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Power system distribution planning considering reliability and DG owner's profit

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A novel comprehensive approach to solve a distribution systems' planning problem and to determine the optimal size, location, and technology of the distributed generation (DG) units with respect to the reliability of the system is presented in this paper. The objective functions of this optimization problem are power losses, DGs installation and operation costs, the DG owner's and the Distribution Company's profits as economic objectives. In the proposed method, new indices are defined to evaluate the reliability of the system. These indices calculate energy not supplied and volt ampere reactive not supplied due to active and reactive power shortages. Also, the average interruption frequency (AIF) and average interruption duration (AID) have been considered be minimized during optimization problem. The last two (AIF and AID) are modeled by the adequacy transition rate of DGs among states and are combined as a new objective function. To handle several objective functions, an adaptive fuzzy interactive multi-objective optimization method is used. The results on the IEEE 34-bus and 69-bus power distribution system showed the efficiency of proposed indices for reliability assessment of distribution system planning. *Published by AIP Publishing.* https://doi.org/10.1063/1.5001977

NOMENCLATURE

$B_{i,j}$	Susceptance between bus i and j
C_{DG}	Fixed and variable cost for DG
C_{FC}	Total cost of fuel cell
C_L	Power losses
C_1, C_2	Acceleration (learning) factors
C_{PV}	Total cost of photovoltaic
C_{WT}	Total cost of wind turbine
CP_{DG}	Contract price of selling DG power between the DG owner and the DisCo ($/MWh)
CP_{sub}	Contract price of selling substation power between the substation and the DisCo ($/MWh)
CPDisCo	Contract price of selling DicCo power between the customers and the DisCo ($/MWh)
d	Number of down states
$f(\bar{X})$	The optimal solution
$G_{i,j}$	Conductance between bus i and j
Gr	Annual rates of benefit

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I_l	Current of the l-th feeder
IEAR	Interrupted energy assessment rate of load type ($/kWh)
k	Shape parameter
$LC_{p(i)}$	Real load curtailments due to real power shortage
$LC_{Q(i)}$	Real load curtailments due to reactive power shortage
LF	Loading factor
Loc	Positions of each DG
nb	Number of buses
nc	Number of contingencies
nTyp	Number of considered digits for each DG
n_FC	Number of FCs
n_PV	Number of PVs
n_WT	Number of WTs
P_{DG}	Total active power of DG (MW)
$P_{FC,i}$	Active power production of the *i*th fuel cell power source (kW)
P_{Load}	Total active power consumption in each bus (MW)
P_n	Power output of each DG
$P_{(p),i}/Q_{(p),i}$	Peak active and reactive load for load point i
$P_{r,pv}$	Rated power of photovoltaic
P_{wt}	Output power of wind turbine
$P_{wt,rated}$	Rated output power of wind turbine
PFC	Active power of FC
PPV	Active power of PV
PWT	Active power of WT
PLR_i	Part load ratio of the *i*th FC
Q_{DG}	Total reactive power of DG (MVAR)
Q_{FC}	Reactive power of FC
Q_{Load}	Total reactive power consumption in each bus (MVAR)
$QC_{p(i)}$	Reactive load curtailments due to real power shortage
$QC_{Q(i)}$	Reactive load curtailments due to reactive power shortage
R	Solar irradiance
R_C	Certain radiation point and usually set to 150 W/m2
R_l	Resistance of the l-th feeder
r_1, r_2	Random numbers $\in [0, 1]$
R_{STD}	Solar radiation in the standard conditions usually set to 1000 W/m2
S_l	Power transferred from the l-th feeder (MVA)
S_i^{DG}	DG power output in the i-th load point (MVA)
$S_i^{DG,MAX}$	DG capacity limit in the i-th load point (MVA)
S_i^{Tr}	Total power from main grid to the i-th substation (MVA)
$S_i^{Tr,MAX}$	Maximum substation capacity limit for i-th substation (MVA)
S_l^{MAX}	Thermal capacity limit of the l-th feeder (MVA)
t	Time index referring to each hour of the day
Typ	Type of each DG
V	Particle velocity vector
V_{ci}	Cut-in speed
V_{co}	Cutoff speed
V_i	Voltage of i-th bus
V_{rated}	Rated speed
V_i^{MAX}	Maximum acceptable voltage of the i-th node (p.u.)
V_i^{MIN}	Minimum acceptable voltage of the i-th node (p.u.)
VAr	Volt Ampere reactive
w	Inertia weight factor $\in [0.4, 0.9]$

w_h	Hourly weight factor
w_m	Monthly weight factor
X	Particle position vector
X_{gbest}	Global best position
X_{pbest}	Personal best position
Y	Total number of the years in the planning horizon
α	Demand growth rate
η_i	Electrical efficiency of the ith FC
θ	Set of non-dominates solutions
$\theta_{i,j}$	Phase angle between bus i and j
λ	Failure rate
λ_i	Failure rate of load point i
λ_s	Scale parameter
μ	Repair rate
μ_{fi}	i-th membership function
μ_{ri}	i-th reference membership value
σ	Transition rate

I. INTRODUCTION

Due to the importance of the power distribution systems as a final connection between the utility and customers, flexible and intelligent planning methodologies to determine the best size, location, and type of generations to meet the future demand are required.[1] Some technical and economic aims, for example, cost reduction, reliability, voltage profile improvement, active loss reduction,. are objective functions for planners to solve the issue.[2,3] Due to the emerging distributed generation (DG) in power systems, the appropriate size and site of DGs can optimize various objectives and satisfy technical constraints.[4]

