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A fuzzy environmental-technical-economic model for distributed generation planning

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ABSTRACT

To determine the optimal size, location and also the proper technology of distributed generation (DG) units in distribution systems, a static fuzzy multiobjective model is proposed in this paper. The proposed model can concurrently optimize a number of conflicting and competing objective functions including economic, technical and environmental attributes. The economic function is the profit of a distribution company (DisCo) from selling the DG output power to its customers. The contribution of this model is the consideration of some DG marginal revenues in the economic function. Inclusion of marginal revenues would not only reduce the investment risks of DG technologies, but also would enable the optimal penetration of DG units. The proposed DG planning framework considers various DG technologies such as photovoltaic (PV), wind turbine (WT), fuel cell (FC), micro-turbine (MT), gas turbine (GT) and diesel engine (DE). The system uncertainties (including those for the energy demand, energy price and DG technologies operating and investment costs) are modeled using fuzzy numbers. The numerical case studies have been carried out using the IEEE 37-node distribution test system to demonstrate the performance of the proposed DG planning model.

1. Introduction

In conventional investment planning approaches, the major objective of electric utilities was to achieve the least-costs that met the pre-specified technical characteristics of the power system. However, electricity restructuring and environmental awareness have introduced major challenges to the traditional planning approaches so that other objectives/attributes such as revenues of the stakeholders, technical characteristics of distribution networks and the pollutants emissions have found comparable importance with respect to the investment and operations costs.

Due to the various advantages of DG technologies in distribution networks, both of the distribution power companies (DisCos) and big energy customers could invest in and operate DG units [1]. This upgrading option has found an important role especially in the developing countries to control excessive load growth. The aim of distributed generation expansion planning (DGEP) is to obtain the sizes, locations and also technologies of the DG units that meet the peak demand forecast in an optimal manner. In this regard, a wide variety of DG technologies exists, which should be assessed on a common platform.

Previous works on defining DG planning frameworks could be classified mainly into two categories: single objective (SO) and multiobjective (MO) planning models. Depending on a planner's point of view, several objective functions have been used in the SO-DGEP. Some of the published works used technical characteristics to solve the DGEP problem [2,3]. In some other research works, the cost function was considered as the main objective of the DGEP problem using heuristic iterative search methods [4,5] or mathematical programming approaches [6].

The main advantage of MO over the SO optimization problems is that a set of optimal (non-dominated) solutions are found instead of one optimal solution; this gives more flexibility to the planner for selecting the best final plan. The authors of references [7] and [8] present two multiobjective models for DG planning. However in [7], the employed model was defined based on the various cost terms and in [8] only the technical functions were considered as objectives for the DG planning. Haghifam et al. in [9] presented an interesting fuzzy MO framework; however, the DG technologies and environmental issues were not considered in their model. The multi attribute decision making (MADM) is

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another suitable rank based optimization model for strategic planning [10,11]. The MADM algorithms are more useful for small size problems with specific solution plans and limited number of actions/strategies and uncertain factors.

Due to the increasing awareness about environmental pollutions, mid-term and long-term targets have been set to reduce the emission intensity of energy supply in several regions of the world. Therefore, the environmental issue will play an important role in the future planning strategies. For this purpose, a comprehensive planning framework is necessary to evaluate the economic, technical and environmental characteristics of various DG technologies and choose an optimal planning scheme, which is the best compromise among these characteristics. In the new competitive environment, the new models for DGEP in power systems should be based on profit assessment instead of cost assessment. This paper presents a static fuzzy multiobjective framework for the DGEP problem to determine the optimal sizes, locations and technologies of DG units. The proposed planning framework aims to maximize the total expected profit of a DisCo (including various revenue and cost terms) while minimizing the violation risks of technical parameters (from their desired values) and gas emission amounts. From a DisCo point of view, DG units are feasible alternatives for distribution network and substation expansions especially in the competitive electricity market environments with various marginal economic benefits. The main contributions of this paper are as follows:

(a) Proposing a fuzzy multiobjective framework including economic, technical and environmental objective functions to find optimal solutions for the locations, sizes and technologies for new DG units to be installed within the current distribution system.
(b) Considering six conventional DG technologies in the planning process. These technologies are modeled in the planning process according to their technical (distribution load flow (DLF), short circuit and reliability analysis), economic and environmental characteristics.
(c) Considering the marginal revenue functions of various DG technologies according to their characteristics and abilities. Some of these marginal revenue functions have double-edge effects and could have disadvantages if they are not properly planned and operated. Therefore, including these functions in the planning process could help the DG investors find the optimal penetration of DG units.

The remaining sections of this paper are organized as follows: Section 2 describes the overview of the DGEP framework and presents the problem formulation and the fundamental of non-dominated sorting genetic algorithm is discussed in Section 3. Section 4 illustrates numerical results on a typical case study and finally some concluding remarks are provided in Section 5.

2. Overview of the distributed generation expansion planning framework

In this paper a static fuzzy multiobjective model is presented to address the DGEP problem which is shown in Fig. 1. This model determines the sizes (penetration level), locations and technologies of DG units in three stages. In the first stage, data gathering is done and the input parameters are divided into deterministic and non-deterministic parameters. The non-deterministic data parameters are modeled using triangular fuzzy numbers. In the second stage, a MODM DG planning problem is formulated. Then the modified non-dominated sorting genetic algorithm (NSGA-II)

