modules are categorized as clean type and the remaining DG types are included in the polluting units. The researchers have analyzed the DG planning problem in multi-objective format considering each of the introduced economic,

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technical and environmental functions together or solely. In multi-objective planning problems 2 or 3 objective functions are optimized simultaneously and a set of solutions called pareto points are obtained. For example, the authors in Ref. [5] aimed to reduce the power loss and to improve the voltage stability of the distribution system, the authors in Ref. [13] aimed to maximize cost-savings of energy not supplied (ENS) as well as cost-savings of energy loss. In Ref. [14], the total cost of power consumed by the distribution system is defined as the economic function and the energy not supplied is defined as the technical function. Both of the economic and technical functions are optimized simultaneously in this paper. Reducing the operation cost of the DG units and the polluting units were presented in Ref. [15] and finally in Ref. [16] all of the economic, technical and environmental functions are considered as the objective functions of the multi-objective planning problem. The authors in these papers worked on the DG planning problem in one year or in a period of time from static point of view. Since the DG planning problems in static viewpoint are solved based on the load of the entire year of the planning period, the calculated costs and incomes are not exact. The investment time of installing the DG units are not obtained in static ways. So, the results of the DG planning problem including the size and the site of the DG units are not reliable. Also, in these studies, some of the economic parameters are assumed as the objective function. Thus, the authors in this study decide to propose the dynamic way, as the most complete way, to study the presented DG planning problem to cover the mentioned deficiencies of the last studies. All of the economic parameters shown in Fig. 1 are considered in this study. This paper aims to maximize the total revenue of the distribution system considering uncertainties related to the output power of the intermittent nature units and the stochastic nature of the electricity price and global fuel price. The government based on the global fuel price of the related year determines the electricity price of each year. The global changes in fuel cost effects on the operation cost of the DG units such as GTs, DEs and MTs. The electricity price has a direct effect on the purchased energy cost, energy loss cost and the income of selling the required power to the customers. Therefore, the variations in electricity price and global fuel price of each year of the planning period will effect on the total revenue of the distribution system. Encouraging and punishment functions alongside the defined costs and incomes are considered in this study.

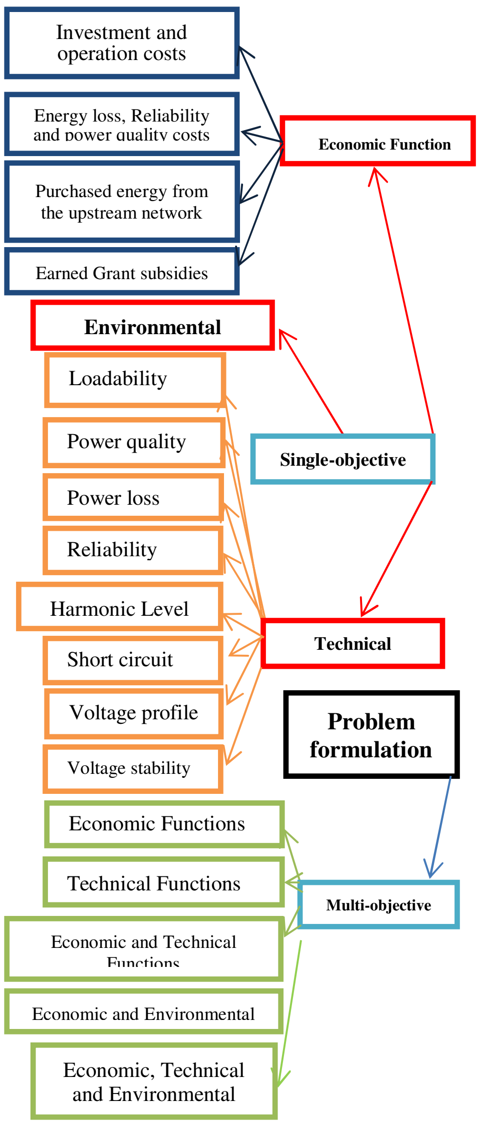

Fig. 1. Classification of the planning problems from modeling and objective function formulation point of view

The encouraging mechanism includes the grant subsidies paid to the DISCO because of supplying the required power from clean technologies instead of using from the conventional generation or polluting DG units. The punishment function is the emission tax because of generating the polluting gases. Thus, the grant subsidies and emission taxes are classified as the incomes and the costs of the DISCO, respectively. A method based on the probability rules is proposed to model the generation and load uncertainties. Also, a sensitivity analysis in each year of the planning period is carried out on the stochastic nature of the prices using a proposed model. It is considered that the electricity price of each year has a significant dependency to the global fuel price of the related year. The different DG types including WTs, PV modules, fuel cells (FCs), DEs, MTs and GTs are included in the DG planning process. In order to make real condition, the load duration curve (LDC) is used to model the loads. Unlike the last studies that a constant load growth rate is considered for the planning study, it is assumed that the load growth rate of each year follows from a real case in Iran. Since the presented dynamic DG planning problem is a multi-dimensional problem, the traditional and old methods such as GA and PSO, … cannot be used to solve these problems in a small number of iterations. So it is needed to use from strong and fast speed evolutionary strategies in finding the optimum solution. The imperialist competitive algorithm (ICA) is employed to solve the presented dynamic DG planning problem. The results of the ICA will be compared with the GA to show its high speed and high strength. Fig. 2 shows the trend of solving the dynamic DG planning problem with the innovations of the presented study.

2. MODELING GENERATION AND LOAD

The solar radiance and wind speed are assumed to follow from Rayleigh distribution function in each year. The defined probability distribution of the solar radiance and wind speed are divided into different states. The solar radiance and wind speed in each state is within specific limits. The output power of the PV array in each state *y* is calculated using the mean value of irradiance of each state as Eq. (1). The complete formulations of the PV modules are referenced in [17]. Consider that sy1 and sy2 are the lower and upper limits of the y^{th} state. s_{ay} is the average value of s_{y1} and s_{y2} . For example, if the second state has the limits of 0.1 and 0.2 kW/m^2, the mean value for this state (s_{ay}) is 0.15 kw/m^2. The output power of the WTs during each state is calculated using Eq. (2).

$$P_S(s_{ay}) = N \times FF \times V_{oc}(s_{ay}) \times I_{sc}(s_{ay}) \tag{1}$$

$$P_V(V_{av}) = \begin{cases} 0 & 0 \le V_{av} \le V_{ci} \\ P_{rated} \times \frac{V_{av}-V_{ci}}{V_r-V_{ci}} & V_{ci} \le V_{av} \le V_r \\ P_{rated} & V_r \le V_{av} \le V_{co} \\ 0 & V_{co} \le V_{av} \le \infty \end{cases} \tag{2}$$

To apply the DG units' uncertainty and the different load levels to the planning problem, the probability generation load matrix (M_{PGL}) is defined in this section. In this matrix, all of the combinations of DG units' generations and load levels in a year with the related probabilities are considered. The M_{PGL} is a $(N_{DG}+3)$-column-matrix. Each row of this matrix shows a combination of the DG units' generations and load. The 1st to N_{DG}^{th} columns of M_{PGL} correspond to each DG type generation state as a percentage of its rated power, the $(N_{DG}+1)^{th}$ column corresponds to the different load levels, the $(N_{DG}+2)^{th}$ column corresponds to the probability of the related state and the $(N_{DG}+3)^{th}$ column is the same as the $(N_{DG}+2)^{th}$ column except that the forced outage rate of each DG type is considered. Thus, the output power of the unit will be zero. The probability of occurrence of each state with and without considering forced outage rate (the $(N_{DG}+3)^{th}$ and $(N_{DG}+2)^{th}$ columns respectively) is given in Eqs. (3) and (4):

$$M_{PGL,N_{DG}+2}^{g} = \prod_{n=1}^{N_{DG}+1} P\{M_{PGL,n}^{g}\} \tag{3}$$

$$M_{PGL,N_{DG}+3}^{g} = \prod_{n=1}^{N_{DG}+1} P\{M_{PGL,n}^{g,fail}\} \tag{4}$$

Where $M_{PGL,n}^{g}$ represents the element in g^{th} row and n^{th} column of matrix M_{PGL}. $P\{M_{PGL,n}^{g}\}$ and $P\{M_{PGL,n}^{g,fail}\}$ are the probabilities related to occurrence of the mentioned element with and without considering the forced outage rate.

$$P\{M_{PGL,n}^{g,fail}\} = \begin{cases} P\{M_{PGL,n}^{g}\} \times (1-F.O.R) & ,g \ne k \\ P\{M_{PGL,n}^{g}\} + F.O.R \times \sum_{g=1,g\ne k}^{gtot} P\{M_{PGL,n}^{g}\} & ,g = k \end{cases} \tag{5}$$

As seen in Eq. (5), two relations are considered for the probability of each state of DG units considering F.O.R. The second relation only is used for the k^{th} state that the output power of the DG is zero. Unavailability of the renewable technology includes the hours that the renewable resource is working out of operating range in addition to the hours that the DG is in forced outage time.

