A Multiobjective Particle Swarm Optimization for Sizing and Placement of DGs from DG Owner's and Distribution Company's Viewpoints

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***Abstract*—Distributed generations (DGs) have significant benefits in the electric power industry, such as a reduction in CO2 and NOX emissions in electricity generation, improvement of voltage profile in distribution feeders, amending voltage stability in heavy load levels, enhancement of reliability and power quality, as well as securing the power market. Despite the numerous advantages of DG technologies, weak capability in dispatching and management of DGs is a major challenge for distribution system operators. Hence, during recent years, several studies about various aspects of control, operation, placement, and sizing of DGs have been conducted. This paper presents a novel application of multiobjective particle swarm optimization with the aim of determining the optimal DGs places, sizes, and their generated power contract price. In the proposed multiobjective optimization, not only are the operational aspects, such as improving voltage profile and stability, power-loss reduction, and reliability enhancement taken into account, but also an economic analysis is performed based on the distribution company's and DG owner's viewpoints. The simulation study is performed on the IEEE 33-bus distribution test system and the consequent discussions prove the effectiveness of the proposed approach.**

***Index Terms*—DG placement and sizing, distributed generation, electric distribution system, multiobjective optimization method, multiobjective particle swarm optimization (MOPSO).**

NOMENCLATURE

b_{mn}, g_{mn}	Susceptance and conductance of the branch between the mth and the nth buses (Ω^{-1}).
$C_{\text{MWh},p}$	Cost of the active power bought from the substation based on the amount of its MW (U.S.$/MWh).
CF	Capacity factor of DG units.
Cost_{inv}	Investment cost of DGs (U.S.$/MW).
$\text{Cost}_{\text{maint}}$	Maintenance cost of DGs (U.S.$/MWh).
$\text{Cost}_{\text{oper}}$	Operational cost of DGs (U.S.$/MWh).
CP_{DG}	Contract price of selling DG power between the DG owner and the DisCo (U.S.$/MWh).
I	Current of each branch (in amperes).
$\text{INF\_}R$	Inflation rate.
$\text{INT\_}R$	Interest rate.
L_b	Length of branch b (in meters).
N_{BUS}	Total number of buses.
N_{DG}	Total number of DG units.
N_b	Total number of branches.
N_{NS}	Total number of not supplied loads for each fault.
N_Y	Total number of years in the planning horizon.
$P_{\text{DG}}, Q_{\text{DG}}$	Active and reactive power rating of DG units (in megawatts (MW) and MVAR).
P_n, Q_n	Injected active and reactive power in the nth bus (MW and MVAR).
$P_{L,n}$	Active power of the load connected to the nth bus (MW).
P_{Loss}	Active power losses of the network (MW).
P_{sub}	Active power supplied by the substation (MW)
r_b	Resistance of the bth branch (Ω).
T_d	Total number of days in a year.
T_h	Total number of hours in a year (in hours).
V_n	Voltage of the nth bus.
x_b	Reactance of the bth branch (Ω).
θ_{mn}	Impedance angle of the branch located between the mth and the nth buses.
λ_b	Fault rate in the bth branch (f/km.yr).

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TABLE I
REVIEW OF LITERATURE

Reference Number	Operational Constraints: Emission	Active power loss	Reactive power loss	Reliability of power supply	Voltage profile improvement	Voltage stability	Economic Constraints: DG's Total cost	DG owner's benefit	DisCo's benefit	Method Of Optimization
[4]		✓			✓	✓				Combined GA-PSO
[5]		✓			✓	✓				GSS
[6]		✓		✓	✓		✓		✓	Dynamic programming
[7]		✓			✓		✓	✓	✓	GA
[8]		✓		✓	✓		✓		✓	IPSO
[9]		✓	✓		✓					ANN
[10]		✓			✓					ABC
[11]		✓			✓		✓		✓	GA
[12]		✓		✓	✓		✓			Cost/worth analysis
[13]		✓			✓				✓	GA
[14]		✓	✓		✓					Power flow analysis
[15]		✓			✓					Power flow analysis
[16]		✓			✓					Fuzzy EP algorithm
[17]		✓			✓	✓	✓		✓	GA
[18]	✓				✓		✓			HBMO
[19]	✓				✓		✓			Immune-GA
[20]	✓	✓			✓		✓	✓	✓	immune-genetic
[21]	✓				✓		✓			Binary PSO

I. INTRODUCTION

UNDENIABLE advantages of renewable energies cause great enhancement of the penetration level of these new sources in power systems. Prominent among these include fuel savings, supplying remote places, the passion for cleaner energy sources, the economic opportunities presented for investors in the deregulated electric industry environments, and the potential benefits for utilities (congestion alleviation, reduction of losses, better asset utilization, etc.) [1].

Traditionally, utilities have served load demand by utilizing central generation, transmission, and distribution systems. However, in recent decades, utilities tend to deploy small-to-medium size distributed-generation (DG) units scattered across a power system. DGs can either be treated like other renewable sources of energy, such as combined heat and power units (CHP), photovoltaic cells (PV), small wind turbines, or like the traditional ones such as gas turbines [3]. Power-loss reduction, voltage profile improvement, reliability enhancement, power-quality (PQ) improvement, lower greenhouse gas emissions, and shorter construction schedules are mentioned in different papers as advantages of using DGs in power systems [1], [2].