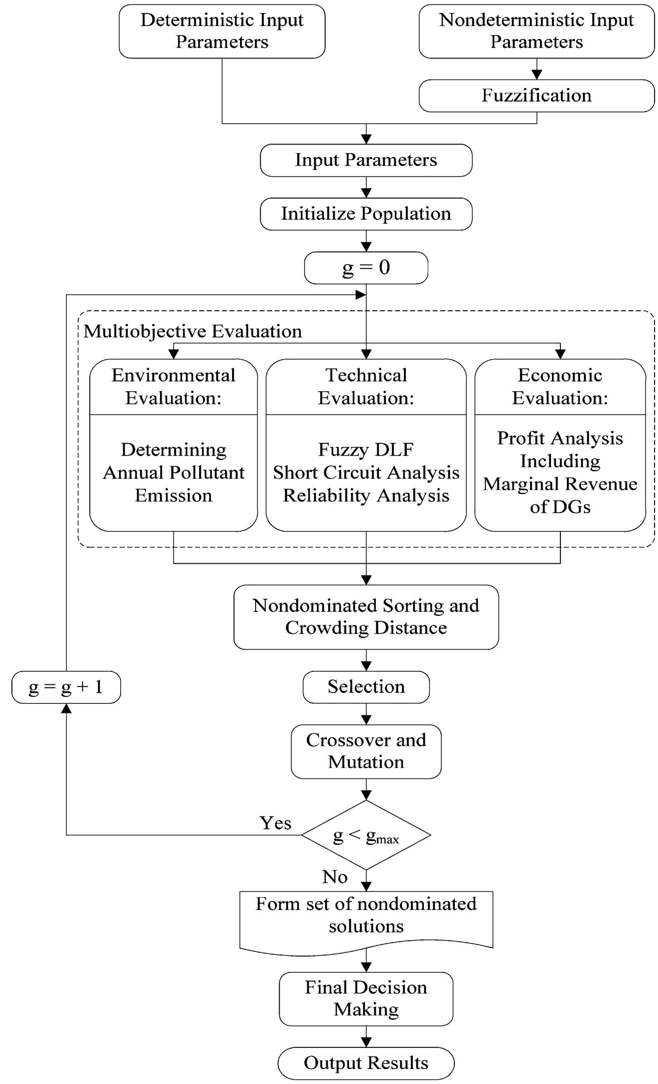

Fig. 1. Proposed algorithm for distributed generation expansion planning.

is applied to solve the formulated MODM DG planning problem. Three main objective functions, which address the economic, technical and environmental issues, are defined in this paper. The employed economic function is defined based on the profit (cost and revenue) evaluation of each planning scheme; the marginal economic benefits of various DG technologies are included in the economic function. The technical objective function is determined as the weighted sum of the violation risks of several technical parameters. For this purpose, a fuzzy distribution load flow (DLF), single and three-phases short circuits are executed to determine the technical indices. The reliability analysis of the DG units on the expected annual interruption cost is also included in the marginal revenue function. The annual emission amounts of the pollutant gases are considered as the environmental objective function. Due to the conflicting nature of the objective functions, it is generally impossible to obtain an optimal solution at which all the objectives are optimized. A set of non-inferior solutions are created at this stage and the final decision is made in the third stage based on the normalized fuzzy membership function for choosing the best solution among the obtained set of non-dominated solutions.

2.1. Input parameters

The input data for the planning process are divided into certain and uncertain data parameters. The certain parameters are the distribution system characteristics such as network configuration, resistance (R) and reactance (X) of the branches, capital costs of DG technologies, and emission rates of DG technologies for different gases. On the other hand, the load data, electricity market price, operation costs and capacity factors of the DG technologies are considered uncertain data parameters. The uncertain parameters are modeled through fuzzy numbers (with three discrete numbers as their ranges of uncertainty).

2.2. Problem formulation

The problem formulation of the DGEP is proposed in such a manner to cover economic, technical and environmental issues. The assumptions considered in the DGEP problem are listed as follows [12].

- There are no geographic or primary resource limitations to install various DG technologies within the distribution system.
- The proposed DG planning model is presented from the prospective of a DisCo in an energy market environment.
- The proposed DG planning model is a one-stage (static) planning strategy.
- To exploit the advantages of using DG units for reducing the energy not served (ENS) index, the islanding operation of DG technologies is permitted.

2.2.1. Objective functions and constraints

A multiobjective optimization problem is generally expressed in the form of Eq. (1). In this paper three objective functions are optimized concurrently as follows:

$$\begin{aligned} &\min\ F(x) = \{-f_1(x), f_2(x), f_3(x)\} \\ &\text{s.t.}\ \ g(x) \le 0,\ \ h(x) = 0 \end{aligned} \tag{1}$$

where f_1 denotes the profit function, f_2 and f_3 are the technical and the environmental functions, respectively. Note that the minus sign behind f_1 in (1) is due to the fact that f_1 is the profit function and has to be maximized.

2.2.1.1. Economic function (f_1). Economic evaluation is the major driving force behind any investment choice. This function is profit based and consists of cost, revenue and marginal revenue terms corresponding to the DG planning schemes (2). In this equation, three terms are considered as marginal revenues of the DG technologies, namely economic benefits of upgrade investment deferral, expected annual interruption cost reduction and energy losses curtailment. However, there are some other marginal revenues and incentives especially for renewable technologies (such as long-term bilateral contracts for selling their output powers, emission reduction credits and heat selling for CHP units), which are not considered in this paper.

$$f_1 = R_\mathrm{W} + R_\mathrm{DG} - C_\mathrm{DG} + \sum_{i=1}^{3} \mathrm{MR}_i \tag{2}$$

where R_W and R_DG are the revenues from selling the grid power and DG units output power, respectively; C_DG is the total investment cost of DG units, and MR denotes the marginal revenue of DG units.

(a) Revenue of selling the grid power (R_W):

$$R_\mathrm{W} = \sum_{i=1}^{\mathrm{ns}} \mathrm{CPV} \times P_{\mathrm{sub},i} \times \mathrm{LF} \times \left(\rho_\mathrm{r} - \tilde{\rho}_\mathrm{W}\right) \times 8760 \tag{3}$$

$$\mathrm{CPV} = \sum_{t=1}^{T_p} \left((1+i)(1+l)/(1+d)\right)^t \tag{4}$$

where CPV is the cumulative present value during the planning horizon.