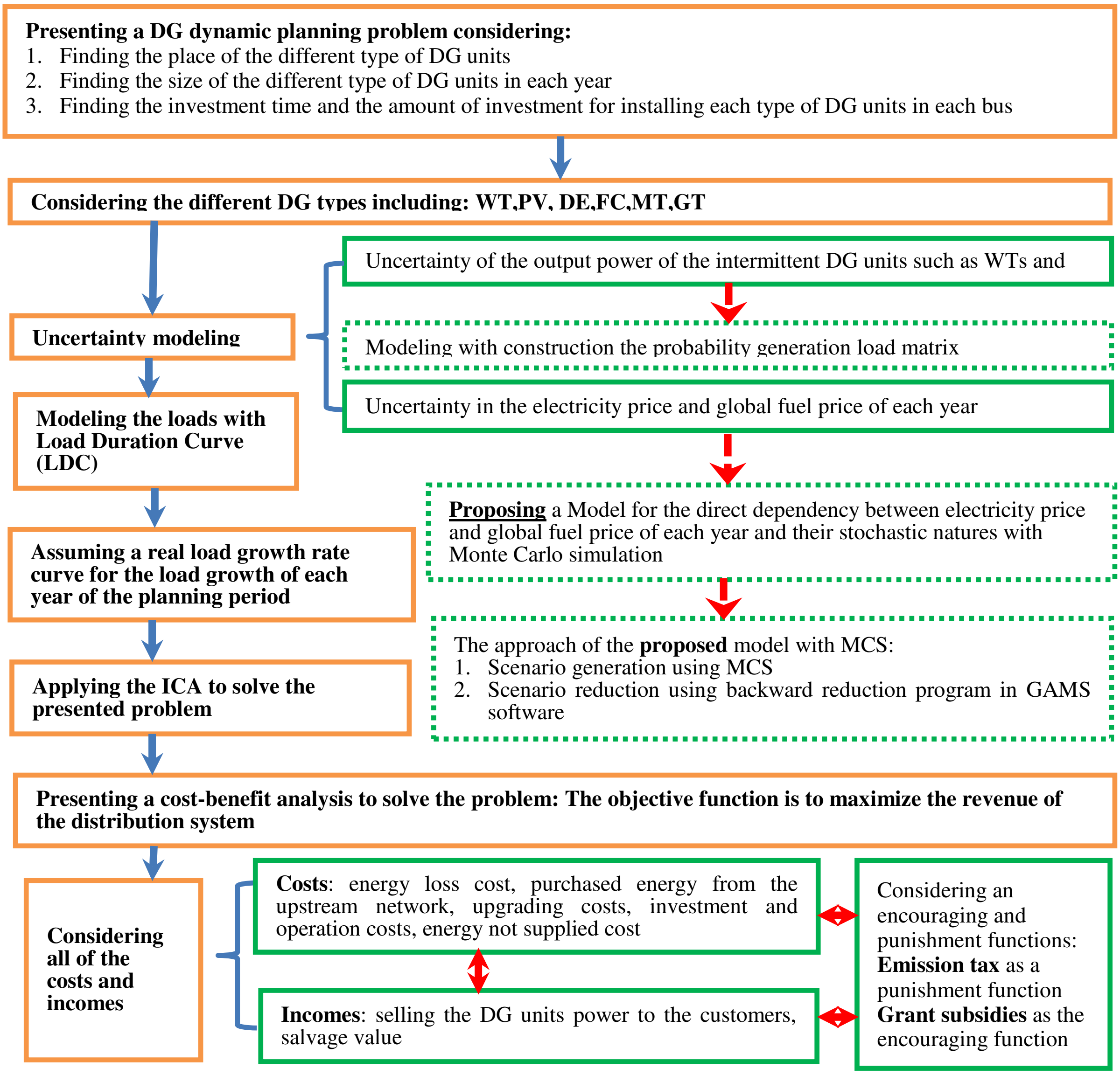

Fig. 2. The trend of solving the dynamic DG planning problem, innovations and important points

3. SCENARIO GENERATION USING MONTE CARLO SIMULATION

The proposed model is based on generating a large number of scenarios of electricity price and global fuel price using Monte-Carlo simulation (MCS) and reducing the produced scenarios to a small number through the backward reduction program using GAMS software. In the following, the complete explanations of the Monte-Carlo simulation and the proposed method are presented. In this paper, a scenario is produced by sampling the electricity price and fuel price variations for each year of the planning period. Parameters are generated from the uniformly distributed random number/samples lying between [0,1] and following a certain distribution type. The most widely used technique for generation of random parameters is inverse transform method which is used in this paper [18]. Fig. 3 shows the MCS method process. Fig. 4 shows the random sampling from the cumulative distribution function. The sampling process is repeated several times (1000-10000) to generate desired the number of scenarios. Fig. 5 shows the sampling process of dependent and independent parameters in MCS method. Calculating the total costs considering all of the reduced scenarios are shown in Fig. 6. As shown in Fig. 6, the generated scenarios in MCS are reduced to an appropriate number to be possible to analyze.

4. ICA METHOD

The ICA is a novel heuristic evolutionary algorithm based on the human's socio-political evolution and it has shown a good convergence rate to achieve globally optimal solution. The ICA is proposed in 2007 by Atashpaz-Gargari and Lucas [19]. The complete flowchart of solving the presented DG planning problem is shown in Fig. 7 [20, 21].

5. PROBLEM FORMULATIONS

The Eqs. (6)-(21) show the costs and incomes of the distribution system. The aim of this study is to maximize the total revenue of the distribution system.

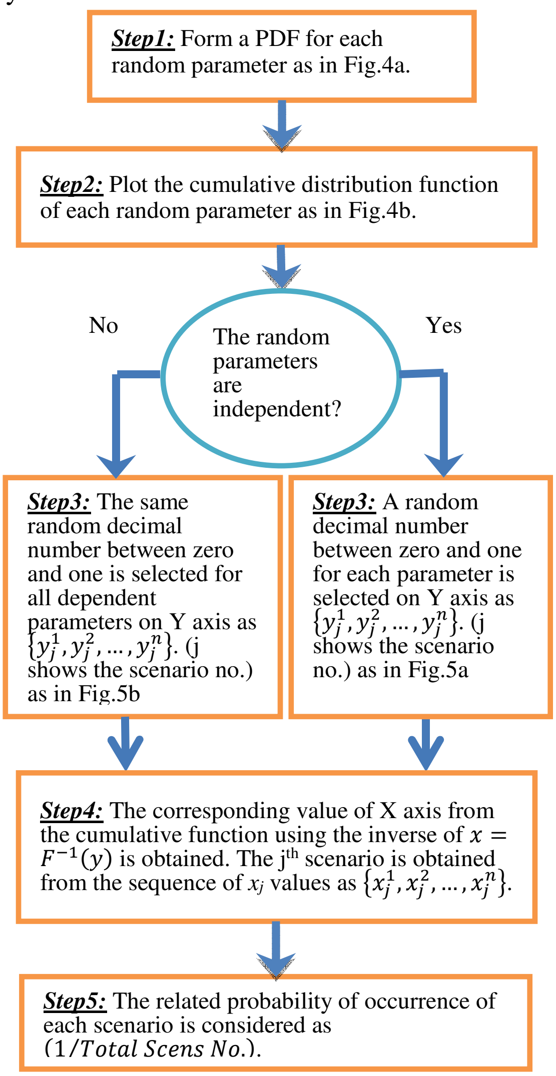

Fig. 3. The MCS method process

- **Cost Function of Energy Losses (*CEL*)**

The power loss of each state in each year of the planning period is multiplied in its probability $(M^g_{PGL,N_{DG}+3})$. Eq. (7) shows the total cost of energy loss.