In conventional distribution system planning (DSP) problems, the planners have decision variables, such as where, when, and what type of lines and/or substations should be added to the system to reach the optimal plan.[5] The solution techniques to solve this problem could be divided into two categories: heuristics[6,7] and classic methods[8,9] But various emerging DG technologies and their effects on the distribution system performance have also received much attention in the literature.[10] In addition, solving the DSP problem, including DGs, has two techniques: heuristics[11] and classic methods.[12] To have accurate modeling, some papers have solved the DSP problem with DGs as a dynamic and probabilistic problem, which considers the uncertainty of resources.[13,14]

Because the customers are directly affected by any fault in the distribution system, it seems that more attention should be paid to the reliability of power distribution systems.[15,16] The influence of DG on the reliability aspect in DSP was investigated in Ref. 17. A method for solving DSP in the presence of DGs with respect to investment cost and loss reduction was developed in Refs. 18 and 19. Considering DGs on the reliability evaluation of the distribution system has been studied extensively in the literature[20–26] but the frequency and duration of system interruptions[27] could also be considered as reliability metrics, which are addressed in this study.

In addition to reliability as a technical objective, economic objectives focus on the costs and profits of the DG owner (DGO) and/or the Distribution Company (DisCo) as an important issue in the deregulation of a power system. In this regard, there are some surveys that considered the objectives from the viewpoint of the DGO.[28] In Refs. 29 and 30, the DisCo's satisfaction distinct from the DGO's, who want to deploy DGs in the power network to gain profit by selling electricity, have been considered.

This paper proposes a new planning approach that evaluates the reliability of a power distribution system that uses energy not supplied (ENS) and volt-ampere reactive (VAr) not supplied (VNS) due to active and reactive power shortages and the DG adequacy analysis as well as economic objectives. Minimizing the DisCo's and DGO's cost and maximizing their profit are two different viewpoints in DG planning that may not give the same result. Therefore, profit objectives as well as cost-based objectives have been considered in this study. To evaluate the reliability of a system, the frequency and duration of interruption as important issues have been addressed by minimizing the average interruption frequency (AIF) and average interruption duration (AID) by using the Markov model. Also, to evaluate the impact of reactive power on the reliability of a system, VAr not supplied is offered as well as ENS. The proposed approach solves the problem by a multi-objective adaptive particle swarm optimization (PSO) algorithm based on the fuzzy interactive method.

The paper is organized as follows: problem formulation and system modeling are explained in Sec. II. The optimization method and solution algorithm are presented in Sec. III. The implementation of the proposed method and results are provided in Sec. IV. Finally, the conclusion is drawn in Sec. V.

II. PROBLEM STATEMENT, MODELING, AND FORMULATION

A. System modeling

1. Load modeling

The time varying loads, which take place at the same time annually, are determined by historical loading data; therefore, monthly and hourly weight factor data are used to construct a load model. The active and reactive powers of the load connected to the i_{th} bus in the h_{th} hour of the day in the y_{th} year are[30]

$$P_{i,h,y} = P_{(p),i} \times w_h \times w_m \times (1+\alpha)^y, \tag{1}$$

$$Q_{i,h,y} = Q_{(p),i} \times w_h \times w_m \times (1+\alpha)^y. \tag{2}$$

2. DG modeling

In this survey, wind, solar, and fuel cells (FC) are considered as DG units. Because the primary energy source for the renewable DGs, such as a wind turbine (WT) and photovoltaic (PV), is intermittent, their power outputs are time varying. The output power of a WT depends on the wind speed, which varies with time. The Weibull probability distribution function (PDF) is used to represent the wind speed for long-term planning.[31]

$$f(v) = \frac{k}{\lambda_s}\left(\frac{v}{\lambda_s}\right)^{k-1} e^{-\left(\frac{v}{\lambda_s}\right)^k} \quad (k>0, v>0, \lambda_s>0). \tag{3}$$

The active power generated by a WT can be calculated based on

$$P_{WT} = \begin{cases} 0 & 0 \le v \le v_{ci} \\ P_{WT,rated}\dfrac{v - v_{ci}}{v_{rated} - v_{ci}} & v_{ci} \le v \le v_{rated} \\ P_{WT,rated} & v_{rated} \le v \le v_{co} \\ 0 & v_{co} < v. \end{cases} \tag{4}$$

For the PV generation system, the output power depends on the solar irradiance and has a high degree of uncertainty. The beta PDF is mostly used to model the probability of solar irradiance, which is expressed by Eq. (5), and its output power can be calculated by Eq. (6).[31]

$$f(R) = \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)} R^{\alpha-1}(1-R)^{\beta}, \tag{5}$$

$$P_{PV}(R) = \begin{cases} P_{r,PV}\dfrac{R^2}{R_{STD}R_c} & 0 \le R \le R_c \\ P_{r,PV}\dfrac{R}{R_{STD}} & R_c \le R \le R_{STD} \\ P_{r,PV} & R_{STD} \le R_c. \end{cases} \tag{6}$$

A fuel cell (FC) is considered as a dispatchable power resource. The output power for a FC is predictable. Thus, the output power model for this DG is simple and depends on the operation hours. In this study, the FC injects reactive power as well as active power.

B. Reliability evaluation by using the Markov analysis method

Most real-world devices have constant failure rates, so they can be represented and analyzed by the Markov model. In power systems, components have a constant failure rate with exponential distribution; therefore, the behavior of the system does not change with time and could be studied by the Markov model. The Markov model studies the frequency and duration of the outages by using the system components. To explain the importance of the frequency and duration of the outages, for example, if we consider two single component systems, one with reliability indices λ and μ and the other with indices 2λ and 2μ, then the availability for both systems is the same. But the second system fails twice and also is repaired twice as fast. This situation can have a major effect on the operation of the system and its economics. Therefore, it can be vital to evaluate the frequency and duration of encountering the various states of the system.