(b) Revenue of selling the DG units power (R_DG):

$$R_\mathrm{DG} = \sum_{i=1}^{\mathrm{nb}} \sum_{j \in \mathrm{Tech}} \left(\rho_\mathrm{r} - \tilde{C}_{\mathrm{o}j}\right) \times \mathrm{CPV} \times P_{\mathrm{DG},ij}^{\mathrm{Cap}} \times \tilde{\alpha}_j \times 8760 \tag{5}$$

(c) Total investment cost of DG technologies (C_DG):

$$C_\mathrm{DG} = \sum_{i=1}^{\mathrm{nb}} \sum_{j \in \mathrm{Tech}} \mathrm{IC}_j \times P_{\mathrm{DG},ij}^{\mathrm{Cap}} \tag{6}$$

(d) Marginal revenue of upgrade investment deferral:

$$\begin{aligned} \mathrm{MR}_1 = {} & C_\mathrm{ut}\left(\left(\frac{(1+i)}{(1+d)}\right)^{T_\mathrm{ut}^0} - \left(\frac{(1+i)}{(1+d)}\right)^{T_\mathrm{ut}^1}\right) \\ & + \sum_{k=1}^{\mathrm{nl}} C_\mathrm{ub} \times L_k \left(\left(\frac{(1+i)}{(1+d)}\right)^{T_{\mathrm{ub},k}^0} - \left(\frac{(1+i)}{(1+d)}\right)^{T_{\mathrm{ub},k}^1}\right) \end{aligned} \tag{7}$$

(e) Marginal revenue of the annual interruption cost reduction:

$$\mathrm{MR}_2 = \mathrm{EAIC}_1 - \mathrm{EAIC}_0 \tag{8}$$

$$\mathrm{EAIC} = \sum_{i=1}^{\mathrm{nb}} \sum_{k=1}^{\mathrm{nl}} \mathrm{CPV} \times P_{\mathrm{c},ik}^{\mathrm{f}} \times L_k \times \lambda \times T_\mathrm{f} \times C_{\mathrm{ue},i} \tag{9}$$

(f) Marginal revenue of energy losses reduction:

$$\mathrm{MR}_3 = \left(P_{\mathrm{loss},0} - P_{\mathrm{loss},1}\right)\rho_\mathrm{r} \times \mathrm{LF} \times \mathrm{CPV} \times 8760 \tag{10}$$

2.2.1.2. Technical function. In addition to economic evaluation, it is important that a solution candidate (DG planning scheme) is capable of meeting the technical requirements of the distribution network simultaneously. This function is defined as the weighted sum of technical violation risk [9]. The technical parameters employed to model the violation risks include the risk of over/

under voltage (RI_{volt}) through nodes of the distribution networks, the risk of overloading (RI_{flow}) in line segments and transformers, the risk of increasing power losses (RI_{loss}) with respect to the base case (i.e. without DG installation) and the violation risk of short circuit capacity. For this purpose a fuzzy distribution load flow (DLF) is applied based on the forward-backward algorithm including distributed generation models [13], and the concept of fuzzy numbers [14]. Also, single and three-phase short circuit analyses including the DG technologies within the distribution network are executed [15]. Technical violation risk indices are defined using the concept of fuzzy constraint modeling, which are explained in Section 2.2.2.

$$f_2 = wt_1 RI_{volt} + wt_2 RI_{flow} + wt_3 RI_{loss} + wt_4 RI_{sc} \tag{11}$$

(a) The risk value of over/under voltage [9]:

$$RI_{volt} = \max\{RI_{volt,k} | k \in nl\} \tag{12}$$

$$RI_{volt,k} = \text{risk}\left\{\left(\tilde{V}_k < V_{min}\right) \& \left(V_{max} < \tilde{V}_k\right)\right\} \tag{13}$$

(b) The risk value of overflow [9]:

$$RI_{flow} = \max\left\{RI_{flow,k} | k \in (nl, ns)\right\} \tag{14}$$

$$RI_{flow,k} = \text{risk}\{P_k > P_k^{max}\} \tag{15}$$

(c) The risk value of increasing energy losses with respect to the base case:

$$RI_{loss} = \text{risk}\left\{\tilde{P}_{loss} \geq \tilde{P}_{loss}^{b}\right\} \tag{16}$$

(d) The risk value of single/three-phase short circuit capacity with respect to the base case:

$$RI_{sc} = \max\left\{\max\left(RI_{sc,k}^{1\Phi}, RI_{sc,k}^{3\Phi}\right) | k \in nb\right\} \tag{17}$$

$$RI_{sc,k}^{1\Phi} = 100 \times \left(SC_k^{1\Phi} - SC_{k,b}^{1\Phi}\right) \Big/ \left(SC_{k,b}^{1\Phi}\right) \tag{18}$$

$$RI_{sc,k}^{3\Phi} = 100 \times \left(SC_k^{3\Phi} - SC_{k,b}^{3\Phi}\right) \Big/ \left(SC_{k,b}^{3\Phi}\right) \tag{19}$$

2.2.1.3. Environmental function. Nowadays with increasing the awareness of environmental pollutions, sometimes DG technologies with low costs and appropriate technical characteristics may not be the best solution from the environmental viewpoint. In the employed objective function, the annual amount of pollutant gas emissions is minimized [16]. The main pollutant gases are CO_2, NO_x, SO_2, CO and PM_{10}.

$$f_3 = \sum_{i=1}^{nb} \sum_{j \in Tech} \sum_{k=1}^{ng} P_{DG,ij}^{Cap} \times we_k \times ER_{jk} \times \tilde{\alpha}_j \times 8760 \tag{20}$$

2.2.1.4. Constraints.

(a) Maximum installed DG capacity at each node:

$$\sum_{j \in Tech} P_{DG,ij}^{CAP} \leq P_{DG}^{max}, \quad \forall i \in nb \tag{21}$$

(b) Distribution load flow constraints which satisfy the convergence of the algorithm [13].

2.2.2. Fuzzy modeling of uncertainties

Several uncertain parameters should be considered and analyzed when planning a power system expansion. In this paper, the fuzzy numbers are used to model the uncertain parameters (which is convenient for evaluating random numbers with discrete PDFs). The triangular fuzzy numbers (TFN) are defined based on three values [14]: optimistic (P_1), possible (P_2) and pessimistic (P_3) values as shown in Fig. 2.