$$P^{g,yr}_{loss} = P^{g,yr}_{G1} + \sum_{i=1}^{N_{bus}}[(\sum_{n=1}^{N_{DG}} P^n_{rated}(i,yr) \times M^g_{PGL,n}) - M^g_{PGL,N_{DG}+1} \times P_d(i) \times \prod_{cy=1}^{yr}(1+gr(cy))] \quad (6)$$

$$CEL = \sum_{yr=1}^{Ty}\left(\sum_{g=1}^{gtot}(P^{g,yr}_{loss} \times M^g_{PGL,N_{DG}+3}) \times \left(\frac{1+inf}{1+d}\right)^{yr}\right) \times price_{loss} \times 8760 \quad (7)$$

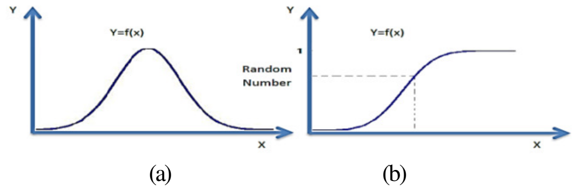

Fig. 4. Monte Carlo sampling from CDF (a) Probability distribution function (b) Cumulative distribution function (CDF)

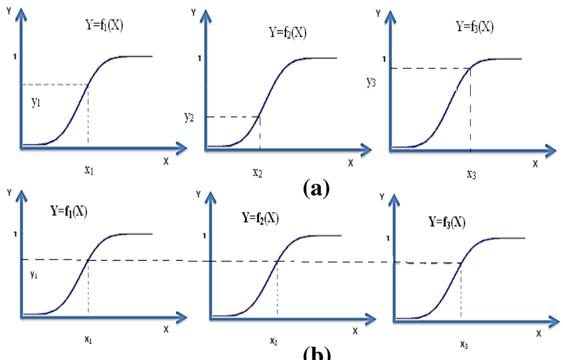

Fig. 5. Monte Carlo sampling for (a) Independent and (b) Dependent parameters

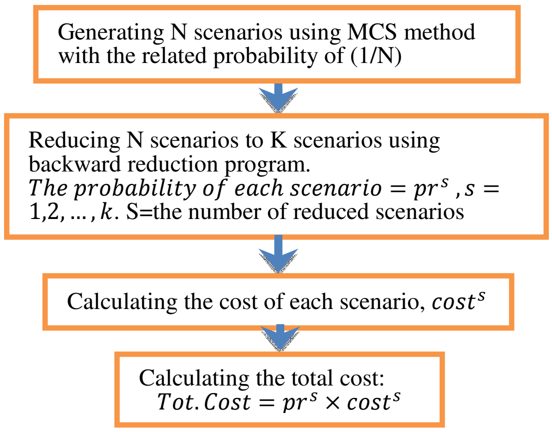

Fig. 6. Calculating the total cost considering all of the generated scenarios

- **Cost function of purchased energy from transmission system (*CEtr*)**

$$CEtr = \sum_{yr=1}^{Ty}\left(\sum_{g=1}^{gtot}(P^{g,yr}_{G1} \times M^g_{PGL,N_{DG}+3}) \times \left(\frac{1+inf}{1+d}\right)^{yr}\right) \times price_{tr} \times 8760 \quad (8)$$

- **Cost function of energy not supplied (*CENS*)**

The first relation of Eq. (9) considers the state that the islanded loads in addition to the islanded distribution system real power loss are larger than the total DG capacity on the islanded section; and the second relation is vice versa. In the second relation all of the loads are restored by the installed DG capacity.

$$ENS^{g,yr} = \sum_{i,j} L_{ij} \times \lambda_{ij} \times \begin{cases} \left(P_{DG}^{g,yr}(ij) - P_{lzone}^{g,yr}\right) \times T_{res} + \left(P_{D}^{int,g,yr}(ij) - P_{DG}^{g,yr}(ij) + P_{lzone}^{g,yr}\right) \times T_{rep} & if\ P_{D}^{int,g,yr}(ij) + P_{lzone}^{g,yr} > P_{DG}^{g,yr}(ij) \\ P_{D}^{int,g,yr}(ij) \times T_{res} & if\ P_{D}^{int,g,yr}(ij) + P_{lzone}^{g,yr} < P_{DG}^{g,yr}(ij) \end{cases} \quad (9)$$

$$P_{DG}^{g,yr}(ij) = \sum_{j\in is}\left(\sum_{n=1}^{N_{DG}} P_{rated}^{n}(j,yr) \times M_{PGL,n}^{g}\right) \quad (10)$$

$$P_{D}^{int,g,yr}(ij) = \sum_{j\in is}\left(M_{PGL,N_{DG}+1}^{g} \times P_{d}(j) \times \prod_{cy=1}^{yr}(1 + gr(yr))\right) \quad (11)$$

$$CENS = \sum_{yr=1}^{Ty}\left(\sum_{g=1}^{gtot}\left(ENS^{g,yr} \times M_{PGL,N_{DG}+3}^{g}\right) \times \left(\frac{1+inf}{1+d}\right)^{yr}\right) \times price_{ENS} \quad (12)$$

where "*is*" is the buses in islanded zone after failing the branch between buses *i*, *j*.

- **Cost function of the distribution system upgrades (CU)**

Equation (13) shows the upgrading cost of the distribution system. In this paper, only the investments for replacing the overloaded branches with the higher capacity ones are considered as the upgrading investment costs. If the line flow ($LF^{g,yr}_{ij}$) between buses *i* and *j* is higher than the loading limit of the related line (SL_{ij}), the feeder should be replaced with a higher capacity ones with the probability of the related state $M_{PGL,N_{DG}+3}^{g}$, otherwise the upgrading cost will be zero.

$$CU = \sum_{yr=1}^{Ty}\left(\sum_{g=1}^{gtot}\left(\sum_{ij} L_{ij} \times price_{uc} \times M_{PGL,N_{DG}+3}^{g} \times \begin{cases} 1\ if\ LF_{ij}^{g,yr} > SL_{ij} \\ 0\ if\ LF_{ij}^{g,yr} < SL_{ij} \end{cases}\right) \times \left(\frac{1+inf}{1+d}\right)^{yr}\right) \quad (13)$$

- **Cost function of emission pollutants (*CET*)**

The emission tax paid by the DISCO has two parts. The first part corresponds to the emission tax of the power purchased from the transmission system and the second part corresponds to the emission tax of the polluting DG units. The different emission pollutants include p = $CO2$, NOx, CO, PM10 and SO2. Eq. (14) shows the emission tax of each year. Since some DG technologies such as WTs and PV modules have an uncertain nature, the capacity factor of each DG type is multiplied in its capacity. The capacity factor of the other DG technologies is assumed to be one. The total emission tax which should be paid by the DISCO for all of the planning period is obtained in Eq. (15).