However, with inappropriate design and planning of high penetration of DGs, power systems will face some problems, including: decreasing reliability, increasing power losses, reducing voltage stability, and other safety issues [4]. In order to maximize the benefits of using DGs in power systems, it is crucial to find the best location and size of DGs simultaneously to improve the voltage stability and reliability of the grid [5]. In addition, in the deregulated markets, the DG owner's and the DisCo's economic objectives should be considered. Generally, cost minimization and technical improvement of the network are the main goals of the DisCo while the DG owner's main aim is to maximize his or her revenue as much as possible by selling electricity to the distribution network.

A diversity of different objectives has been defined and considered in DG placement problems in papers. These objectives can be categorized into two major groups: 1) operational objectives and 2) economic objectives. Generally, the operational constraints consist of voltage stability improvement [6], [7], [19]; active loss reduction [5]–[18], [21]; reactive loss reduction [10], [15]; reliability of supply [7], [9], [13]; emission reduction [19]–[22]; and voltage profile improvement [5]–[22]. Costs and benefits associated with the deployment of the DGs in the network for the DisCo and/or the DG owner(s) are the main parts of the economic objective function. It should be mentioned that almost all literature has used the total cost of DGs (investment, operation, and maintenance costs) as their main parameter; however, a few of them [8], [21] have considered the DisCo satisfaction distinct from the DG owners who want to deploy DGs in the power network to gain profit by selling electricity. In these papers, the defined mechanism calculates the contract price of generated electricity between the DG owner(s) and the DisCo. Different literature and their assumptions are summarized in Table I.

This paper presents a novel multiobjective approach for calculating the DG optimum placement, sizing, and contract price simultaneously. It is assumed that the DG owner wants to install three dispatchable units and synchronous DG units in the network. The proposed method is based on economic and operational objectives from the DG owner's and the DisCo's points of view. The multiobjective particle swarm optimization (MOPSO) method has been used to solve this problem subject to appropriate operational constraints. The proposed method benefits over most of the earlier surveys are: a) dynamic daily load modeling with an annual increase rate for all buses; b) both the DisCo's and the DG owner's economic objective consideration; and c) taking various operational issues of the power grid into consideration, such as power loss, voltage profile, stability, and reliability of the system; and d) planning incentive strategies with the aim of encouraging the development of DGs in the power grid.

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The rest of this paper is organized as follows: Section II discusses the main objective functions and related constraints. In Section III, the MOPSO technique is explained briefly. In Section IV, the simulation is done on a specific test system and the results are clarified. Finally, the paper concludes in Section V.

II. Problem Definition

This section introduces the proposed approach for the DG planning problem. The optimization problem is based on maximizing the DG owner's profit and minimizing the DisCo's cost simultaneously. In addition to modeling cost and profit functions, multiobjective optimization methods must be applied to find the optimum value of the planning parameters which are the DG's size, location, and the electricity contract price between the DG owner and the DisCo.

Regarding the number of variables as well as their range of variation, solving this problem using mathematical or classical methods is neither efficient nor possible. Moreover, these methods have very low convergence speed. Hence, heuristic methods have a special preference for solving this problem. The heuristic algorithms can be classified into two main categories: 1) single objectives and 2) multiobjectives. Using the former one, one possible solution is summing all of the objective functions by appropriate coefficients. In the other words, the multiobjective problem is converted to a single objective one. This method is called the weighted sum method. But this technique is not appropriate for solving this problem too, because there is a strong interconnection between the DisCo's and the DG owner's economic equations in a way that optimizing one of the objective functions overweighs the other one and, in the final solution, one of the objective functions is optimized while the other one is not. Moreover, high sensitivity of economic equations to the variation in size, location, and contract price of DGs makes classical and single objective heuristic optimization methods inefficient. Therefore, heuristic multiobjective methods are better choices; they consider two distinct objective functions instead of one objective function, and they consider the domination of each one through another. Consequently, in this paper, the multiobjective version of PSO or MOPSO is chosen to solve the DG placement problem.

The following assumptions should be made before the formulation of the problem:

- There are no geographic or primary resource limitations to install various DG technologies within the distribution system.
- Connection between the DG unit and a bus is modeled as a negative PQ load in load-flow analysis [2], [21].
- The proposed DG placement model is presented from the perspectives of the DisCo and the DGs owners in an energy market environment.
- To exploit the advantages of using DG units for reducing the energy not served (ENS) index, the islanding operation of DG technologies is permitted [22].

In the following part, different functions related to the main problem are introduced.

A. DG Owner's Cost and Profit Functions

As an investor, the DG owner's main purpose is to gain profit as much as possible without serious considerations about power grid operational conditions. According to this fact, the following cost and profit functions can be defined for the DG owner as follows.

1) Investment Cost: This cost contains the different initial costs, such as the amount of money spent on unit construction, installation, and essential equipment. for each unit of generation. This cost can be formulated as the following equation:

$$C_{\text{investment}} = \sum_{i=1}^{N_{\text{DG}}} P_{\text{DG},i} \times \text{Cost}_{\text{inv}} \tag{1}$$

where i denotes the distributed generation index. That is, $P_{\text{DG},i}$ denotes the active power generated by the ith unit.

2) Operational Cost: Costs of fuel, generation, and other similar ones can be combined together as the operational cost. The equation for modeling the present worth of this cost is as follows:

$$C_{\text{operational}} = \sum_{j=1}^{N_N} \sum_{i=1}^{N_{\text{DG}}} P_{DG,i} \times \text{CF}_i \times T_h \times \text{Cost}_{\text{oper}} \times \left(\frac{1+\text{INF\_}R}{1+\text{INT\_}R}\right)^j \tag{2}$$

where j denotes the year index.