2.2.2.1. Uncertain parameters modeling. In this paper, three input parameters for the DG planning are considered as uncertain parameters: the forecasted load, electricity market price and parameters related to the DG technologies. The forecasted load and electricity market price are inherently two conventional uncertain parameters in the planning problems and are modeled using the TFN approach. The operating cost and the capacity factor of DG technologies are also considered as two other uncertain parameters in this paper. Due to the technological improvement of DG units and also the intensive variation of the worldwide energy prices, it is not appropriate to set deterministic values for the operation costs of various DG types during a particular planning horizon. Also, the capacity factor of DG technologies is difficult to be predicted precisely in a year especially for renewable technologies with intermittent characteristics.

2.2.2.2. Constraints modeling as risk functions. One of the advantages of using fuzzy logic/theory in optimization problems is to handle the constraints in soft forms [9]. In this form, instead of assigning a true or false value, a certain degree of violation is

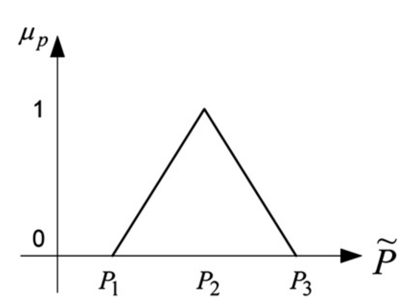

Fig. 2. Triangular fuzzy model.

defined as the risk function. For instance, the voltage constraint (Eq. (22)) at each node of a distribution network is expressed as the risk of violation using the following upper and lower limits (Eq. (23)).

$$V^{\min} \leq V_k \leq V^{\max} \tag{22}$$

$$\mathrm{RI}_{\mathrm{volt}} = \mathrm{risk}\left\{\left(V_k \leq V^{\min}\right)\Big|\left(V^{\max} \leq V_k\right)\right\} \tag{23}$$

To obtain a value that demonstrates the above statement, a risk index is defined as the ratio between violation areas (A_{vl} and A_{vr}) and total area (Eq. (23)), which is shown in Fig. 3 [9].

$$\mathrm{RI}_{\mathrm{volt}} = (A_{\mathrm{vl}} + A_{\mathrm{vr}})/A_{\mathrm{tot}} \tag{24}$$

2.2.3. Final decision making

Mathematically, none of the solutions in the trade-off region has a priority with respect to other solutions. Due to the subjective imprecise nature of the decision maker's judgment, a fuzzy satisfying method is applied here to select the preferred solution among non-dominated solutions [17]. Through fuzzy set theory, each objective function is presented with a linear membership function. If the objective function is monotonically decreasing, Eq. (25) is used for normalizing vice versa if the objective function is monotonically increasing Eq. (26) is applied.

$$\mu_i^k = \frac{f_i^{\max} - f_i^k}{f_i^{\max} - f_i^{\min}} \tag{25}$$

$$\mu_i^k = \frac{f_i^k - f_i^{\min}}{f_i^{\max} - f_i^{\min}} \tag{26}$$

where $f_i^{\min}$ and $f_i^{\max}$ are the absolute satisfactory and unsatisfactory values of ith objective function according to the decision maker's opinion, respectively. The normalized membership function of the kth non-dominated solution in the objective space is defined as follows [17]:

$$\mu^k = \frac{\sum_{i=1}^{N_f} \mu_i^k}{\sum_{k=1}^{N_p} \sum_{i=1}^{N_f} \mu_i^k} \tag{27}$$

The solution with the maximum membership value is selected as the best compromising solution.

3. Non-dominated sorting genetic algorithm (NSGA-II)

The NSGA-II algorithm uses non-dominated sorting for fitness assignments. Based on this idea, a population of solutions is classified into the number of non-dominated fronts [18]. In this paper, the decision variables (size, location and technology of DG units) are coded using real numbers. The computational algorithm of NSGA-II is used to address the DGEP problem through the following steps [18]:

Step 1 Initialization. Similar to other evolutionary approaches, a population is generated randomly in the search space as initial solutions of the algorithm.
Step 2 Objective evaluation. In this step, the values of objective functions are evaluated for each individual of the population.
Step 3 Non-dominated sorting. The responsibility of this step is to classify individuals into some fronts (layers) according to the dominated concept and fitness of objective functions. One individual is said to dominate another if its solution is no worse than the other in all objectives and also it is strictly better than the other in at least one objective.
Step 4 Crowding distance. After completing the non-dominated sorting, the crowding distance is utilized to sort the classified individuals in the same front.
Step 5 Selection. The selection is carried out based on the binary tournament between two randomly chosen individuals from the population.
Step 6 Cross-over. The Simulated Binary Crossover (SBX) as an approach for real GA numbers is used in this step. It works with two parent solutions and generates two offspring.
Step 7 Mutation. In this step, the polynomial approach is used for mutation. The probability distribution can also be a polynomial function, instead of a normal distribution.

The above process except Step 1 is repeated for the maximum number of generations.

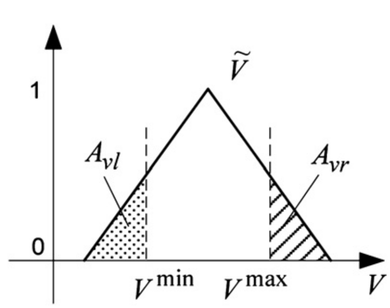

Fig. 3. Fuzzy voltage constraint modeling as a risk value.

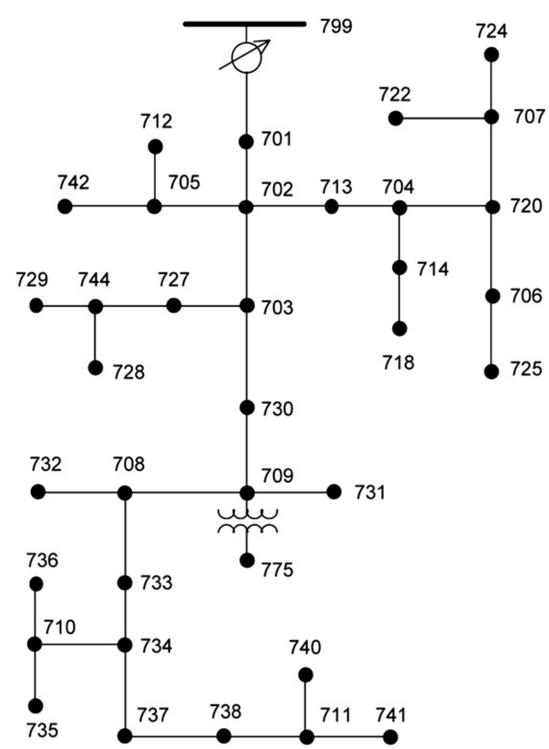

Fig. 4. IEEE 37-node distribution test system [19].