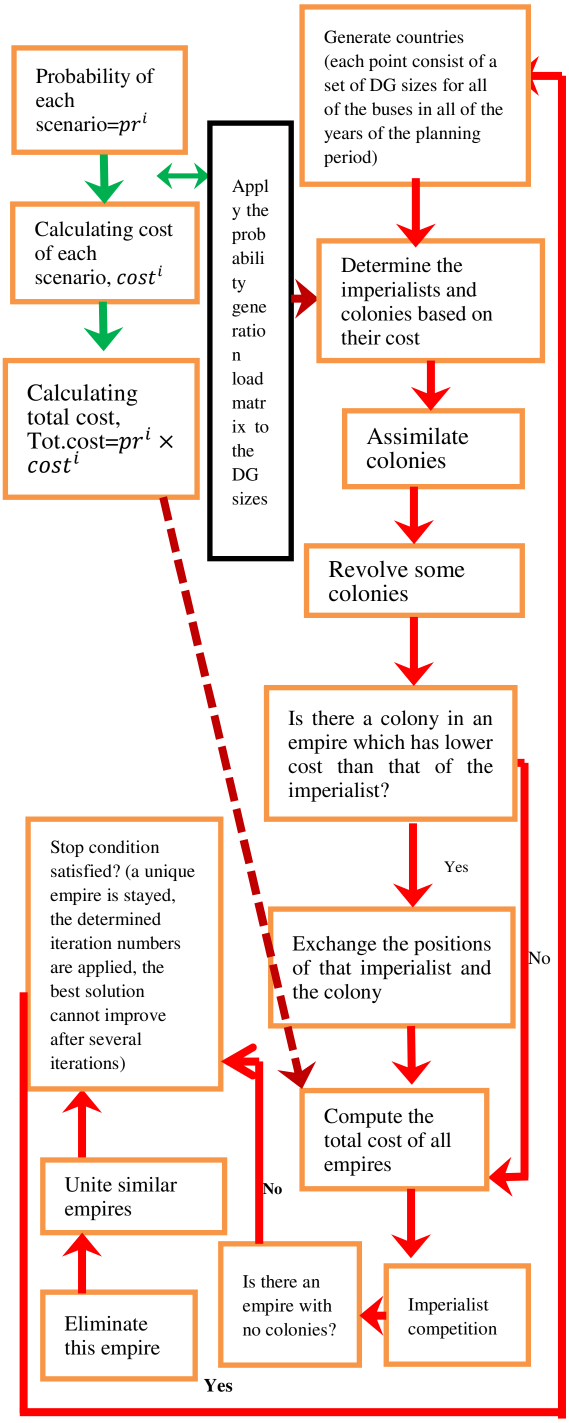

Fig. 7. Flowchart of solving the dynamic DG planning problem

$$CET^{yr} = \underbrace{\left(\sum_{g=1}^{gtot}\left(P_{G1}^{g,yr} \times M_{PGL,N_{DG}+3}^{g}\right) \times \sum_{p=1}^{pn}\left(Em_{p}^{conv} \times pricetax_{p}\right)\right)}_{Conventional\ Generation\ Emission\ Tax} + \underbrace{\left(\sum_{i=1}^{N_{bus}}\sum_{n=1}^{N_{DG}}\left(P_{rated}^{n}(i,yr) \times CF_{n} \times \sum_{p=1}^{pn}\left(Em_{p}^{n} \times pricetax_{p}\right)\right)\right)}_{DG\ Types\ Emission\ Tax} \quad (14)$$

$$CET = \sum_{yr=1}^{Ty}\left(CET^{yr} \times \left(\frac{1+\inf}{1+d}\right)^{yr}\right) \quad (15)$$

- **Operation cost function of the DG technologies (*OPC*)**

$$OPC = \sum_{yr=1}^{Ty}\left[\sum_{n=1}^{N_{DG}}\left(\sum_{i=1}^{N_{bus}} P_{rated}^{n}(i,yr) \times priceop_n\right) \times \left(\frac{1+\inf}{1+d}\right)^{yr}\right] \quad (16)$$

- **Investment cost function of the DG technologies (*INC*)**

$T_{installing}^{n}$ is the year of installing the n^{th} DG type in the planning period.

$$INC = \sum_{n=1}^{N_{DG}}\sum_{i=1}^{N_{bus}}(P_{rated}^{n}(i,Ty) \times priceinv_n) \times \left(\frac{1+\inf}{1+d}\right)^{T_{installing}^{n}} \quad (17)$$

- **Selling energy (*ISE*)**

$$ISE = \sum_{yr=1}^{Ty}\left[\sum_{g=1}^{gtot}\left(\sum_{i=1}^{N_{bus}}\left(M_{PGL,N_{DG}+1}^{g} \times P_d(i) \times \prod_{cy=1}^{yr}(1+gr(yr))\right) \times M_{PGL,N_{DG}+3}^{g}\right) \times pricesel \times \left(\frac{1+\inf}{1+d}\right)^{yr}\right] \times 8760 \quad (18)$$

- **Grant subsidies function (*IGS*)**

This grant subsidy is paid to the DISCO because of the pollution not generated due to employing clean technologies [22].

$$IGS = pricegr \times \sum_{n=1}^{N_{DG}}\left[\begin{cases}\sum_{p=1}^{pn}\sum_{yr=1}^{Ty}\left(Em_{p}^{conv} - Em_{p}^{n}\right) \times \left(\sum_{i=1}^{N_{bus}} P_{rated}^{n}(i,yr) \times CF_n \times \left(\frac{1+\inf}{1+d}\right)^{yr}\right) \times 8760 \\ 0\end{cases}\right] \quad (19)$$

The first relation of Eq. (19) is used when $\sum_{p=1}^{pn} Em_{p}^{conv} < \sum_{p=1}^{pn} Em_{p}^{n}$. When the amount of produced emission pollutants of the DG units for a certain amount of output power becomes larger than the amount of emission pollutants for the same amount of the produced power from the transmission system, any grant subsidy is not paid to the DISCO.

- **Income salvage value (*ISV*)**

The DG units' structures' value at the end of the planning period is included in the incomes of the distribution system.

$$ISV = \sum_{n=1}^{N_{DG}}\left(INC^{n} \times persal \times \left(\frac{1+\inf}{1+d}\right)^{yr}\right) \quad (20)$$

- **Total objective function**

The aim of this paper is to maximize the total revenue of the distribution system shown in Eq. (21).

$$Revenue = Total\ Incomes - Total\ Costs \quad (21)$$

- **Power flow equations**

$$P_{G}^{g,yr}(i) + \left(\sum_{n=1}^{N_{DG}} P_{rated}^{n}(i,yr) \times M_{PGL,n}^{g}\right) - M_{PGL,N_{DG}+1}^{g} \times P_d(i) \times \prod_{cy=1}^{yr}(1+gr(yr)) = \sum_{j=1}^{N_{bus}} V_{g}^{yr}(i) \times V_{g}^{yr}(j) \times Y(i,j) \times cos\left(\delta_{g}^{yr}(i) - \delta_{g}^{yr}(j) - \theta(i,j)\right) \quad (22)$$

$$Q_{G}^{g,yr}(i) - M_{PGL,N_{DG}+1}^{g} \times Q_d(i) \times \prod_{cy=1}^{yr}(1+gr(yr)) = \sum_{j=1}^{N_{bus}} V_{g}^{yr}(i) \times V_{g}^{yr}(j) \times Y(i,j) \times sin\left(\delta_{g}^{yr}(i) - \delta_{g}^{yr}(j) - \theta(i,j)\right) \quad (23)$$

- **Maximum penetration of dg units in the distribution system and in each bus [22, 23]**

$$\sum_{i=1}^{N_{bus}}\sum_{n=1}^{N_{DG}}(P_{rated}^{n}(i,yr) \times CF_n) \leq 0.6 \times P_{G1}^{yr} + 0.3 \times \sum_{i=1}^{N_{bus}} P_d(i) \times \prod_{cy=1}^{yr}(1+gr(yr)),\ yr = 1,..,Ty \quad (24)$$

$$\sum_{n=1}^{N_{DG}}(P_{rated}^{n}(i,yr) \times CF_n) \leq P_{bus}\ for\ \ yr = 1,..,Ty\ \ \&\ \ i = 1,2,..,N_{bus} \quad (25)$$

In this study, the load is divided into 5 levels. Fig. 8 shows the LDC. There is not any reverse power flow in all of the DG units' generation states and load levels. In this study, it is considered that 70% of the operation cost of the pollutant DG units (GT, DE, MT) belongs to the fuel cost. Thus, variation in fuel costs lead to variation in 70% of the base operation cost. The remaining operation cost (30% of the base operation cost) is constant.

The DG units' capacity standard sizes are the multiples of 50 kW. Any DG units should not be installed in the first bus. The PDF of solar irradiance and wind speed are assumed the same for all of the years. The solar radiance and wind speed data are referenced in [24]. In this study, the same as the last studies [22, 23, 25, 26], it is considered that during the planning period only the loads are increased based on the defined load growth rate curve in the next section and the topology of the network is not changed after 5 years. It means that during the planning period any lines or branches or other devices are not added to the distribution system.