To evaluate the reliability of a distribution system, including the DG, these power sources need to be modeled. The DG system model consists of the adequacy of the DG output power to supply the demand.

In many applications, the components are represented as a two-state Markov model: up and down. This model is suitable for both the conventional and the renewable DG units. For example, the state transition diagram (STD) is shown in Fig. 1 for a distribution system model, which includes the main grid and one DG.

To find the steady-state probability, the state transition matrix (STM) of the system is formed by the STD. The square matrix (Q) is formed from the STM. The long run (or steady state) probabilities can be found by setting all time derivatives of the probabilities to equal zero and by solving the set of Markov equations (Kolmogorov equations). Because the matrix Q is singular, an additional equation is used, i.e., the sum of all probabilities must be equal to one.[32] The general format for the Markov equations is

$$\begin{bmatrix} -\sum_{j=2}^{n}\sigma_{1j} & \sigma_{21} & .. & \sigma_{n1} \\ \sigma_{12} & -\sum_{\substack{j=1 \\ j\neq 2}}^{n}\sigma_{2j} & .. & \sigma_{n2} \\ .. & .. & .. & .. \\ \sigma_{1n} & \sigma_{2n} & .. & -\sum_{j=1}^{n-1}\sigma_{nj} \end{bmatrix} \begin{bmatrix} P_1(t) \\ P_2(t) \\ .. \\ P_n(t) \end{bmatrix} = \begin{bmatrix} P'_1(t) \\ P'_2(t) \\ .. \\ P'_n(t) \end{bmatrix} .. \tag{7}$$

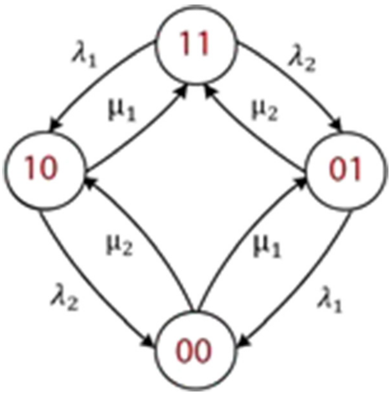

FIG. 1. State transition diagram (STD).

Besides finding the steady-state probabilities of the system, it is also useful to find the frequency of occurrence of the down states. The expected frequency of any state is the probability of that state multiplied by the rates of departure from that same state. The expected frequency and the system failure frequency can be written as

$$f_i = P_i * \sum_{j=2}^{n} \sigma_{ij}, \tag{8}$$

$$f_{system} = \sum_{i=1}^{d} f_i. \tag{9}$$

The AIF for a component over one year is defined as a number of failures over one year and the AID is the duration in hours for all interruptions in one year

$$\mathrm{AIF} = 8760\,\mathrm{f}_{\mathrm{system}}, \tag{10}$$

$$\mathrm{AID} = 8760\,\mathrm{q}, \tag{11}$$

where $\mathrm{f}_{\mathrm{system}}$ is the system failure frequency and q is the probability of failure. If the load could not be met, then the system status would be down, so the AIF and AID are calculated based on the mentioned formulas.[33]

C. Objective functions

The proposed DSP optimization problem is based on maximizing the DisCo's and DGO's profits, and on minimizing reliability and power losses.

Because both active and reactive powers are affected by the failure rate of lines, the energy not supplied due to the real/reactive power shortages ($\mathrm{ENS_p/ENS_Q}$) and the VAr not supplied due to the real/reactive power shortages ($\mathrm{VNS_p/VNS_Q}$) are also defined as customer indices.[34] The procedure to calculate these indices is presented in Fig. 2.

$$ENS_P = \sum_{i=1}^{nc} LC_{P(i)}.\lambda_i, \tag{12}$$

$$ENS_Q = \sum_{i=1}^{nc} LC_{Q(i)}.\lambda_i, \tag{13}$$

$$VNS_P = \sum_{i=1}^{nc} QC_{P(i)}.\lambda_i, \tag{14}$$

$$VNS_Q = \sum_{i=1}^{nc} QC_{Q(i)}.\lambda_i. \tag{15}$$

The value-based technique based on the cost concept is used for evaluating the reliability of the proposed method. Therefore, the equation for calculating expected customer outage cost (ECOST) is considered as follows:[35]

$$ECOST = \sum_{i=1}^{nl} IEAR_i.ENS_i. \tag{16}$$

By combining the four mentioned indices, one metric that shows the total expected customer outage cost is obtained