Table 1
Fuzzy modeling of uncertain parameters.

Uncertain parameters		Lower value	Middle value	Upper value
Operating cost of DG technologies (Cent/kWh)	DE	3.5	4.5	5.5
	GT	3	4	5
	MT	4	5	6
	FC	4	5	6
	WT	0.5	1	1.5
	PV	0.25	0.50	0.75
Capacity factor of DG technologies (%)	DE	32	35	40
	GT	50	55	58
	MT	30	35	40
	FC	35	40	45
	WT	15	20	30
	PV	15	25	30
Market price (Cent/kWh)		4	8	12

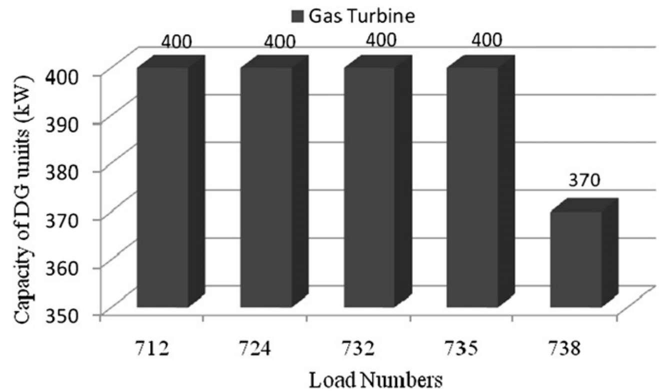

Fig. 5. Size, location and technology of DG units in the optimal planning scheme in scenario A.

4. Numerical results

The proposed planning framework was implemented in the MATLAB environment and applied to the IEEE 37-node distribution test system (as shown in Fig. 4). The distribution test system consists of 25 load points and one junction substation of 2500 kVA capacity connecting the remainder of the system to the main grid. The maximum forecasted demand at the beginning of the planning horizon is equal to 2734 kVA with a load growth rate equal to 4% and therefore, it is necessary to meet the required demand either by upgrading the junction substation or the local power supplies. It is assumed that the DisCo has to plan for a peak load growth to be served in a10-year duration by investing in DG capacities, whereas the forecasted demand is uncertain and has an error equal to 20%. The network data for this system can be found in [19] and the information of DG technologies is presented in Tables 1 and 2 including capital costs, operating costs, capacity factors and emission rates. The discount and inflation rates are assumed to be 9% and 6%, respectively during the planning horizon [17]. The maximum installed capacity at each node is assumed 400 kW. Six conventional DG technologies namely photovoltaic (PV), wind turbine (WT), fuel cell (FC), micro-turbine (MT), gas turbine (GT) and diesel engine (DE) are considered in this paper with different economic, technical and environmental characteristics. Three different case study scenarios are investigated in this section to evaluate three generations of DG planning models, and to compare the proposed DG planning model with the earlier ones. These planning scenarios are discussed as follows.

(1) Scenario A: single objective based planning model. This scenario is defined according to the traditional planning model, which has been frequently used in the literature. The goal of this model is to minimize a cost function with respect to the technical constraints during the planning horizon. The environmental function, which was introduced in Section 2.2.1.3, is neglected in this scenario and the technical objective functions (RI_{volt}, RI_{flow}, RI_{loss} and RI_{sc}) are considered as constraints. The objective function consists of investment and operating costs of the candidate DG technologies, cost of purchased energy by the DisCo and cost of energy losses. A simple genetic algorithm is used to solve this problem. After the convergence of GA, the value of the employed cost function reaches to 19.827 million dollars (M$) for the best planning scheme during the utilized planning horizon. The detailed costs of this function are 1.97 M$ for the investment cost, 5.41 M$ for the operating cost, 11.83 M$ for the purchased energy from the grid and 0.617 M$ for energy losses. The size, location and proper technology of the optimal planning scheme are presented in Fig. 5. It is observed that the gas turbine is selected as the only technology in the selected planning scheme with the total capacity of 1970 kW.

(2) Scenario B: multiobjective based planning model with cost evaluation. In this scenario, the planning model is promoted by defining a multiobjective planning framework instead of the single objective function of scenario A. The multiobjective planning framework of this scenario considers the cost function, technical function and environmental functions. However, this model is not completely developed as the proposed model of the present paper. In other words, the economic objective function of scenario B is just the cost function and not the profit function. The other two objective functions (technical and environmental) are applied as defined in Section 3. The weighting factors of the technical and environmental objective functions may be chosen based on the importance/criticality of each attribute or index. Therefore, it is possible to use multi attribute decision making approaches like analytical hierarchy process (AHP) to determine the weight factors. However, for brevity, an equal weighting factor is considered in both technical and environmental functions. To determine the set of non-dominated solutions, the NSGA algorithm is executed using the parameters in Table 3. The obtained non-dominated solutions are shown in Fig. 6, which shows a trade-off between cost and environmental function. Fig. 6 shows that decreasing of the annual amount of emissions leads to increasing the total cost of DG planning schemes and vice versa. In other words, it shows that utilization of renewable and clean power technologies (in order to decrease the emissions) would increase the

Table 2
Deterministic parameters of DG technologies [17,20].

Tech.	Capital cost ($/kW)	Emission rate of pollutant gases (kg/kWh)				
		CO_2	NO_x	SO_2	CO	PM_{10}
DE	500	0.65	4.483	0.093	1.275	0.16
GT	1000	0.63	0.236	0.002	0.144	0.016
MT	1500	0.72	0.091	0.002	0.247	0.018
FC	3500	0.46	0.006	0.012	0.002	0
WT	4500	0	0	0	0	0
PV	5000	0	0	0	0	0

Table 3
Parameters of the NSGA-II algorithm.