6. RESULTS AND DISCUSSIONS

The presented dynamic DG planning problem is applied on the 9 bus and 33 bus test distribution systems shown in Figs. 9 and 10. Fig. 11 shows the load growth rate of the planning period which follows from the load growth rate of Iran industrial power from 1968 to 2011 [27]. The technical and required data of the 9-bus test distribution system and the presented problem is referenced in [17, 22, 25]. In this study, six types of DG units including WTs, GTs, PV modules, FCs, DEs and MTs are considered in DG planning process. 5 states for the WTs' generation and 5 states for the PV modules' generation are considered. As shown in Fig. 8, the load is modeled with 5 levels in load duration curve (LDC). Since the remaining DG types only have 1 state in generating power, the total states of probability generation load matrix equals to 125 (5 states WT×5states PV×1×1×1×1 (other DG types)×5 load levels=125 states). Now, the probability generation load matrix has 125 rows and 8 columns. Table 1 shows an example of the M_{PGL} matrix. In this table, 3 states for the WTs' generation as (0,0.5,1) with the related probabilities of (0.3,0.4,0.3), 3 states for the PV modules' generation as (0,0.5,1) with the related probabilities of (0.4,0.4,0.2), 3 states for the load levels as (0.5,0.7,0.9) with the related duration time per year of (0.4,0.6,0.8) and 1 state for the other DG types are considered. Thus, the probability generation load matrix has 27 states (3×3×1×1×1×1×3=27 rows or 27 states).

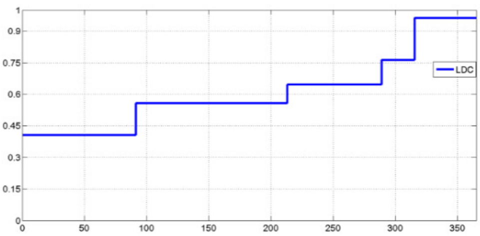

Fig. 8. The Load Duration Curve (LDC)

As explained in the last sections, 10000 scenarios using MCS method are generated for the electricity price and fuel price variations for the planning period. The produced scenarios are reduced with backward reduction program in GAMS software to an appropriate number to make it possible to analyze. Each reduced scenario has its own probability. The cost and income functions are calculated for each scenario. The total costs and incomes are computed with the sum of all of the individual costs and incomes (calculated for each scenario) with the related probabilities. The imperialist competitive algorithm as explained in Section 4 is used to solve the DG planning problem. In order to show the applicability of the ICA method in solving the planning problem, the results are compared with the continuous GA. The results of planning problem using CGA (Continuous GA) and ICA methods are shown in Table 2. As shown in this Table, the ICA can find a better solution than the continuous GA. The maximum capacity of WTs, GTs, FCs, PV modules, MTs and DEs are 2, 2, 2, 1, 1 and 2.5 MW, respectively. The forbidden buses for placement of each type of the DG units are as follows:

WTs: [1, 3, 4, 6, 9], PV modules: [1, 3, 5], other DG types (GTs, DEs, FCs, MTs): [1].

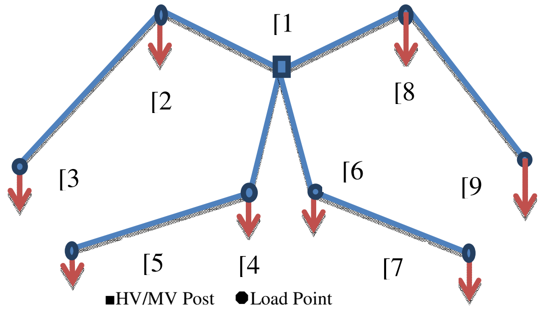

Fig. 9. The 9 bus test distribution system

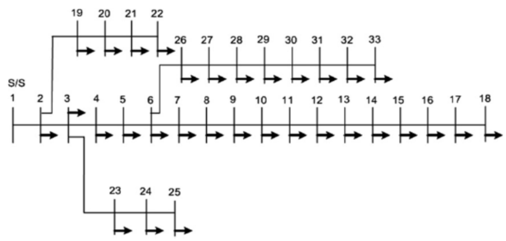

Fig. 10. The 33 bus test distribution system

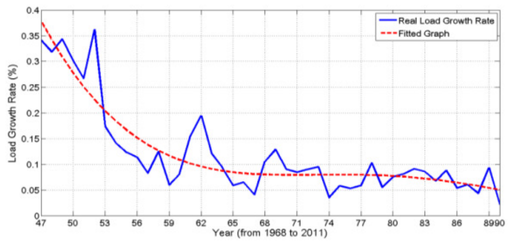

Fig. 11. Load growth rate (real case of Iran from 1968 to 2011)

In this section two scenarios are defined. In the first scenario it is considered that in each bus more than one type of the DG units can be placed as in [17, 22, 26]. In the second scenario it is assumed that only one type of the DG units can be placed.

Scenario#1 (more than one type of the DG units can be placed in each bus): The polluting DG units including GT and DE cannot achieve any part of the total installed capacity of the DG units. The reason is in their high amount of polluting gases that result in high emission taxes. Only in the 4th and 5th years of the planning period, the MTs have a capacity of 1 MW in the 9th bus. The DG sizes calculated for each year of the planning period are shown in Figs. 12 to 16. Since the GT and DE units' capacity for all of the years are zero, both of these units are shown in Fig. 16. The total size of the DG units for each year is shown in Fig. 17. In Fig. 18 the total capacity of the DG units for each bus during the planning period is shown. As expected, the total installed capacity of the DG units in the distribution system and in each bus is increased from the first to the end of the planning period (Fig. 17, 18). Table 3 shows the individual and total costs and incomes of the distribution system before and after installing the DG units.

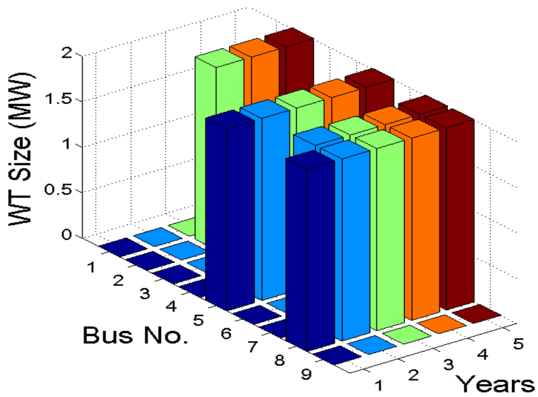

Fig. 12. WTs' sizes for each year of the planning period

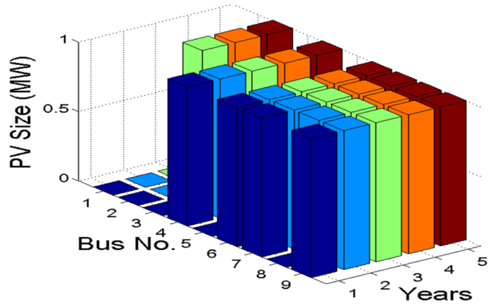

Fig. 13. PV Modules' sizes for each year of the planning period

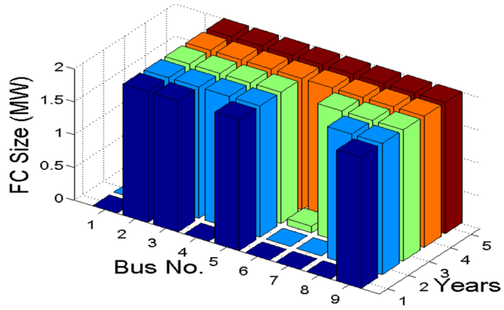

Fig. 14. FCs' sizes for each year of the planning period

As shown in the results of this Table, the total revenue in the first year is the minimum value among the other years of the planning period. The reason is that most of the DG units are installed in the first year. So, the investment costs of installing these DG units are paid in the first year of the planning period. The total revenue of the distribution system before the DG planning is negative (-50.613M$) while after the presence of the DG units the total revenue of the distribution system becomes a positive value (102.2437M$).