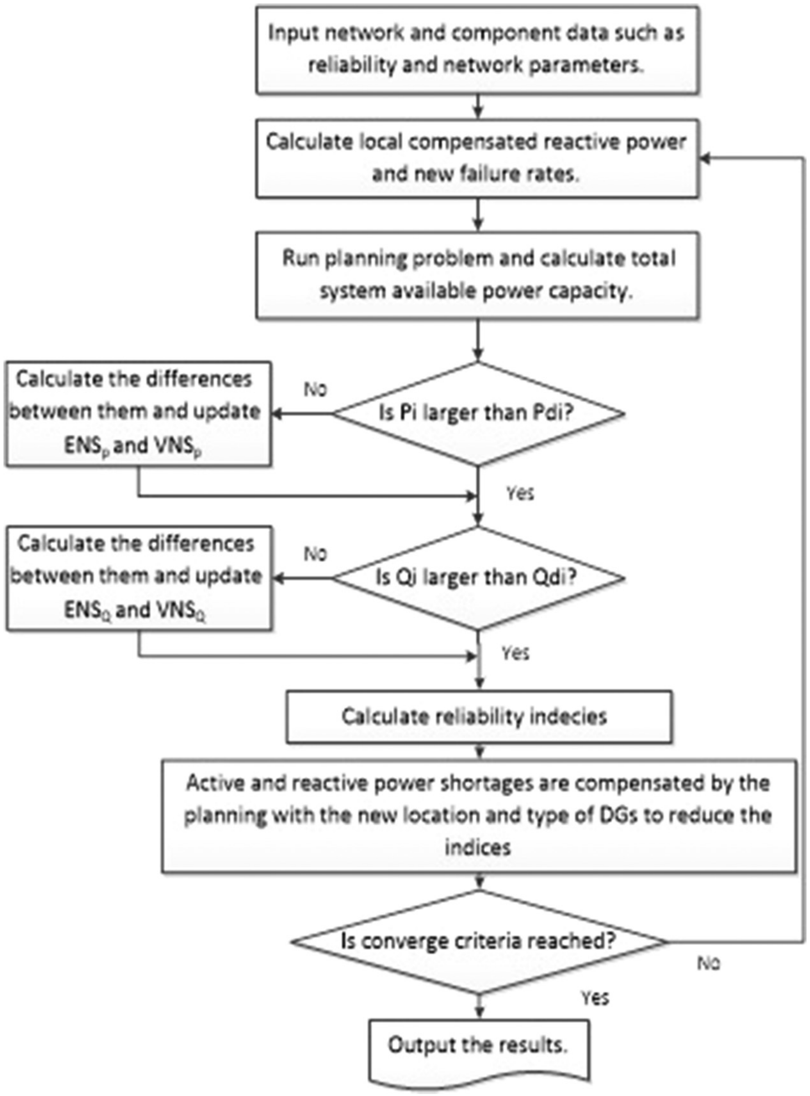

FIG. 2. Procedure of reliability evaluation.

$$ECOST = \sum_{i=1}^{nl} IEAR_{pi} \times ENS_{pi} + \sum_{i=1}^{nl} IEAR_{pi} \times ENS_{Qi} + \sum_{i=1}^{nl} IEAR_{qi} \times VNS_{pi} + \sum_{i=1}^{nl} IEAR_{qi} \times VNS_{Qi}. \tag{17}$$

Finally, the AIF, AID, and ECOST are properly normalized to combine the effect of each other under a uniform formulation

$$Reliability\_Index(RI) = \frac{AIF}{AIF_{\max}} + \frac{AID}{AID_{\max}} + \frac{ECOST}{ECOST_{\max}}. \tag{18}$$

The other main objective in this paper was regarding the DisCo's and the DGO's profits. Therefore, these two objectives are calculated at the same time and must be maximized. It should be noted that power losses are considered as costs in the cost function. The objectives are as follows:

$$Total\_profit = (Sell_{DGO} - C_{DG}) + (Sell_{DisCo} - C_{DisCo}). \tag{19}$$

Sell$_{\mathbf{DGO}}$: Selling the generated power to the DisCo, based on the contract price as the DG owner's income. This profit is formulated as follows:

$$Sell_{DGO} = \sum_{y=1}^{Y}\sum_{m=1}^{12}\sum_{t=1}^{24}\sum_{n=1}^{NDG} P_{n,t} \times 8760 \times CP_{DG} \times \left(\frac{1}{1+RIR}\right)^{y}. \tag{20}$$

The number 8760 refers to the total number of the hours in a year. CP$_{DG}$ is the contract price of selling DG power between the DG owner and the DisCo (\$/MWh). RIR is the real interest rate, which can be calculated by the Eq. (22).[30]

$$1 + RIR = \frac{1 + \text{interest rate}}{1 + \text{inflation rate}}. \tag{21}$$

C$_{\mathbf{DG}}$: Consists of operating expenses such as fuel and generation costs as well as the maintenance cost, which includes mechanical and electrical costs. The equation for modeling these expenses is expressed individually for each DG

$$C_{DG} = C_{FC} + C_{WT} + C_{PV}. \tag{22}$$

Fuel cell cost[36]

$$C_{FC,i} = 0.04^{\$\text{kWh}^{-1}} \times \frac{P_{FC,i}}{\eta_i}, \tag{23}$$

$$PLR_i = \frac{P_{g,i}}{P_{\max,i}},$$
$$\begin{cases} if \quad PLR_i < 0.05 \Rightarrow \eta_i = 0.2716 \\ if \quad PLR_i \geq 0.05 \Rightarrow \eta_i = 0.2716PLR_i^5 - \\ 2.9996PLR_i^4 + 3.6503PLR_i^3 - 2.0704PLR_i^2 \\ +0.3747. \end{cases} \tag{24}$$

Wind turbine and photovoltaic costs[37]

$$C_{PV,i} = a + b \times P_{PV,i}, \tag{25}$$

$$C_{WT,i} = a + b \times P_{WT,i}, \tag{26}$$

$$a = \frac{Capital\cos t(\$kW^{-1}) * Capacity(kW) * Gr}{Lifetime(Year) * 365 * 24 * LF},$$

$$b = Fuel\cos t(\$kW^{-1}) + O\&M\cos t(\$kW^{-1}).$$

Sell$_{\mathbf{DisCO}}$: Selling the generated power to the customers based on the contract price. This profit is formulated as follows:

$$Sell_{DisCO} = \sum_{y=1}^{Y}\sum_{m=1}^{12}\sum_{t=1}^{24} P_{sell,t} \times 8760 \times CP_{DisCo} \times \left(\frac{1}{1+RIR}\right)^{y}. \tag{27}$$

CPDisCo is the contract price of selling DisCo power between the customers and the DisCo (\$/MWh).