Parameter	Value	Parameter	Value
Population	500	Generation (g_{max})	300
Crossover	0.9	Mutation	0.125

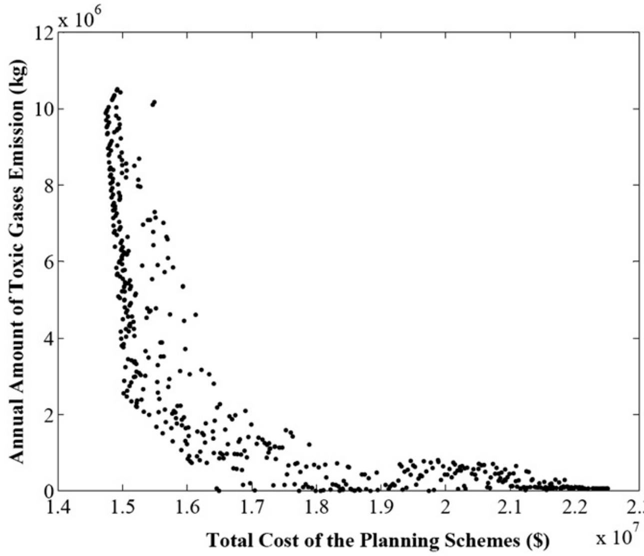

Fig. 6. Trade-off curve between cost and environmental objective functions.

total cost of DG planning schemes. The total cost of DG planning schemes varies between 15 and 22.5 M$. The normalized membership function presented in Section 2.2.3 helps the decision maker to select the best compromise solution. The best optimal planning scheme which is presented in Fig. 7 includes photovoltaic, fuel cell, micro-turbine and gas turbine technologies with a total capacity of 2000 kW. In this scheme, the values of economic (including investment and operating cost of DG units, cost of energy purchased and energy losses), technical and environmental objective functions are 16.22 M$, 36.3% and 3170 ton, respectively. It could be useful to find the situation of the best planning scheme (in Fig. 6) by comparing the values of the economic and the environmental objective functions of the best planning scheme with the vertical and horizontal axes of Fig. 6. Due to considering the environmental function in this scenario, the clean technologies like FC and PV have been entered to the optimal planning scheme with respect to the previous scenario (A). However, the penetration percentage of total DG units is almost the same in both of the studied scenarios (A & B).

(3) Scenario C: multiobjective based planning model with profit evaluation. In this scenario, the proposed DG planning model is evaluated (with respect to the DG planning models of scenarios A & B). This model is based on the multiobjective optimization explained in Section 2.2.1. However, in this model the profit

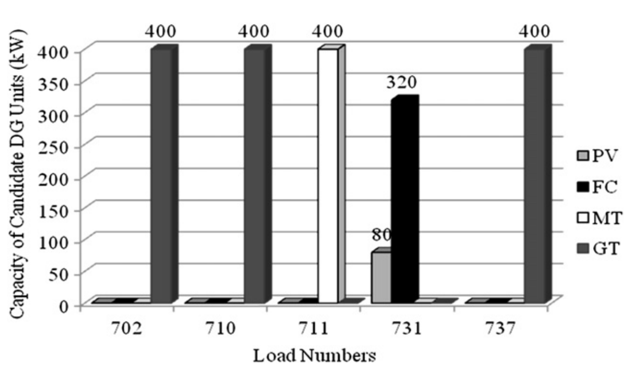

Fig. 7. Size, location and technology of DG units in the optimal planning scheme in scenario B.

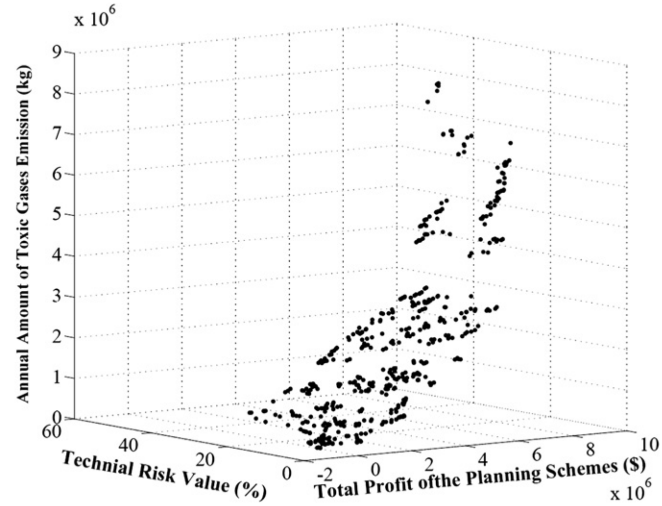

Fig. 8. Three dimensional trade-off curve between objective functions.

function (with DG marginal revenues) is used instead of the cost function in scenarios A & B. The retail electricity price (ρ_r) is assumed fixed and 30% larger than the average market price (ρ_w) in Table 1. The cost of energy not served is assumed to vary at each node of the distribution system depending on its importance as given in [17]. Also, the unit upgrading cost of branch (C_{ub}) and upgrading cost of transformer (C_{ut}) are assumed 0.15 (M$/km) and 0.05 ($/kVA), respectively [5]. Three dimensional trade-off curves of this scenario are presented in Fig. 8. It is observed that if the planner aims to reduce the gas emissions, the profit of the planning schemes will be reduced dramatically. Even in some schemes, the profit could become negative showing that for investing in renewable and clean technologies, some supporting policies like low-loan and grants for low emissions are needed; otherwise, the profits of the planning schemes would become negative.

Table 4 presents three schemes as three minima points of each objective function which are located on the boundary points of the Pareto set in Fig. 8. It should be noted that these are not the optimal planning schemes according to the multiobjective optimization, but they are just the optimal planning schemes in their individual single objective functions and are on the borders of the Pareto set. Similar to scenario B, in order to determine the best planning scheme among non-dominated solutions of Fig. 8, it is necessary to apply the normalized fuzzy membership function in Section 2.2.3.

Table 5 presents the first eight schemes and their objective values among non-dominated solutions according to the normalized membership function. In this table, the best solution in each objective function and its rank among non-dominated solutions of the multiobjective optimization result has been included. Table 5 shows that solution number 14 was selected as the best planning

Table 4
The best planning schemes w.r.t each objective function individually.