3) Maintenance Cost: This term includes costs of renewing, repairing, and restoring unit equipment in case of necessity. The present worth of this cost can be formulated as follows:

$$C_{\text{maintanance}} = \sum_{j=1}^{N_N} \sum_{i=1}^{N_{\text{DG}}} P_{\text{DG},i} \times \text{CF}_i \times T_h \times \text{Cost}_{\text{maint}} \times \left(\frac{1+\text{INF\_}R}{1+\text{INT\_}R}\right)^j . \tag{3}$$

4) DG Owner's Income: The DG owner gains profit from selling generated power to the DisCo based on the contract price. The present worth of the DG owner's income is

$$\text{IN}_{\text{DG}} = \sum_{j=1}^{N_{\text{Y}}} \sum_{i=1}^{N_{\text{DG}}} P_{\text{DG},i} \times \text{CF}_i \times T_h \times \text{CP}_{\text{DG}} \times \left(\frac{1+\text{INF\_}R}{1+\text{INT\_}R}\right)^j . \tag{4}$$

B. DisCo's Costs

The DisCo not only considers his or her own profit, but also takes into account the operational conditions of the power grid, such as voltage profile and stability, branch current limits, customer security, and reliability. Consequently, the DGs' locations, sizes, and the contract prices are the vital factors for the DisCo. The DisCo's costs are defined with the following functions:

1) Cost of Purchasing Power From the DG Owner: The DisCo buys all of the power generated by DGs from the DG

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owner based on the contract price. This DisCo's cost ($\mathrm{C_{DG}}$) has already been formulated as the DG owner's income in (4). In fact, the DisCo profits the DG owner by purchasing power from him or her. This is the so-called strong interconnection between the DisCo and the DG owner from economic standpoints.

2) Cost of Buying Power From the Substation: The power, which is beyond the DG units capacities, should be bought by the DisCo from the substation. This power is computed by the following equation:

$$P_{\mathrm{sub},t,j} = \sum_{n=1}^{N_{\mathrm{Bus}}} P_{L,n,t,j} + P_{\mathrm{Loss},t,j} - \sum_{i=1}^{N_{\mathrm{DG}}} P_{\mathrm{DG},i} \quad (5)$$

where

$$P_{\mathrm{Loss},t,j} = \sum_{b=1}^{N_b} r_b \times I_{b,t,j}{}^2. \quad (6)$$

In (5) and (6), n and b refer to the bus and branch indices, respectively. Furthermore, t is the time index referring to each hour of the day.

Buying power from the substation is another cost that the DisCo should spend. The present value of this cost is

$$C_{\mathrm{sub}} = \sum_{j=1}^{N_Y} \sum_{t=1}^{24} P_{\mathrm{sub},t,j} \times T_d C_{\mathrm{MWh},P} \times \left(\frac{1+\mathrm{INF\_}R}{1+\mathrm{INT\_}R}\right)^j. \quad (7)$$

It is obvious that the proper location and size of DGs can decrease power losses in the system and, consequently, it can impact the mentioned cost.

3) Customer Interruption Cost: Customer satisfaction and welfare in case of a failure in the power grid are imperative. Therefore, the cost associated with the interruptions and failures in supplying customers' loads is the DisCo's responsibility. On account of this fact, the customer interruption cost (CIC) in (8) is utilized to evaluate the present worth of this expense

$$\mathrm{CIC} = \sum_{j=1}^{N_Y} \sum_{b=1}^{N_b} C_{\mathrm{int}} \times \lambda_b \times L_b \times \sum_{k=1}^{N_{\mathrm{NS}}} P_{L,k,j} \times \left(\frac{1+\mathrm{INF\_}R}{1+\mathrm{INT\_}R}\right)^j \quad (8)$$

where k denotes the not-supplied loads index. According to (8), CIC is a term which calculates the interruption cost based on the amount of energy which is not supplied (ENS) for all customers. C_{int} is the price of interruption in supplying each load during repair time and depends on the type of loads (residential, commercial, or industrial).

C. Objective Functions and Constraints

In this section, the objective functions and their related constraints for solving this optimization problem are introduced.

1) Objective Functions: According to the above formulations for the DG owner's and the DisCo's costs and profits, the objective functions for finding the appropriate locations, sizes, and contract price, which simultaneously maximize the DG owner's profit and minimize the DisCo's cost, results in the following equations. In these equations, F_1 is the difference between the DG owner's profits and cost functions which are introduced in Sections II-A-1to A-4. Furthermore, F_2 is the summation of the DisCo's costs which are introduced in Sections II-B-1–B-3.

$$\begin{cases} F_1 = \max(\mathrm{IN_{DG}} - C_{\mathrm{inv}} - C_{\mathrm{main}} - C_{\mathrm{operate}}) \\ F_2 = \min(C_{\mathrm{sub}} + C_{\mathrm{DG}} + \mathrm{CIC}) \end{cases}. \quad (9)$$

2) Constraints and Limitations: This optimization problem is subjected to various constraints as follows.

a) Bus Voltages and Branch Currents Limits: In this optimization problem, DGs' locations and sizes should be determined in such a way that bus voltages and branch currents remain in standard intervals during the planning period. These limitations are defined as follows:

$$I_{b,t,j} \leq I_b^{\max} \quad (10)$$
$$V^{\min} \leq V_{n,t,j} \leq V^{\max} \quad (11)$$

where $V^{\min}$ and $V^{\max}$ are the minimum and maximum allowed amounts of voltage in each bus, respectively. $I_b^{\max}$ also denotes the maximum amount of current that can flow in each line according to the lines thermal limitations.