C$_{\mathbf{DisCo}}$: The DisCo purchases all of the power from the DG owner based on the contract price. This DisCo's cost has already been formulated as the DG owner's income. Another DisCo's cost is the cost of buying power from the substation. This cost is obtained by the following equation:

$$P_{sub,t} = \sum_{n=1}^{Nbus} P_{sub,n,t} + P_{loss,t} + \sum_{i=1}^{NDG} P_{DG,i}, \tag{28}$$

$$P_{Loss,t} = \sum_{l=1}^{L} R_l \cdot |I_l|^2, \tag{29}$$

$$C_{DisCO} = \sum_{y=1}^{Y} \sum_{m=1}^{12} \sum_{t=1}^{24} P_{sub,t} \times 8760 \times CP_{sub} \times \left(\frac{1}{1+RIR}\right)^y, \tag{30}$$

where $\mathrm{CP}_{\mathrm{sub}}$ is the contract price of selling substation power between the substation and the DisCo ($/MWh).

D. Problem constraints

The constraints of the planning problem are formulated as follows.[38]

1. Power-flow equations

This constraint is met by load flow calculation

$$\sum P_{DG} - \sum P_{Load} = V_{t,i} \sum_{j=1}^{nb} V_{t,j}(G_{i,j} * \cos\theta_{ij} + B_{i,j} * \sin\theta_{ij}), \tag{31}$$

$$\sum Q_{DG} - \sum Q_{Load} = V_{t,i} \sum_{j=1}^{nb} V_{t,j}(G_{i,j} * \cos\theta_{ij} - B_{i,j} * \sin\theta_{ij}). \tag{32}$$

2. Distribution feeder limit

This limit takes into consideration the capacity of the feeder

$$S_l \le S_l^{MAX} \quad l = 1, 2, 3, \ldots, L. \tag{33}$$

3. Substation and DG capacity limits

The power delivered by the substation and the DG unit must be less than their capacity

$$S_i^{Tr} \le S_i^{Tr,MAX} \quad \forall i \in N, \tag{34}$$

$$S_i^{DG} \le S_i^{DG,MAX} \quad \forall i \in M. \tag{35}$$

4. Voltage limits

Voltage value at each node should remain within acceptable limits

$$V_i^{MIN} \le V_i \le V_i^{MAX} \quad i = 1, 2, 3, \ldots, nb. \tag{36}$$

5. Maximum DG penetration

The total DG capacity is considered to be less than 40% of the total load

III. OPTIMIZATION METHOD AND SOLUTION ALGORITHM

A. Adaptive particle swarm optimization

In the original PSO algorithm, each particle is updated by a velocity vector. The velocity vector can be affected by three parameters: its own previous best value (pbest), the best position of all particles (gbest), and the inertia weight factor. The inertia weight factor is used to control the impact of the previous value of velocities on the current velocity. The velocity and position vector are updated as follows:[39]

$$v_j^{(t+1)} = wv_j^{(t)} + c_1 r_1 (pbest_j - x_j^{(t)}) + c_2 r_2 (gbest_j - x_j^{(t)}), \tag{37}$$

$$x_j^{(t+1)} = x_j^{(t)} + v_j^{(t+1)}. \tag{38}$$

The position vector is updated until a convergence criterion is satisfied. In this study, type, location, and size of DGs as well as fixed capacitor are decision variables (x) in the algorithm.

$$\begin{aligned} x = [&P_{FC1}, P_{FC2}, \ldots P_{FC\_nFC}, P_{PV1}, P_{PV2}, \ldots P_{PV\_nPV}, P_{WT1}, P_{WT2}, \ldots P_{FC\_nWT}, \\ &Q_{FC1}, Q_{FC2}, \ldots Q_{FC\_nFC}, Q_{Cap1}, Q_{Cap2}, \ldots Q_{Cap\_nCap}, Loc_1, Loc_2, \ldots, Loc_{nb}, \\ &Typ_1, Typ_2, \ldots, Typ_{nTyp}]_{n*Y}, \end{aligned} \tag{39}$$

where n is the summation of the decision variables and y is the number of years.

Also, c1, c2, and w are learning coefficients and weight factor; these parameters are usually equal to 2, 2, 0.4–0.9, respectively. The position vector is updated until a convergence criterion is satisfied.

The disadvantages of PSO algorithm are that it is easy to fall into local optimum. To solve this issue and improve the convergence property of the PSO algorithm, this paper presents two modifications to adjust the constant parameter of the original PSO.

1. Adjusting the learning coefficients

The parameters c1 and c2 in conventional PSO are considered as constant values. In this paper, these coefficients are computed adaptively during the optimization procedure as follows:[40]

$$c_{1,2} = 1 + \left[1 + \exp\left(-\frac{gbest}{g0}\right)^n\right]^{-1}, \tag{40}$$

where n = 2 and $g0$ is the $gbest$ in the first iteration.

2. Fuzzy formulation for adjusting w

The weight factor creates the balance between global and local searches of the PSO algorithm based on the effect of the past velocity. A large value increases the global search performance, and a small value improves the local search. This parameter is often held constant or linearly changed for the entire run of the PSO, but this method cannot guarantee achieving the global optimum instead of the local optimum in many cases. The best choice could be computed based on changes in gbest, and, in this regard, the fuzzy logic method is used. The inputs of the fuzzy method are the normalized function value (NFV) and *w,* while

$$NFV = \frac{FV - FV_{\min}}{FV_{\max} - FV_{\min}}, \tag{41}$$

where FV is a current best evaluation and the calculated value of FV from this equation at the first iteration may be used as FV_{min} for the next iterations. FV_{max} is a very large value, which is greater than any feasible solution.