Scheme no.	Size (kW), location and technology of candidate DG units
3	$P^{GT}_{701} = 230$, $P^{DE}_{701} = 110$, $P^{GT}_{705} = 400$, $P^{PV}_{713} = 20$, $P^{GT}_{713} = 360$, $P^{GT}_{722} = 260$, $P^{FC}_{728} = 90$, $P^{MT}_{728} = 250$
4	$P^{PV}_{701} = 200$, $P^{MT}_{701} = 100$, $P^{GT}_{720} = 400$, $P^{FC}_{731} = 210$, $P^{GT}_{731} = 180$, $P^{FC}_{737} = 360$, $P^{PV}_{741} = 350$
299	$P^{PV}_{722} = 220$, $P^{WT}_{729} = 200$, $P^{WT}_{360} = 400$, $P^{PV}_{738} = 10$, $P^{PV}_{741} = 270$

Table 5
Ranking of the planning schemes according to the values of the normalized membership functions.

Scheme no.	Actual objective function value			Normalized objective function value			Normalized membership function ($\times 10^{-3}$)	Rank
	Profit function (M$)	Technical function (%)	Environmental function (1000 ton)	Profit function	Technical function	Environmental function		
14	7.35	15.4	2.95	0.8462	0.7916	0.6329	2.442	1
358	6.00	15.3	1.74	0.6922	0.7927	0.7828	2.439	2
443	7.23	16.4	2.85	0.8326	0.7685	0.6452	2.416	3
490	6.74	15.9	2.51	0.7759	0.7801	0.6872	2.412	4
202	4.03	8.5	1.40	0.4685	0.9490	0.8246	2.411	5
4*	2.62	6.3	0.70	0.3072	1.0	0.9124	2.387	6
98	6.55	17.5	2.34	0.755	0.7427	0.7085	2.373	7
255	3.52	12.8	0.82	0.4098	0.8509	0.8976	2.321	8
299†	1.95	27.4	0	0.2314	0.5173	1.0	1.881	348
3+	8.71	37.9	5.09	1.0	0.2760	0.366	1.776	405

* The best scheme in the technical function viewpoint, † The best scheme in the environmental function viewpoint, + The best scheme in the profit function viewpoint.

Table 6
The cost and revenue values of the profit function in scheme 14.

R_{w} (M$)	R_{DG} (M$)	C_{DG} (M$)	MR_1 (M$)	MR_2 (M$)	MR_3 (M$)
3.55	4.25	2.34	0.668	0.863	0.359

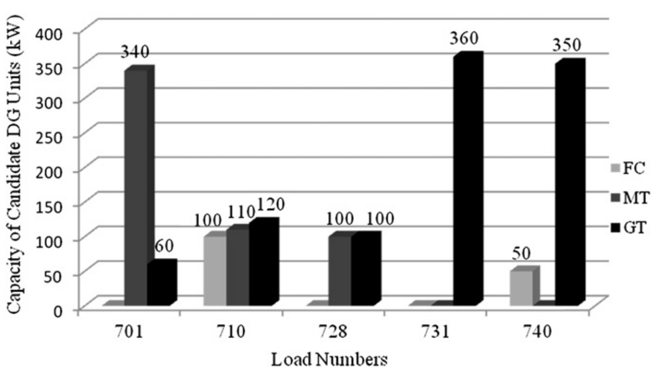

Fig. 9. Size, location and technology of DG units in the optimal planning scheme in scenario C.

scheme among the non-dominated solutions. The values of the profit, technical and environmental objective functions in this scheme are 7.35 M$, 15.4% and 2950 ton, respectively. The detailed values of the cost and revenues in the profit function (f_1) are given in Table 6. The profit values of selling energy from the grid and DG units (of the planning scheme 14) are 3.55 and 4.25 million dollars, respectively and the total investment cost of DG technologies is 2.34 million dollars. The marginal revenues of the upgrade investment deferral, the annual interruption cost reduction and the energy losses reduction are 0.668 M$, 0.863 M$ and 0.359 M$, respectively. It is shown that the marginal revenue of the interruption cost reduction has the largest value among other marginal revenues in scenario C. The net profit value of the best planning scheme is 7.35 M$ according to Eq. (2) while this value is 5.46 M$ without considering the marginal revenues. Including the marginal revenues into the DG planning objective could help the DG investors/operators to distinguish the profitability of different planning options with respect to various marginal revenue sources. As it was illustrated, some of the considered marginal revenues like energy losses reduction and investment deferral may have double-edge (cost and benefit) effects. In other words, although DG units could have economic benefits for the investors/operators (if they are properly planned), but high penetration of DG units could have negative effects on the distribution systems as well. For example, high capacity of DG units leads to the increase power flow through branches and may increase the energy losses or investment costs to upgrade the distribution systems. Thus it could be asserted that a more appropriate penetration of DG units was planned in scenario C. It was shown that the total capacity of DG units in the best planning scheme (shown in Fig. 9) was reduced to 1690 kW. Fig. 9 shows the optimal locations, sizes and types of DG technologies of the best planning scheme. It was observed that in the profit based analysis, the PV unit was omitted in the selected DG planning scheme. The penetration rate of FC, MT and GT technologies in this scheme were 8.9%, 32.5% and 58.6%, respectively.

5. Conclusion

This paper presented a static fuzzy multiobjective model to determine the sizes, locations and the technologies of distributed generation units in an uncertain energy market environment. Six conventional technologies were considered as the potential upgrading options in the planning process. The proposed model covered different aspects of these technologies including economic, technical and environmental issues in a multiobjective mathematical representation. The economic evaluation of this model was profit based by considering three marginal revenues as potential benefits of various DG technologies. However, there are more marginal revenues that could be considered. The NSGA-II algorithm was applied to the IEEE 37-bus distribution system under three different scenarios (two of the existing DG planning models versus the proposed DG planning model) to assess the ability and performance of the proposed model with respect to previous ones. It was shown that the proposed multiobjective planning model (in scenario C) had advantages over the traditional models in scenario A and B (especially in the profit objective function and financial risk reductions). The economic evaluation of the proposed model was more suitable for energy market environments, where money making from the DG invested outputs is the most important objective while minimizing their risks. It was also shown that the marginal revenues (included in the proposed profit function) were useful in modeling some hidden aspects of DG technologies utilization.