b) DG Capacity Limit: It should be assumed that the active and reactive capacity of each DG is limited to a specific interval as follows:

$$P_{\mathrm{DG},i}^{\min} \leq P_{\mathrm{DG},i} \leq P_{\mathrm{DG},i}^{\max} \quad (12)$$
$$Q_{\mathrm{DG},i}^{\min} \leq Q_{\mathrm{DG},i} \leq Q_{\mathrm{DG},i}^{\max}. \quad (13)$$

In these inequalities, $P_{\mathrm{DG},i}^{\min}$, $P_{\mathrm{DG},i}^{\max}$, $Q_{\mathrm{DG},i}^{\min}$ and $Q_{\mathrm{DG},i}^{\max}$ are the minimum and maximum amounts of active and reactive powers that can be generated by the ith DG unit.

c) Contract Price Limits: It is logical to say that the contract price between the DG owner and the DisCo is limited according to the electricity market conditions and this inequality can be formulated as follows:

$$\mathrm{CP_{DG}^{\min}} \leq \mathrm{CP_{DG}} \leq \mathrm{CP_{DG}^{\max}} \quad (14)$$

where $\mathrm{CP_{DG}^{\min}}$ and $\mathrm{CP_{DG}^{\max}}$ are the minimum and maximum amounts of the contract price that can be determined according to the market electricity price and other economic considerations.

d) Power-Flow Constraints: It is obligatory for active and reactive power injections to satisfy the power-flow equations

$$P_n = V_n \sum_{m \in N} V_m \left(g_{mn}\mathrm{Cos}(\theta_{mn}) + b_{mn}\sin(\theta_{mn})\right) \quad (15)$$
$$Q_n = V_n \sum_{m \in N} V_m \left(g_{mn}\mathrm{Sin}(\theta_{mn}) - b_{mn}\mathrm{Cos}(\theta_{mn})\right). \quad (16)$$

e) DG Owner Capitalization Constraint: The amount of capitalization that the DG owner can afford is limited and is described by the following inequality:

$$C_{\mathrm{investment}} \leq C_{\mathrm{investment}}^{\max} \quad (17)$$

where $C_{\mathrm{investment}}^{\max}$ denotes the maximum affordable amount of capitalization from the DG owner's point of view.

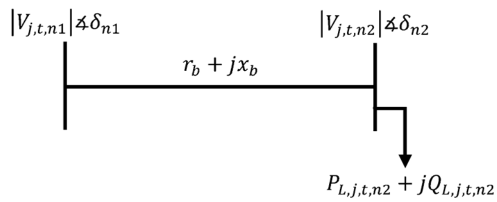

Fig. 1. Representative branch of a radial distribution system.

D. Operational and Economic Indices

In this section, in order to have a better evaluation of the operational condition of the power grid and the profitability of the contract between the DG owner and the DisCo from their own viewpoints, some operational and economic indices are introduced as follows.

1) Operational Indices: In order to judge the operational state of the grid, some indices are introduced in the following sections. For better evaluation, per-unit (p.u.) values of these indices are also calculated. The nominators and denominators of these p.u. indices are, respectively, the related values of the defined indices in the presence and absence of DGs in the grid.

a) Total Voltage Profile Index (TVPI): This index measures the variation of all bus voltages from V_{rated} (1 p.u.). Since the flatter voltage profile is more appropriate, the total voltage profile index (TVPI) is considered as follows [4]:

$$\text{TVPI} = \sum_{j=1}^{N_Y}\sum_{t=1}^{24}\sum_{n=1}^{N_{\text{Bus}}} |V_{\text{rated}} - V_{n,j,t}| \tag{18}$$

$$\text{TVPI}_{\text{p.u.}} = \frac{\text{TVPI}_{\textit{with}\ \text{DG}}}{\text{TVPI}_{\text{without DG}}}. \tag{19}$$

b) Total Voltage Stability Index (TVSI): In radial distribution networks where each receiving node is fed by only one sending node, this index can be a good measure for evaluating voltage stability. According to Fig. 1, for all buses from two to N, the stability index (SI) is calculated as follows [27]:

$$\text{VSI}_{j,t,n2} = |V_{j,t,n1}|^4 - 4\times(P_{L,j,t,n2}\times x_b - Q_{L,j,t,n2}\times r_b)^2 - 4 \times(P_{L,j,t,n2}\times r_b + Q_{L,j,t,n2}\times x_b)^2 \times |V_{j,t,n1}|^2. \tag{20}$$

The higher the VSI is for each bus, the better the stability of that relevant node shall be. The total voltage stability index (TVSI) and its per-unit value are defined as

$$\text{TVSI} = \sum_{j=1}^{N_Y}\sum_{t=1}^{24}\sum_{n=2}^{N} \text{VSI}_{j,t,n} \tag{21}$$

$$\text{TVSI}_{\text{p.u.}} = \frac{\text{TVSI}_{\textit{with}\ \text{DG}}}{\text{TVSI}_{\text{without DG}}}. \tag{22}$$

c) Total Power-Loss Index (TPLI): As the lower active power loss is more appropriate in case of power grid operation, therefore, the total power loss index (TPLI) and its per-unit value are defined as follows [4]:

$$\text{TPLI} = \sum_{j=1}^{N_Y}\sum_{t=1}^{24}\sum_{b=1}^{N_b} r_b \times {I_{j,t,b}}^2 \tag{23}$$

$$\text{TPLI}_{\text{p.u.}} = \frac{\text{TPLI}_{\text{with DG}}}{\text{TPLI}_{\text{without DG}}}. \tag{24}$$