To apply the fuzzy logic, the objective function should be described by membership functions. In this paper, all the membership functions are modeled with a triangular shape with one of the three following status: small (S), medium (M), and large (L). Output variables of fuzzy sets are presented in three forms of linguistic values; NE (negative), ZE (zero), and PE (positive), with related membership functions, as shown in Fig. 3. There are nine possible rules for

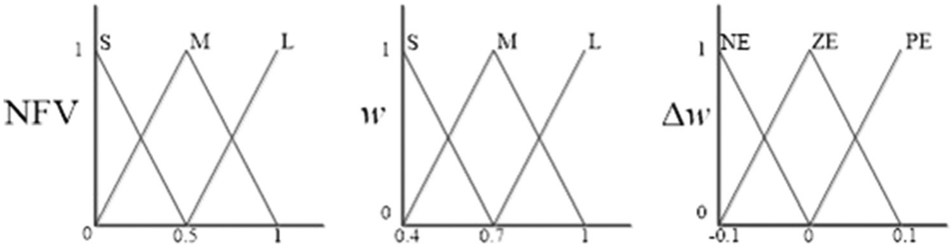

FIG. 3. The membership functions.

TABLE I. Fuzzy rules for w correction.

	Inputs		Output
Rule no.	NFV	w	Δw
1	S	S	ZE
2	S	M	NE
3	S	L	NE
4	M	S	PE
5	M	M	ZE
6	M	L	NE
7	L	S	PE
8	L	M	ZE
9	L	L	NE

two input variables and three linguistic values for all input variables, which are listed in Table I. Each fuzzy rule is from an "IF-THEN" statement, for example: If *NFV* is *(L)* and *w* is *(M),* then Δw is *(ZE)*. The fuzzy rules are shown in Table I; these are used to modify the weight factor correction (Δw). Both positive and negative corrections are required for the inertia weight. Therefore, a range of [−0.1–0.1] was chosen for Δw. The new value of w when using fuzzy logic is computed as follows:[41]

$$w^{k+1} = w^k + \Delta w. \tag{42}$$

B. Multi-objective optimization by using the interactive fuzzy method

Multi-objective optimization is used to combine different objectives that are usually in conflict. Therefore, the planner of the system is unable to make the final decision based on his or her individual point of view among a wide range of suitable solutions. These optimal solutions are known as Pareto-optimal solutions.

All multi-objective optimizations can be formulated as follows:

$$\begin{aligned} &min\, F = \left[f_1(x), f_2(x), \ldots, f_n(x,)\right]^T \\ &s.t. \\ &g_i(X) < 0 \quad i = 1, 2, \ldots, N_{\text{ueq}} \\ &h_i(X) = 0 \quad i = 1, 2, \ldots, N_{\text{eq}}. \end{aligned} \tag{43}$$

There are various techniques to minimize (or maximize) some functions as multi objective problems simultaneously. Due to the different types of the objective functions and also the different optimal values of each objective function in this paper, the interactive fuzzy method is implemented. A fuzzy set theory is used to formulate all the objective functions. The membership functions of each objective functions are formulated in Eq. (27). Figure 4 shows the shape

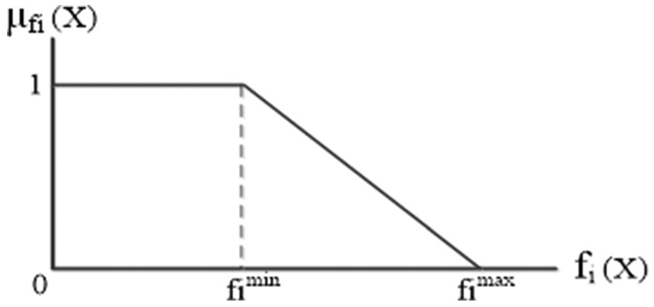

FIG. 4. A membership function for objective functions.

of each membership function. The upper and lower limits (f^{max} and f^{min}) are calculated by single objective optimization for each objective function separately.

$$\mu_{fi}(X) = \begin{cases} 1 & for \quad f_i(X) \le f_i^{\min} \\ 0 & for \quad f_i(X) \ge f_i^{\max} \\ \dfrac{f_i^{\max} - f_i(X)}{f_i^{\max} - f_i^{\min}} & \quad f_i^{\min} \le f_i(X) \le f_i^{\max}. \end{cases} \tag{44}$$

After defining the membership functions, the decision maker can select a suitable value in the range of [0,1] for μ_{ri} (i={1,2,…, p}), where p is the number of objective functions and all Pareto-optimal solutions are obtained. By this approach, the decision-maker can show the importance of each objective function and find the satisfying solution.

Because the target of the proposed approach is to obtain a set of solutions for the multi-objective DSP problem, it is necessary to apply a method that can obtain a set of optimal solutions. The Pareto-optimal method is a suitable approach for the multi-objective problem, which can obtain a set of solutions instead of one solution. This method is based on the dominance concept, so X_1 dominates X_2 as following:

$$\begin{aligned} &\forall i = \{1,2,\ldots,n\}, \quad f_i(X_1) \le f_i(X_2), \\ &\exists j = \{1,2,\ldots,n\}, \quad f_j(X_1) < f_j(X_2). \end{aligned} \tag{45}$$

For fuzzy multi-objectives, the fuzzy solution can be calculated as[42]

$$f(\bar{X}) = \min_{X\in\theta}\left\{\max_{i=1,\ldots,n} |\mu_{ri} - \mu_{fi}(\bar{X})|\right\}. \tag{46}$$

IV. CASE STUDY AND NUMERICAL RESULTS AND DISCUSSION

A. Assumptions

Figure 5 shows the monthly and hourly weight factors of each bus. Because the price of the electricity supplied by the substation varies with the amounts of power bought during the day, three price levels for low, medium, and peak load levels during a day are considered. The

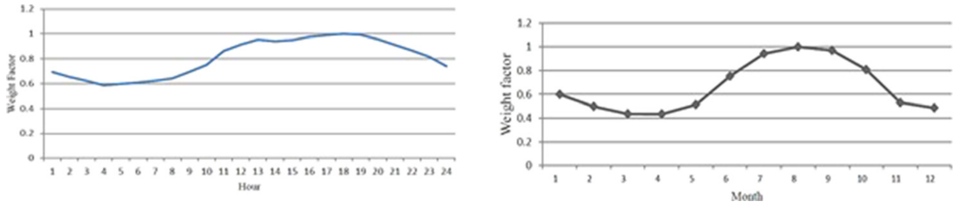

FIG. 5. Monthly and hourly weight factors of the peak load.