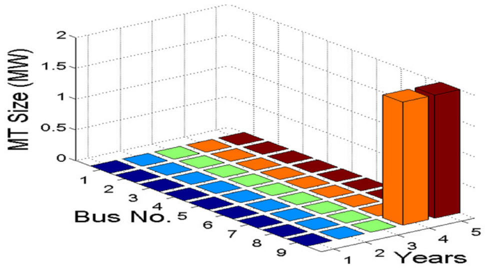

Fig. 15. MTs sizes for each year of the planning period

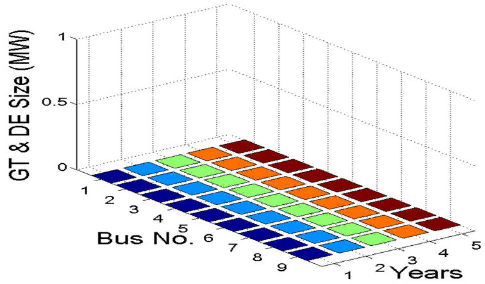

Fig. 16. GTS & Des' sizes for each year of the planning period

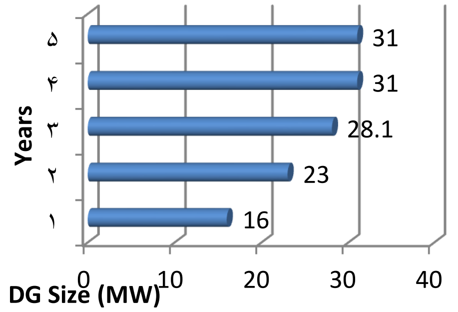

Fig. 17. Total DG sizes for each year of the planning period

It should be noted that the emission tax is not calculated in the total costs of the distribution system. Fig. 19 shows the power loss of the distribution system before and after installing the DG units. As seen in this figure, the power loss of the distribution system is decreased during the planning period in the presence of the DG units. Fig. 20 shows the energy not supplied of the distribution system. As seen after DG placement, with the reduction in energy not supplied of the distribution system, reliability of supply is increased and the customer interruptions are decreased. Thus, the presence of the DG units causes to increase the social welfare of the society. The increase in social welfare cannot be modeled with any cost function. Fig. 21 shows the power purchased by the DISCO from the transmission system. It can be seen that, after DG placement, the power purchased from the transmission system is decreased. The reduction in power purchased of the transmission system means that the polluting gases which is raised by using the conventional generation is decreased. In addition, the total cost of purchased power is decreased, too.

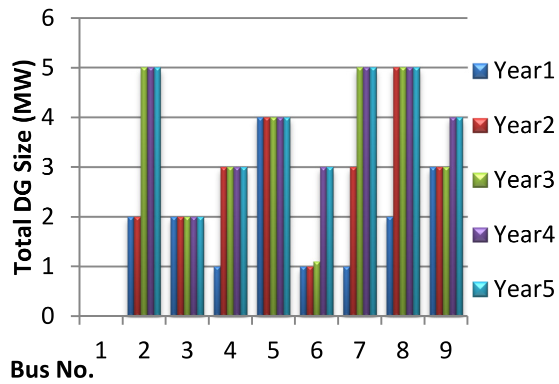

Fig. 18. The total DG size of each bus in each year

Table 1. An example for the final scenario generation

WT output power (percentage of the peak load)	PV output power (percentage of the peak load)	GT output power (percentage of the peak load)	FC output power (percentage of the peak load)	DE output power (percentage of the peak load)	MT output power (percentage of the peak load)	Load Level	Probability of occurrence of this state
0	0	1	1	1	1	0.4	0.3×0.4×0.4
0	0	1	1	1	1	0.6	0.3×0.4×0.6
0	0	1	1	1	1	0.8	0.3×0.4×0.8
0	0.5	1	1	1	1	0.4	0.3×0.4×0.4
0	0.5	1	1	1	1	0.6	0.3×0.4×0.6
0	0.5	1	1	1	1	0.8	0.3×0.4×0.8
0	1	1	1	1	1	0.4	0.3×0.2×0.4
0	1	1	1	1	1	0.6	0.3×0.2×0.6
0	1	1	1	1	1	0.8	0.3×0.2×0.8
0.5	0	1	1	1	1	0.4	0.4×0.4×0.4
0.5	0	1	1	1	1	0.6	0.4×0.4×0.6
0.5	0	1	1	1	1	0.8	0.4×0.4×0.8
0.5	0.5	1	1	1	1	0.4	0.4×0.4×0.4
0.5	0.5	1	1	1	1	0.6	0.4×0.4×0.6
0.5	0.5	1	1	1	1	0.8	0.4×0.4×0.8
0.5	1	1	1	1	1	0.4	0.4×0.2×0.4
0.5	1	1	1	1	1	0.6	0.4×0.2×0.6
0.5	1	1	1	1	1	0.8	0.4×0.2×0.8
1	0	1	1	1	1	0.4	0.3×0.4×0.4
1	0	1	1	1	1	0.6	0.3×0.4×0.6
1	0	1	1	1	1	0.8	0.3×0.4×0.8
1	0.5	1	1	1	1	0.4	0.3×0.4×0.4
1	0.5	1	1	1	1	0.6	0.3×0.4×0.6
1	0.5	1	1	1	1	0.8	0.3×0.4×0.8
1	1	1	1	1	1	0.4	0.3×0.2×0.4
1	1	1	1	1	1	0.6	0.3×0.2×0.6
1	1	1	1	1	1	0.8	0.3×0.2×0.8

Table 2. The results of GA and ICA methods

Method	Iterations	Revenue ($)	Cost ($)	Income ($)
CGA	7000	0.890453e8	1.142875e8	2.033328e8
ICA	1000	1.022437e8	1.363054e8	2.3886e8

Table 3. The results of costs and incomes of the planning problem for 9-bus test system scenario#1

Costs & Incomes (M$)	With DG					Without DG				
	Year					Year				
	1	2	3	4	5	1	2	3	4	5
Energy Loss	0.32	0.33	0.39	0.60	0.81	0.53	0.62	0.80	1.18	1.48
Purchased Energy	13.89	12.44	13.41	16.54	19.77	20.11	21.47	23.75	28.76	31.90
Emission Tax	22.31	23.02	25.89	31.58	35.26	24.58	26.15	29.79	35.21	38.94
DG Operation	2.88	4.24	4.98	5.83	5.72	0	0	0	0	0
DG Investment	5.42	2.06	2.03	0.17	0	0	0	0	0	0
ENS	0. 17	0. 17	0. 18	0. 21	0. 25	0.23	0.24	0.28	0.32	0.36
Upgrading	3.45	3.31	3.62	6.10	7.00	5.77	6.28	8.32	9.62	9.99
Selling DG Power	19.58	20.85	22.95	27.59	30.41	19.58	20.85	22.95	27.59	30.42
Grant Subsidy	15.32	21.66	25.59	27.25	26.75	0	0	0	0	0
Salvage Value	0	0	0	0	0.91	0	0	0	0	0
Total Cost	26.13	22.55	24.61	29.46	33.56	26.65	28.60	33.14	39.88	43.73
Total Income	34.90	42.51	48.54	54.84	58.08	19.58	20.85	22.95	27.58	30.42
Total Revenue	8.77	19.95	23.93	25.38	24.52	-7.06	-7.75	-10.19	-12.30	-13.31
Total Revenue of the Planning period (without emission tax)				102.24		-50.61				