d) Energy not Supplied Index (ENSI): The energy not supplied index (ENSI) provides comprehensive information about the amount of loads that will not be supplied in case of failure [26]. This index depends on the failure rate of branches and the amount of interrupted loads in the case of each branch failure. If this index becomes lower, the grid will have better conditions in case of accruing faults. Hence, the total ENSI and its per-unit value are stated as follows:

$$\text{ENSI} = \sum_{j=1}^{N_Y}\sum_{b=1}^{N_b} \Delta t_{\text{Fault}} \times \lambda_b \times L_b \times \sum_{k=1}^{N_{\text{NS}}} P_{L,k,j} \tag{25}$$

$$\text{ENSI}_{\text{p.u.}} = \frac{\text{ENSI}_{\text{with DG}}}{\text{ENSI}_{\text{without DG}}} \tag{26}$$

where Δt_{fault} is the average time that the corresponding load is out of service during the fault occurrence.

2) Economic Indices: In this section, in order to evaluate the economic condition of the contract between the DG owner and the DisCo from their viewpoints, three important economic indices are introduced as follows.

a) Payback Period (PP): In capital budgeting, the payback period refers to the length of time required to recover the cost of an investment. This factor determines whether to undertake the project or not. Given a list of different investments equal to each other, the one with the shorter payback period is the best according to the economic standpoint [28]. The following index is calculated by solving:

$$\text{Investment cost} - \sum_{i=1}^{\text{PP}} (\text{cash inflows in } i\text{th year}) = 0. \tag{27}$$

b) Expected Rate of Return (ERR): The expected rate of return is the return which an investor expects his or her investment to generate over a certain period. The expected rate of return on a single asset is equal to the sum of each possible rate of return multiplied by the respective probability of earning on each return. Since this term is dependent on the market risk of assets, it is variable according to different circumstances [28].

c) Internal Rate of Return (IRR): IRR is the rate of return at which the net present value (NPV) of a flow of payments/incomes is equal to zero. In other words, the rate of return that would make the present value of future cash flows plus the final market value of an investment be equal to the present market price. In order to judge whether an investment is worthwhile, this term is calculated. A greater value of this term compared to a return of an average similar investment opportunity guarantees the success of the mentioned investment. This index can be calculated as follows [28]:

$$\text{Investment cost} - \sum_{j=1}^{N_Y} (\text{cash inflows } in\ i\text{th year}) \times \left(\frac{1+\text{INF\_}R}{1+\text{IRR}}\right)^j = 0. \tag{28}$$

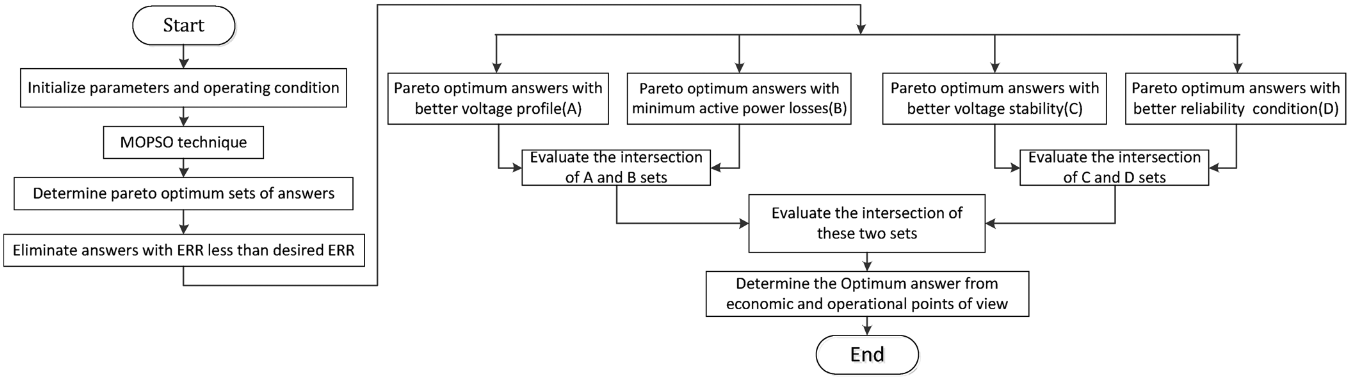

Fig. 2. Flowchart of the proposed method.

E. Selecting the Optimal Solution in Accordance with the DisCo's and the DG Owner's Viewpoints

As discussed earlier, this problem should be solved using multiobjective methods, such as the MOPSO technique. Therefore, the final result of this optimization method is a Pareto optimal set of nondominated solutions [23]. To extract the best compromise solution, various methods have been implemented in the literature, such as a fuzzy-based mechanism called a fuzzy decision-making method which presents a solution to the decision maker [25]. In this paper, a new technique based on economic and operational indices is presented that satisfies both sides of the contract standpoints.

To choose an optimal solution, including DGs' size, location, and the contract price, two important issues should be considered: First, in the optimal solution, the profit of the DisCo and the DG owner should be provided adequately (based on the DG owner's and DisCo's viewpoints). Second, the operational condition of the grid, based on the optimal solution, should be at acceptable levels (based on just the DisCo's viewpoints). It is worthy to note that the operational issues are not directly used in the proposed multiobjective algorithm. Hence, another way must be contrived to include the operational factors in our selection procedure.