TABLE II. The price data of the substation.

Load level	Network situation	Time in 1 year (h)	Market price ($/MWh)
1	Light load	4100	35
2	Medium load	3900	45
3	Peak load	760	50

TABLE III. Specification of DGs.

	WT	PV	FC
Capital cost ($k $W^{-1)}$	1500	6675	…
Capacity (kW)	750	600	1000
Gr	1	1	…
Life time (year)	20	20	…
Loading factor (LF)	0.9	0.9	Not fixed
Fuel cost ($kW h^{-1})	0	0	…
O&M cost ($kW h^{-1})	0.005	0.005	…
Failure rate (f/y)	2	2	6
Repair time (h)	48	24	24

price data are given in Table II. It should be noted that the contract price between the DG owner and the DisCo is considered to be U.S.$45/MWh.

The assumed values for investment cost and reliability data are given in Table III. Other parameter values are given in Table IV.

B. First case study

To show the efficiency of the proposed method, it was tested on two cases of a power distribution system. The first one is the IEEE 34-bus distribution system.[35] Figure 6 shows this system.

The proposed multi-objective optimization to obtain the optimal DG location, size, and type has been solved by the interactive fuzzy PSO method. The DGO and DisCo profits, total cost, ENS, and VNS were calculated as objective functions. This optimization problem has two objective functions that are in conflict to each other; therefore, a reduction in one of them leads to an increase in the other one and vice versa.

However, lower profit or higher initial investment in this planning scheme results in higher reliability of the system. From a financial point of view, the decision maker or planner can reduce the corresponding reference membership function to decrease the initial investment and increase the impact of this objective function. There are some optimal solutions and the min-max method (Eq. (43)) is used in other to choose the best answer. As a result, the location, capacity, and types of each DG and reactive resources are presented in Table V. In this study, a FC injects reactive power; the result is shown in Table V. As can be seen, at the end of each feeder in this radial power system, DGs or reactive resources should be allocated because one of the main objectives in this paper is ENS as well as VNS. For example, if there is a fault at the end of the network (bus 34), then the local loads could be supplied by these allocated DGs, so ENS and VNS will be decreased. The optimal value of the objective functions, such as total cost, ECOST, AIF, and AID, are 3356 M$, 2.72 M$, 65.43, and 3.84 h/yr, respectively. Also the optimal value of $\mathrm{ENS_p}$, $\mathrm{ENS_Q}$, $\mathrm{VNS_p}$, $\mathrm{VNS_Q}$. and active power losses are 224.34 MWh/yr, 48.46 MWh/yr, 241.98 MVarh/yr, 60.12 MVarh/yr, and 193.34 kW, respectively. These values were 1354.84 MWh/yr, 346.41 MWh/yr, 1498.25 MVarh/yr, 406.78 MVarh/yr, and 378.56 kW

TABLE IV. Values of the parameters used.

Parameters	Values
Annual growth rate of load	2%
Load point failure rate (λ f/y)	1
Load point repair time (r h)	4
Interest rate	12.5%
Inflation rate	9%
IEAR_p	2000 (\$/kWh)
IEAR_q	200 (\$/KVarh)
N_Y (year)	5

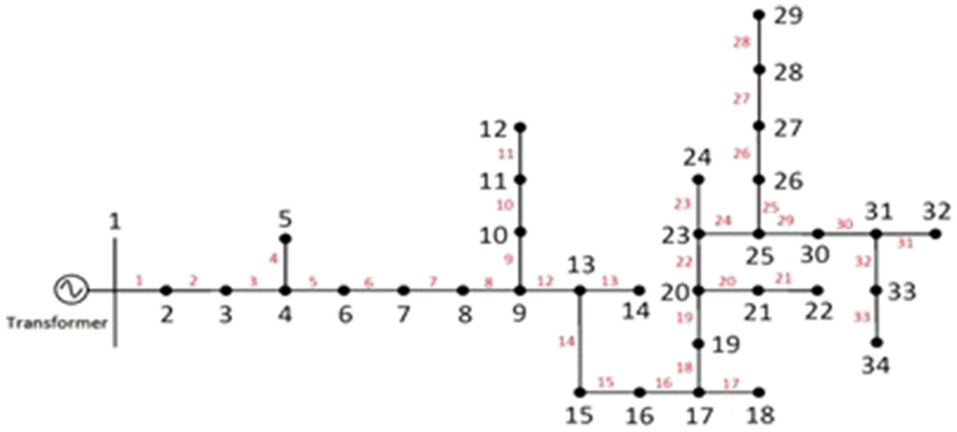

FIG. 6. IEEE 34-bus power distribution system.

TABLE V. Results for DG placement in 34-bus system.

	Optimal capacity (kW/kVar)	Type	Location	Year
DG1	600	FC	34	1
DG2	600	FC	29	3
DG3	600	FC	12	2
DG4	450	WT	22	4
DG5	450	WT	18	1
DG6	450	WT	14	5
DG7	300	PV	22	3
DG8	300	PV	5	4
VAr1	500	Static	32	2
VAr2	500	Static	5	5
VAr3	400	FC	34	1
VAr4	400	FC	29	3
VAr5	400	FC	12	2

before distribution system planning, respectively. The AIF and AID were 84.1 and 5.72 h/yr, respectively, before planning because the probability of down states had a higher value.