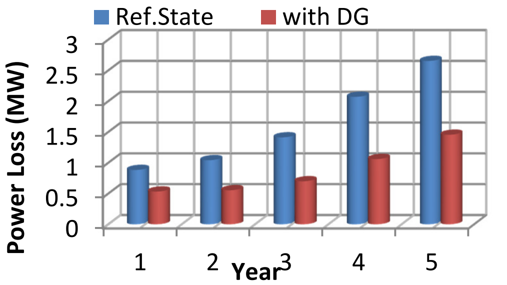

Fig. 19. The power loss of the distribution system in each year

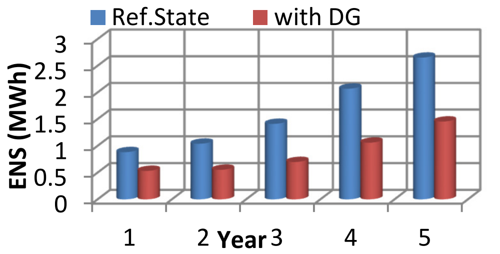

Fig. 20. The ENS of the distribution system in each year

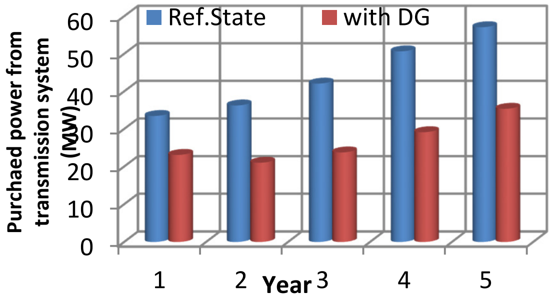

Fig. 21. The power purchased from transmission system in each year

Scenario#2 (only one type of DG units can be placed in each bus): In this scenario, only one type of the DG technologies can be placed in each bus. The maximum capacity of each type of the DG units is considered to be 4 MW. Table 4 shows the DG planning results. As seen in Table4, the capacity of all of the DG units except the FCs is obtained zero for the buses of the distribution system. The reason is that the same as the last scenario, the GTs, MTs and DEs could not obtain any part of the total installed capacity of the DG units due to generating a large amount of emissions. The WTs and PV modules could not obtain any part of the total installed capacity of the DG units due to their uncertain nature. So, only the FCs with medium level of emissions obtained all of the DG units' capacity. Table5 shows the individual costs and incomes of the distribution system. As seen in Table 5, the total revenue of the distribution system in the presence of the FCs is increased in comparison with the non-DG state. It should be noted that the emission tax is not considered in calculation of the total cost of the distribution system.

In the following, the results of applying the dynamic DG planning problem on 33-bus test distribution system are presented. The technical data of this network is referenced in [28]. The candidate buses for placement of each type of the DG units are as follows:

WTs: [2, 12, 28], PV modules: [3, 25, 33], other DG types (GTs, DEs, FCs, MTs): [6, 15, 33].

Only 3 places for each DG type is considered in this section. The reason is that the total maximum load of the 33-bus distribution system is 3.715 MW and 2.3 MVAr and considering the load duration curve, the average total load of the test system will be very lower than 3.715 MW and 2.3 MVAr. Also, a small capacity is considered for each DG type. Maximum capacity of PV modules is assumed 0.1 MW and maximum capacity of the other DG types (WTs, GTs, DEs, FCs and MTs) is considered 0.2 MW.

Table 4. The DG planning results for scenario#2 of 9-bus test system

Year#	Bus#	FC (MW)	WT, PV,GT,DE,MT (MW)
1	2	2	0
	3	2	0
	4	2.25	0
	5	4	0
	6	2	0
	7	4	0
	8	3.45	0
	9	2.25	0
2	2	2	0
	3	2	0
	4	2.25	0
	5	4	0
	6	2	0
	7	4	0
	8	4	0
	9	3.5	0
3	2	4	0
	3	2	0
	4	3.4	0
	5	4	0
	6	2	0
	7	4	0
	8	4	0
	9	4	0
4	2	4	0
	3	4	0
	4	4	0
	5	4	0
	6	4	0
	7	4	0
	8	4	0
	9	4	0
5	2	4	0
	3	4	0
	4	4	0
	5	4	0
	6	4	0
	7	4	0
	8	4	0

Table 5. The results of costs and incomes of the planning problem for 9-bus test system scenario#2

Costs & Incomes (M$)	With DG				
	Year				
	1	2	3	4	5
Energy Loss	0.20	0.23	0.30	0.41	0.57
Purchased Energy	6.59	7.03	7.78	9.82	13.1
Emission Tax	22.70	24.12	27.38	32.22	35.8
DG Operation	6.87	7.30	8.26	9.48	9.30
DG Investment	8.90	0	0	0	0
ENS	0.11	0.11	0.14	0.16	0.20
Upgrading	1.90	2.03	2.46	3.18	4.80
Selling DG Power	19.58	20.85	22.95	27.59	30.4
Grant Subsidy	26.03	27.64	31.31	35.89	35.2
Salvage Value	0	0	0	0	0.81
Total Cost	24.57	16.70	18.94	23.05	28.0
Total Income	45.61	48.49	54.26	63.48	66.5
Total Revenue	-1.66	7.67	7.93	8.21	2.68
Total Revenue of the Planning period (without emission tax)				167.07	

Scenario#1 (more than one type of DG units can be placed in each bus): Table. 6 shows the DG unit's capacity during the planning period. The capacity of the polluting DG units such as DEs and GTs is zero in all of the years. The MTs could obtain a few part of the total installed capacity of the DG units. The reason is that using from these polluting units leads to high emission taxes. Therefore, the DISCO tries to use from other clean technologies.

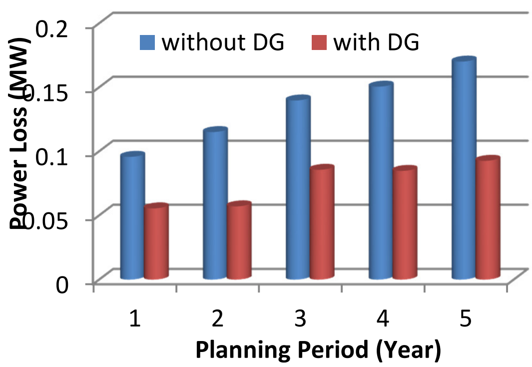

Fig. 22. Power loss of the distribution system with and without DG units

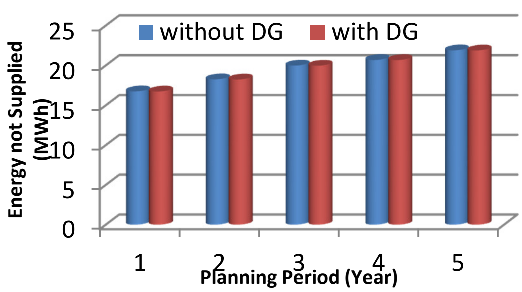

Fig. 23. Energy not supplied of the distribution system with and without DG units

Table 6. The DG planning results for scenario#1 of 33-bus test system

Bus#	Year#	Capacity (MW)					
		WT	PV	GT	FC	DE	MT
2	1	0.2	0	0	0	0	0
3		0	0.1	0	0	0	0
6		0	0	0	0.2	0	0.05
12		0.2	0	0	0	0	0
15		0	0	0	0.2	0	0.05
25		0	0.1	0	0	0	0
28		0.15	0	0	0	0	0
33		0	0.1	0	0.2	0	0
2	2	0.2	0	0	0	0	0
3		0	0.1	0	0	0	0
6		0	0	0	0.2	0	0.15
12		0.2	0	0	0	0	0
15		0	0	0	0.2	0	0.1
25		0	0.1	0	0	0	0
28		0.2	0	0	0	0	0
33		0	0.1	0	0.2	0	0.1
2	3	0.2	0	0	0	0	0
3		0	0.1	0	0	0	0
6		0	0	0	0.2	0	0.15
12		0.2	0	0	0	0	0
15		0	0	0	0.2	0	0.1
25		0	0.1	0	0	0	0
28		0.2	0	0	0	0	0
33		0	0.1	0	0.2	0	0.1
2	4	0.2	0	0	0	0	0
3		0	0.1	0	0	0	0
6		0	0	0	0.2	0	0.15
12		0.2	0	0	0	0	0
15		0	0	0	0.2	0	0.1
25		0	0.1	0	0	0	0
28		0.2	0	0	0	0	0
33		0	0.1	0	0.2	0	0.1
2	5	0.2	0	0	0	0	0
3		0	0.1	0	0	0	0
6		0	0	0	0.2	0	0.15
12		0.2	0	0	0	0	0
15		0	0	0	0.2	0	0.1
25		0	0.1	0	0	0	0
28		0.2	0	0	0	0	0
33		0	0.1	0	0.2	0	0.1

Figures 22 and 23 show the power loss and energy not supplied of the distribution system with and without the DG units. As shown in Fig. 22, the power loss of the distribution system after installing the DG units is decreased during the planning period. As seen in Fig. 23, the reduction in energy not supplied of the distribution system is very low. The reason is that only 3 types of the DG units including WTs, PV modules and FCs with a low capacity are located only in 3 buses. So, in the most islanded sections of the test distribution system after failing the lines, any DG units are not located. Thus, the DG units have not a significant effect in reducing the energy not supplied of the distribution system. However, the reliability of the distribution system is improved in the presence of the DG units. Fig. 24 shows the power purchased by the DISCO from the transmission system before and after installing the DG units. As seen in this figure, the purchased power by the DISCO is decreased in the presence of the DG units, so the emission pollutants are decreased using the DG units.