According to the defined indices in Section II-D, it will be assumed that the ERR and PP are specified. These values are in accordance with the DG owner's agreement; therefore, the values of IRR which are more than the ERR and lower PPs will also be accepted by the DG owner. To motivate the DG owner, it is reasonable to eliminate the Pareto answers with lower values of IRR or higher values of PP indices from the Pareto set. In this case, the remaining points will be agreeable by the DG owner and could be selected from his or her viewpoints. After that, the DisCo's viewpoints should be taken into consideration in order to have better operational condition for the grid besides gaining more profit. In the next step, the introduced operational indices will be calculated for each remaining point. In order to have all of the indices in an appropriate condition, for each index, the first half of points having better conditions are selected. Among the intersection of obtained points for all indices, the point with the lowest DisCo's cost will be chosen ultimately. Consequently, the DG owner and the DisCo will be satisfied because the DG owner will receive adequate profit, and the DisCo's cost will decrease in comparison to the case without using DGs. Furthermore, the operational conditions of the grid will be improved significantly. The flowchart of the algorithm is depicted in Fig. 2.

III. Multiobjective PSO

The multiobjective (MO) format of PSO called MOPSO is suitable in case of minimizing multiple objective functions simultaneously. If $f(x)$ consists of n objective functions, then the multiobjective problem can be defined as finding the vector $x^* = [x_1^*, x_2^* \dots x_m^*]$ in order to minimize $f(x)$

$$\min f(x) = \langle f_1(x) f_2(x) \dots f_n(x) \rangle \text{ subject to } x^* \in \chi.$$

Generally, multiobjective optimization technique results in a set of optimal solutions, instead of one solution. The reason is that none of the solutions can be considered to be better than any other with regard to all objective functions. Consequently, in the MOPSO method, there is not generally one global optimum, but a set of so-called Pareto-optimal solutions [23]. A decision vector x_1 is called Pareto-optimal if there is no other decision vector x_2 that dominates it. In the minimization problem, the solution x_1 dominates x_2 if

$$1)\ \forall i \in \{1, 2, \dots, N_{\text{obj}}\} : f_i(x_1) \le f_i(x_2) \tag{29}$$

$$2)\ \exists i \in \{1, 2, \dots, N_{\text{obj}}\} : f_i(x_1) < f_j(x_2). \tag{30}$$

Like PSO, in the MOPSO algorithm, each particle at the time t is introduced by two borders, its velocity $V_i(t)$ and its position $X_{i(t)}$. According to following equations, each vector will be updated at time $t+1$ as below [24]

$$\begin{aligned} V_i(t+1) &= w(t)V_i(t) + c_1 r_1 \left(L_i(t) - X_i(t)\right) \\ &\quad + c_2 r_2 \left(G_i(t) - X_i(t)\right) \\ X_i(t+1) &= V_i(t) + X_i(t) \end{aligned} \tag{31}$$

where c_1 and c_2 are positive constant coefficients which show the importance of local best and global best, respectively, and r_1 and r_2 are random numbers. w(t) is inertia weight which helps the algorithm to find the Pareto optimal set more rapidly and is almost always constant. $L_i(t)$ and $G_i(t)$ are local best and global best which are selected as follows: At first, the nondominated local set (which contains a position of the nondominated solution) and nondominated global set (which contains a posi-

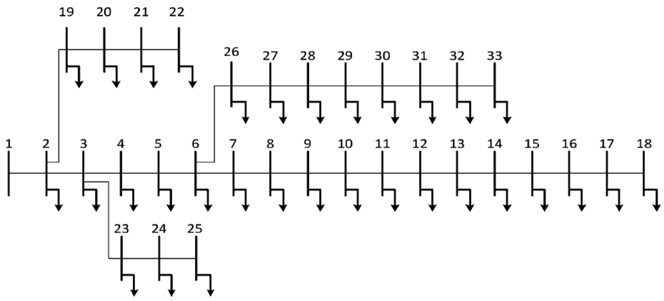

Fig. 3. IEEE 33-bus distribution test system.

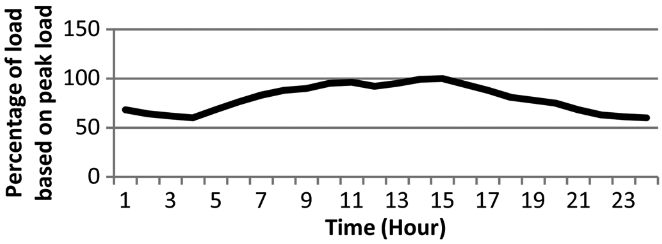

Fig. 4. The 24-h variation curve of each bus load based on the peak value.

tion of the nondominated solution between all members of nondominated local sets) is formed. Then individual distances between members in the nondominated local set of the particle i, and members in the nondominated global set are measured in the objective space. $L_i(t)$ and $G_i(t)$ are the members of these sets that give the minimum distance [24].

IV. Case Study, Results, and Discussion

A. Case Study

For demonstrating the efficiency of the proposed method, simulations have been performed on the 12.66-kV IEEE 33-bus distribution test system [15] which is shown in Fig. 3. It is assumed that the average load of each bus varies with a pattern similar to Fig. 4 in 24 hours of a day with an increasing rate of 2% per year. The load of each bus at the peak hour in the first year of the planning period is shown in Fig. 5. The price of the electricity supplied by the substation varies in favor of different amounts of power bought during the day. For simplification, it is assumed that there are three price levels for low, medium, and peak load levels during a day. The prices' data are given in Table II. Moreover, the contract price between the DG owner and the DisCo are considered to be between U.S.$35/MWh and U.S.$50/MWh. It is assumed that there are three DG units with active power generation within 0.2 and 1 MW with a 0.9 lagging power factor. The commercial information of the DGs is given in Table III [6].