References

[1] Willis HL, Scott WG. Distributed power generation planning and evaluation. New York: Marcel Dekker.
[2] Keane A, O'Malley M. Optimal allocation of embedded generation on distribution networks. IEEE Transaction on Power Systems 2005;20(3):1640–6.
[3] Hedayati H, Nabaviniaki SA, Akbarimajd A. A method for placement of DG units in distribution networks. IEEE Transaction on Power Systems 2008; 23(3):1620–8.
[4] Khattam WE, Bhattacharya K, Hegazy Y, Salama MMA. Optimal investment planning for distributed generation in a competitive electricity market. IEEE Transaction on Power Systems 2004;19(3):1674–84.

[5] Khattam WE, Hegazy Y, Salama MMA. An integrated distributed generation optimization model for distribution system planning. IEEE Transaction on Power Systems 2005;20(2):1158–65.

[6] Ault GW, McDonald JR, Burt GM. Strategic analysis framework for evaluating distributed generation and utility strategies. IEE Proceedings on Generation, Transmission and Distribution 2003;150(4):475–81.

[7] Celli G, Ghiani E, Mocci S, Pilo F. A multiobjective evolutionary algorithm for the sizing and siting of distributed generation. IEEE Transactions on Power Systems 2005;20(2):750–7.

[8] Singh D, Singh D, Verma KS. Multiobjective optimization for DG planning with load models. IEEE Transaction on Power Systems 2009;24(1): 427–36.

[9] Haghifam MR, Falaghi H, Malik OP. Risk-based distributed generation placement. IEE Proceedings on Generation, Transmission and Distribution 2008; 2(2):252–60.

[10] Agalgaonkar AP, Kulkarni SV, Khaparde SA. Evaluation of configuration plans for DGs in developing countries using advanced planning techniques. IEEE Transaction on Power Systems 2006;21(2):973–81.

[11] Zangeneh A, Jadid S, Rahimi-Kian A. A hierarchical decision making model for the prioritization of distributed generation technologies: a case study for Iran. Energy Policy 2009;37:5752–63.

[12] Zeineldin HH, Bhattacharya K, El-Saadany EF, Salama MMA. Impact of intentional islanding of distributed generation on electricity market prices. IEE Proceedings on Generation, Transmission and Distribution 2006;153(2): 147–54.

[13] Teng JH. Modelling distributed generations in three-phase distribution load flow. IEE Proceedings on Generation, Transmission and Distribution 2008; 2(3):330–40.

[14] Wei SH, Chen SM. A new approach for fuzzy risk analysis based on similarity measures of generalized fuzzy numbers. Expert Systems with Applications 2009;36:589–98.

[15] Teng JH. Systematic short-circuit-analysis method for unbalanced distribution systems. IEE Proceedings on Generation, Transmission and Distribution 2005; 152(43):549–55.

[16] Zangeneh A, Jadid S, Rahimi-Kian A. Promotion strategy of clean technologies in distributed generation expansion planning. Renewable Energy 2009;34: 2765–73.

[17] Zangeneh A, Jadid S. Fuzzy multiobjective model for distributed generation expansion planning in uncertain environment. European Transactions on Electrical Power; 2009. doi:10.1002/etep.421.

[18] Deb K, Pratap A, Agarwal S, Meyarivan T. A fast elitist multiobjective genetic algorithm: NSGA-II. IEEE Transaction on Evolutionary Computation 2002;6(2): 182–97.

[19] Kersting WM. Radial distribution test systems. IEEE Transaction on Power Systems 1991;6(3).

[20] Distributed generation in liberalized energy markets. Paris: International Energy Agency, IEA; 2002.

Nomenclature

$\tilde{C}_{oj}$, IC_j: Fuzzy operating cost ($/kWh) and investment cost of *j*th DG technology.
C_{ut}: Upgrading cost of transformer ($/kVA).
C_{ub}: Unit cost of upgrading branch ($/km).
$C_{ue,j}$: Cost of unserved energy at *j*th node ($/kWh).
LF: Load factor.
ρ_r, $\tilde{\rho}_W$: Retail price and Fuzzy market price ($/kWh).
$\tilde{\alpha}_j$: Fuzzy capacity factor of *j*th DG technology.
λ, *L:* Average outage rage and length of branches.
d, i, l: Discount, interest and load growth rate.
nb, nl, ns: Total number of nodes, branches and substations.
T^1_{ut}, T^0_{ut}: Required time to upgrade transformer with and without DGs.
T^1_{ub}, T^0_{ub}: Required time to upgrade branches with and without DGs.
Tech: Set of considered DG technologies.
$EAIC_1$: Expected annual interruption cost with DGs.
$EAIC_0$: Expected annual interruption cost without DGs.
$P^f_{c,ij}$: Unserved power at *i*th node due to fault occurrence at *j*th feeder.
P_{loss_1}: Network power losses with DGs.
P_{loss_0}: Network power losses without DGs.
P^{Cap}_{DG}: Capacity of DG unit (kW).
$P_{sub,i}$: Power flow from the grid through *i*th substation.
we: Weigh factor of the emission function.
wt: Weight factor of the technical function.
V_i: Magnitude voltage at *i*th node.
V_{max}, V_{min}: Maximum and minimum permitted voltage.
$SC^{1\Phi}_{i,1}$, $SC^{1\Phi}_{i,0}$: Single phase short circuit capacity with and without DGs.
$SC^{3\Phi}_{i,1}$, $SC^{3\Phi}_{i,0}$: Three-phase short circuit capacity with and without DGs.
P^{max}_k: Maximum power on *k*th feeder.
ER_{jk}: Emission rate of *k*th gas in *j*th technology (kg/kWh).
ng: Number of pollutant gases.
N_f: Number of objective functions.
N_p: Number of non-dominated solutions.
g_{max}: Maximum number of generations.
T_f: Maintenance duration of faulted branches (h).
T_p: Planning horizon (year).