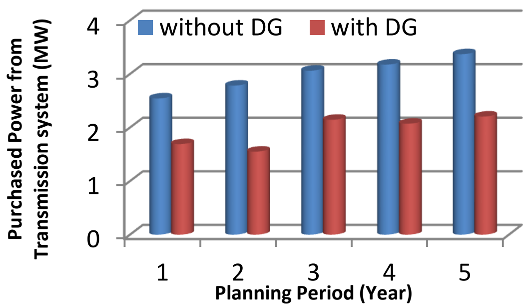

Fig. 24. Purchased power from transmission system with and without DG units

Table 7. The DG planning results for scenario#2 of 33-bus test system

Bus#	Year#	Capacity (MW)					
		WT	PV	GT	FC	DE	MT
2	1	0.2	0	0	0	0	0
3		0	0.1	0	0	0	0
6		0	0	0	0.25	0	0
12		0.2	0	0	0	0	0
15		0	0	0	0.25	0	0
25		0	0.1	0	0	0	0
28		0.15	0	0	0	0	0
33		0	0.1	0	0.2	0	0
2	2	0.2	0	0	0	0	0
3		0	0.1	0	0	0	0
6		0	0	0	0.35	0	0
12		0.2	0	0	0	0	0
15		0	0	0	0.3	0	0
25		0	0.1	0	0	0	0
28		0.2	0	0	0	0	0
33		0	0.1	0	0.3	0	0
2	3	0.2	0	0	0	0	0
3		0	0.1	0	0	0	0
6		0	0	0	0.35	0	0
12		0.2	0	0	0	0	0
15		0	0	0	0.3	0	0
25		0	0.1	0	0	0	0
28		0.2	0	0	0	0	0
33		0	0.1	0	0.3	0	0
2	4	0.2	0	0	0	0	0
3		0	0.1	0	0	0	0
6		0	0	0	0.35	0	0
12		0.2	0	0	0	0	0
15		0	0	0	0.3	0	0
25		0	0.1	0	0	0	0
28		0.2	0	0	0	0	0
33		0	0.1	0	0.3	0	0
2	5	0.2	0	0	0	0	0
3		0	0.1	0	0	0	0
6		0	0	0	0.35	0	0
12		0.2	0	0	0	0	0
15		0	0	0	0.3	0	0
25		0	0.1	0	0	0	0
28		0.2	0	0	0	0	0
33		0	0.1	0	0.3	0	0

Scenario#2 (only one type of DG units can be placed in each bus): In this scenario, in each bus only one type of the DG units can be placed. The maximum capacity of each type of the DG units is considered 0.4 MW. Table7 shows the DG planning results during the planning period. Since the candidate buses for placement of the GTs, DEs, FCs and MTs are assumed the same, so all of the DG units' capacity in these buses are devoted to the FCs the same as the second scenario in the 9-bus test distribution system. As seen in Table 7, the GTs, MTs and DEs could not obtain any part of the total installed capacity of the DG units due to generating high amount of emissions. Since the WTs and PV modules' candidate buses are different from the FCs, so, the WTs and PV modules in spite of their uncertain nature could obtain some part of the total installed capacity of the DG units.

7. CONCLUSION

In this study a dynamic point of view for DG planning problem instead of the old methods such as static or pseudo-dynamic ways is proposed. In the presented study, a probabilistic method is proposed to model the DG units and load uncertainties. A sensitivity analysis on the stochastic nature of the electricity price and global fuel price of each year is carried out using a new proposed method. The ICA is used for the first time to solve a dynamic DG planning problem to show the applicability of this evolutionary strategy in solving the multi-dimensional and non-linear problems. Also, in order to show the applicability of the ICA method in solving the dynamic DG planning problem the results are compared with GA.

Two scenarios are defined. In the first scenario, more than one type of DG units can be located in each bus and in the second scenario, only one type of DG unit can be placed in each bus. The proposed problem is applied on the 9-bus and 33-bus test distribution systems and some important results are obtained as follows:

- The dynamic point of view that is the most complete way with the most exact results is selected and is proposed for DG planning problems. In this way, all of the calculated costs and incomes are more accurate than the static way. So, the results of size, site and type of the DG units in distribution system is more reliable.
- The power loss, energy not supplied and emission pollutants of the distribution system is reduced in presence of the DG units. Therefore, the social

welfare of the customers of the distribution system is increased after DG allocation.

- As shown in the simulation results, considering the emission tax as part of the total costs of the distribution system cause to decrease the total amount of capacity of the polluting DG units, while removing this function cause to increase the capacity of the polluting technologies.
- When it is considered that only one type of DG units can be placed in each bus, the GTs, DEs and MTs could not obtain any part of the total installed capacity of the DG units due to producing a large amount of emissions. In addition, the WTs and PV modules could not obtain any part of the total installed capacity of the DG units due to their uncertain nature. FCs have a medium level of emission pollutants without any uncertainty. Therefore, they obtained the whole capacity of the DG units.
- To make real conditions, some parameters such as the load model or the load growth rate, which were considered constant in the last studies, are modeled with Load Duration Curve (LDC) and a real load growth rate curve.

NOMENCLATURE

Indices	
g	state numbers of probability generation load matrix
$gtot$	Total No. of states of probability generation load matrix
N_{DG}	The total no. of DG types
cy	Counter for year
yr	Year number
N_{bus}	Total number of buses
i,j	Bus number
Ty	Planning period
n	Column no. of M_{PGL} (n^{th} type of DG)
p	Pollutant no.(co_2, co, no_x,..)
pn	Total pollutants (in this paper=5)
Constants	
$price_{loss}$	Energy loss price ($/MWh)
$F.O.R$	Forced outage rate
V_{MPP}	Voltage in MPP (V)
d	Discount rate
$price_{ENS}$	Price of ENS ($/MWh)
$price_{uc}$	Upgrading cost ($/km)
$pricesel$	Price of selling energy ($/MWh)
$pricetax_p$	Tax price of pollutant of type *p* ($/kg)
$price_{tr}$	Transmission system energy price ($/MWh)
L_{ii}	Length of line between buses i,j (km)
λ_{ii}	Failure rate of line between buses i,j (fail/yr.km)
$persal$	Percentage of investment cost=salvage vaue (%)
inf	Inflation rate
SL_{ij}	The capacity limit for the line between buses i,j (MVA)
P_{rated}	Rated power (MW)
V_{ci}	Cut in speed (m/s)
V_{co}	Cut out speed (m/s)
V_r	Rated speed (m/s)
$priceop_n$	Operation price of DG of type *n* ($/MWh)
pricegr	Grant subsidy price
$priceinv_n$	Investment cost of DG of type *n* ($/MVA)
$P_d(i)$	The active load in bus *i*
$Q_d(i)$	The reactive load in bus *i*
$Y(i,j)$	ij^{th} element of admittance matrix (magnitude)
$\theta(i,j)$	ij^{th} element of admittance matrix (angle)
gr	Growth rate of the load
Variables	
INC^n	Investment cost of n^{th} DG type
$V_a^{yr}(i)$	i^{th} Bus voltage in state *g* , year *yr*
$P_{lzone}^{g,yr}$	Power loss of the islanded zone in state *g*, year *yr*
$P_D^{inc,g,yr}(ij)$	The islanded load after failing the line between buses i,j (MW)
$P_{DG}^{g,yr}(ij)$	The DG capacity of the islanded zone after failing the line between buses i,j (MW)
Em_p^n	The amount of produced pollutant of type *p* for the DG type *n* (kg/MWh)
TotScen	The total no. of generated scenarios in MCS
$Q_{G1}^{g,yr}$	Slack bus reactive generation in state *g*, year *yr*
$\delta_a^{yr}(i)$	Voltage angle in state *g*, year *yr* for bus i (V)

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