Although the proposed method can be applied for any number of DG units and any amount of their capacity factors, for simplification in our simulation, it is assumed that DG owners want to install three DG units with the capacity factors of 1.

In this case study, for calculating reliability indices, it is assumed that the failing rate of transmission lines is 0.12 f/km, year and their repair time is 8 h. Other equipment of the grid is considered 100% reliable. Although customer interruption costs are different for residential, commercial, and industrial loads,

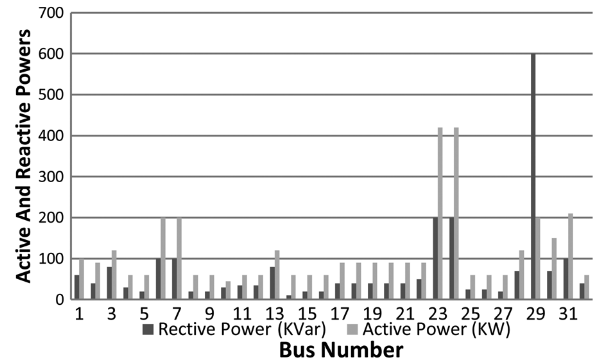

Fig. 5. Load of each bus in a peak hour of the first year.

TABLE II
Technical and Commercial Information

Level	Percentage of peak load	Network situation	Time duration (h/yer)	Market price $(\$/MWh)$
1	0-80	Light load	4380	35
2	80-95	Medium Load	3285	45
3	95-100	Peak load	1095	50

TABLE III
Commercial Information of DGs [8]

Parameter	Unit	Value
DG investment cost	$\$/MW$	318000
DG Operation cost	$\$/MWh$	29
DG maintenance cost	$\$/MWh$	7

TABLE IV
Values of the Used Parameters

Parameters	**Values**
Annual growth rate of loads	2%
λ_b(f/km.year)	0.12
CF	1
$\Delta t_{Fault}(hour)$	8
C_{int} ($/kw)	20
N_{DG}	3
N_Y	20
N_{BUS}	33
N_b	32
Max(CP_{DG}) ($/MWh)	50
Min(CP_{DG}) ($/MWh)	35
Max(P_{DG}) (MW)	1
Min(P_{DG}) (MW)	0.2
PF	0.9 lag
T_h	8760
T_d	365
INT_R (%)	12.5
INF_R (%)	9

for simplification, the average amount of U.S.$20/kW is considered for 8 h of failure for all loads [26]. In addition, it is assumed that the interest rate and the inflation rate are 12.5% and 9%, respectively [6]. The summaries of the parameters' values are given in Table IV.

B. Results and Discussion

The proposed multiobjective optimization has been solved using the MOPSO algorithm in Matlab to obtain the optimum

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TABLE V
ULTIMATE POINTS AND THEIR RELEVANT OPERATIONAL AND ECONOMIC INDICES FOR DIFFERENT AMOUNTS OF ERR

ERR(%)	**15**	**20**	**25**	**30**	**35**	**40**	**45**	**50**
PP(year)	4.11	4.55	4.55	4.55	3.6	3.21	2.9	2.62
DGs size(MW)	[1 1 0.9]	[0.9 0.9 1]	[0.9 0.9 1]	[0.9 0.9 1]	[1 1 0.9]	[1 1 0.9]	[1 1 1]	[1 1 1]
DGs Location	[7 33 15]	[6 32 14]	[6 32 14]	[6 32 14]	[6 32 13]	[7 31 13]	[6 29 12]	[6 29 11]
Contract Price($)	43.6619	43.9757	43.9757	43.9757	46.1017	47.2783	48.5000	49.8580
IRR(%)	31.45	32.45	32.45	32.45	39.1	42.7	46.4	50.55
TVPI(pu)	0.1455	0.1459	0.1459	0.1459	0.1319	0.1349	0.1387	0.1400
TPLI(pu)	0.1642	0.1568	0.1568	0.1568	0.1479	0.1465	0.1620	0.1635
TVSI(pu)	1.229	1.2209	1.2209	1.2209	1.2190	1.2247	1.2164	1.2140
ENSI(pu)	0.2193	0.2512	0.2512	0.2512	0.2494	0.2570	0.3292	0.3581
DG's Profit($)	1917933.67	1964104.28	1964104.28	1964104.28	2822282.18	23863421.4	24587341.5	4360018.97
DisCo's Cost($)	22473057.4	22590177.7	22590177.7	22590177.7	23413942.4	23584313.7	23839253.2	25166959.6
DisCo's revenue	10.60%	10.13%	10.13%	10.13%	6.85%	6.18%	5.16%	0%

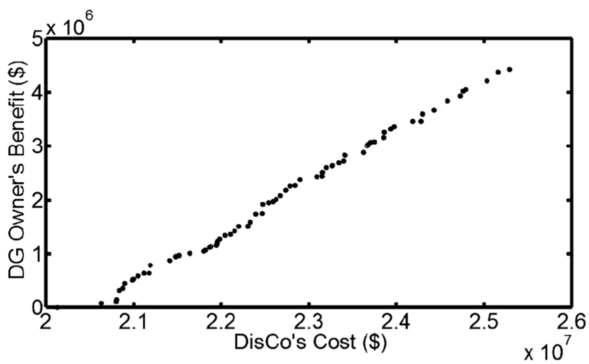

Fig. 6. Pareto optimal set of answers.

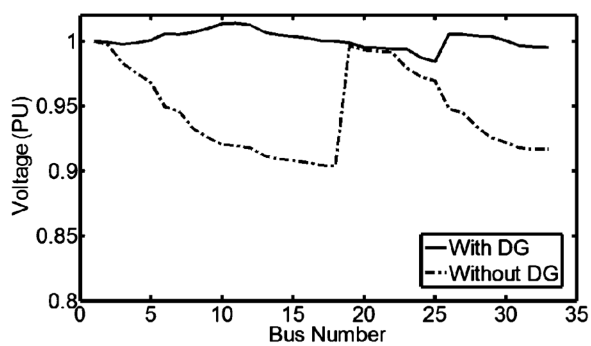

Fig. 7. Voltage profile in first year in light load.

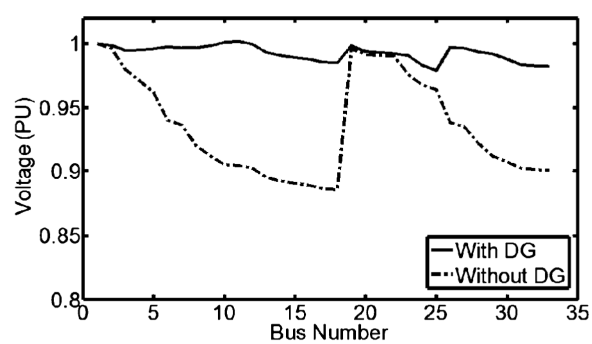

Fig. 8. Voltage profile in the 20th year at peak load.

solution that maximizes the DG owner's profit and minimizes the DisCo's cost. As mentioned before, these two objective functions are dependent of each other seriously in a way that the reduction of one of them results in decreasing the other one. Hence, there is more than one optimal point, and it is imperative to apply a proper methodology to choose the best solution. The Pareto optimal set attained from MOPSO is shown in Fig. 6.

In order to find the optimum solution, different values of the ERR are considered and the optimum solution for each respective ERR is calculated according to the flowchart described in Section II. The data associated with each solution are given in Table V. In this table, for each ERR, the value of operational indices, economic indices, the DG owner's profit, and the DisCo's cost and revenue are brought. Furthermore, the size of DGs, their optimal locations (buses' number where DGs should be constructed), and the amount of the contract prices are shown. Since the interest rate is supposed to be 12.5%, clearly the ERR should be higher than this value to be rational. Besides, the maximum ERR that can be achieved for all points in the Pareto set is 50%.

As can be seen from Table V, the IRR index is always higher than its corresponding ERR. This fact illustrates the incentive policy which is used in the proposed method in order to motivate the investors to spend more money in DG projects. Moreover, according to the data in this table, there is not a certain relation between the optimal solution and the ERR, for example, the simulation results reveal that for ERR within 20% and 32.45% ($\mathrm{ERR} = 20\%$, 25%, 30%, in Table V) only one solution is valid; however, for other values of ERR, more than one solution is obtained. The reason is that none of the points with the IRR amounting between 20% and 32.45% have a proper operational condition in comparison with other points. Therefore, for the case of ERR within 20% to 32.45%, there is only one point with acceptable operational and economic conditions, and this point will be the only solution until the ERR is less than 32.45%. After this ERR, the optimum solution is changed, and a different optimum point with more appropriate operational and economic conditions is obtained. In Table V, the amount of indices demonstrates that not only are the economic viewpoints of the two sides of the contract satisfied, but also the operational conditions of the power grid have improved considerably.

As seen in Table V, after using DG units, the amount of the TVPI, TPLI, and ENSI indices has been decreased by about 80% in comparison with the case without deploying DGs, and the voltage stability of the grid (the TVSI index) has been increased by about 20%. As an example, the voltage profiles for the first year in light load and for the twentieth year in peak load conditions with an ERR of 25% are shown in Figs. 7 and 8, respectively. In Fig. 7, after installing DG units, bus voltages vary from 0.99 to 1.04 p.u., and it was in the range of 0.92 to 1 before installing DGs. In addition, in Fig. 8, the bus voltage variations were within 0.85 to 1, and reduce to the range of 0.96 to 1 after installing DG units.

On account of the aforementioned facts, by using the proposed method not only does the DG owner receive desired profits, but he is also motivated due to the mentioned incentive policy of the proposed strategy. Furthermore, the DisCo's cost decreases compared to the case without using DGs, and the operational conditions of the grid improve considerably.

V. Conclusion

In this paper, the MOPSO algorithm has been used to find the optimal solution of DGs sizing and locating problems, in addition to determining their optimal-generated electricity prices in a competitive market. The goal of this optimization was minimizing the DisCo's cost and maximizing the DG owner's benefit simultaneously. Moreover, a novel approach is proposed to obtain the best solution considering power-loss reduction, voltage profile and stability enhancement, and reliability improvement in the grid. The proposed algorithm results show that in addition to gaining sufficient profit and payback period for the DG owner, the electric utility's cost decreases significantly compared with case of not deploying DGs. Furthermore, simulation results verified the potential of the proposed method in improving operational conditions of the power grid. Finally, it is shown that the introduced approach can be used as a proper incentive energy policy by system operators or utilities to encourage DG investors.

Although the positive effects of DGs in distribution networks' side effects were investigated in this paper, there are some negative impacts on protection, security, system stability, etc. In future works, these negative impacts, as well as implementing renewable DGs with uncertain output power, such as PV panels or wind turbines, will be considered in the modeling and formulations. Moreover, the DG allocation problem in mesh networks can be interesting and serves as a new topic for future studies in this field.

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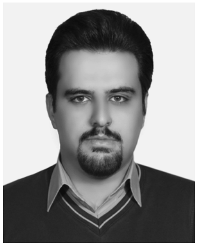

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