The voltage profiles at three different hours in a day related to the last year of planning for the peak load level are shown in Fig. 7. After DG placement, although the load increases at

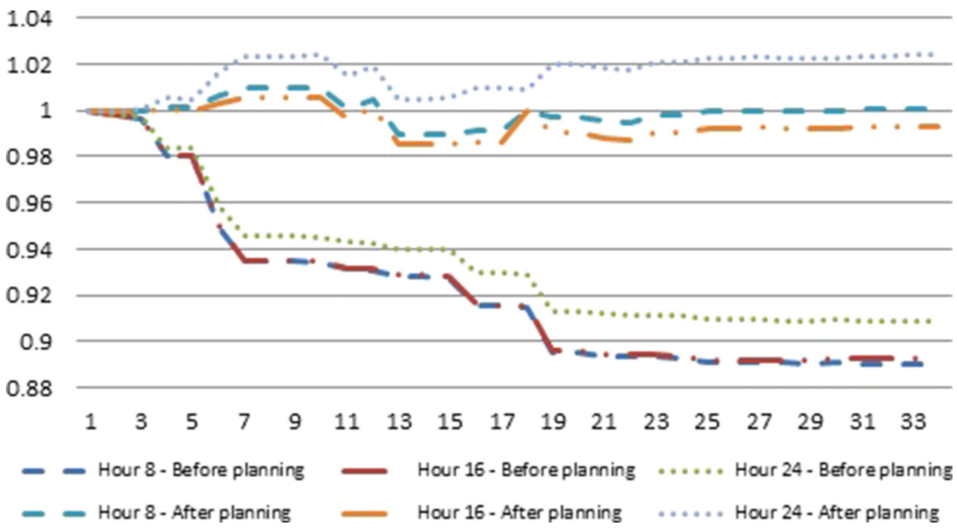

FIG. 7. Voltage profile of the first case related to the last year of the planning.

each bus of the distribution system, an improvement in the voltage profile is observed in comparison with the case of using no DGs. (Because the figure would be unclear, other voltages are not plotted.)

C. Second case study

For further investigation, a larger test system is considered. The 69-bus distribution system is used as an example network.[43] This network is shown in Fig. 8.

The results of this case, such as the location, capacity, and type of each DG and reactive resources, are tabulated in Table VI. It is concluded that the DGs are placed in the areas where ENS and VNS are minimized, on the other hand these places are at the end of the feeders in radial power system. The optimal value of the objective functions, such as total cost, ECOST, AIF, and AID, are 5876 M$, 4.21 M$, 97.46, and 5.39 h/yr, respectively. Also, the optimal value of ENS_p, ENS_Q, VNS_p, VNS_Q, and active power losses are 382.38 MWh/yr, 86.74 MWh/yr, 398.95 MVarh/yr, 105.98 MVarh/yr, and 316.12 kW, respectively; these values before distribution system planning were 2174.25 MWh/yr, 683.85 MWh/yr, 2384.87 MVarh/yr, 746.23 MVarh/yr, and 525.83 kW, respectively. The AIF and AID were 135.35 and 9.05 h/yr before planning. It can be deduced from the result that the optimal planning approach not only met the

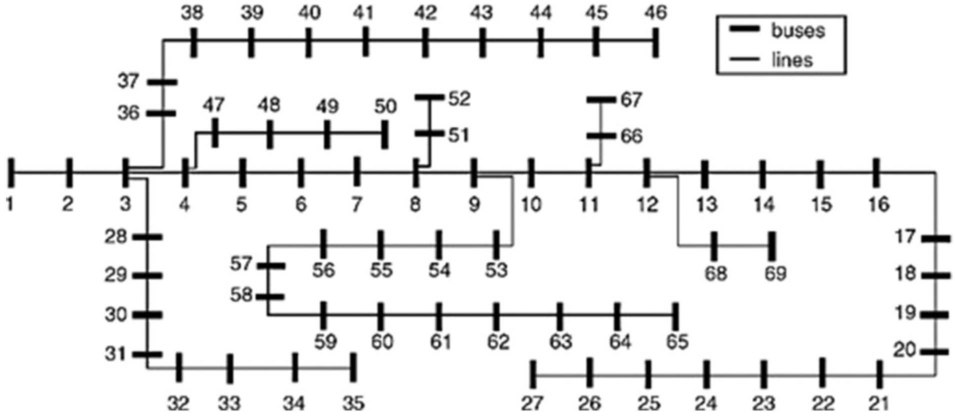

FIG. 8. IEEE 69-bus power distribution system.

TABLE VI. Results for DG placement in 69-bus system.

	Optimal capacity (kW/kVar)	Type	Location	Year
DG1	600	FC	67	2
DG2	600	FC	69	3
DG3	600	FC	65	4
DG4	600	FC	69	4
DG5	600	FC	27	1
DG6	450	WT	27	5
DG7	450	WT	35	3
DG8	450	WT	52	4
DG9	300	PV	50	1
DG10	300	PV	52	2
DG11	300	PV	46	1
DG12	300	PV	67	5
DG13	300	PV	27	2
VAr1	500	Static	35	3
VAr2	500	Static	67	1
VAr3	500	Static	52	5
VAr4	400	FC	67	2
VAr5	400	FC	69	3
VAr6	400	FC	65	4
VAr7	400	FC	69	4
VAr8	400	FC	27	1

load growth but also the system reliability and technical aspects. In addition, because reactive resources have been optimally located in the proposed approach, the reliability indices related to reactive power have been improved in the proposed method.

After using the proposed planning approach, the voltage profiles improved. The results are shown in Fig. 9 (because the figure would be unclear, only three different hours in a day were plotted).

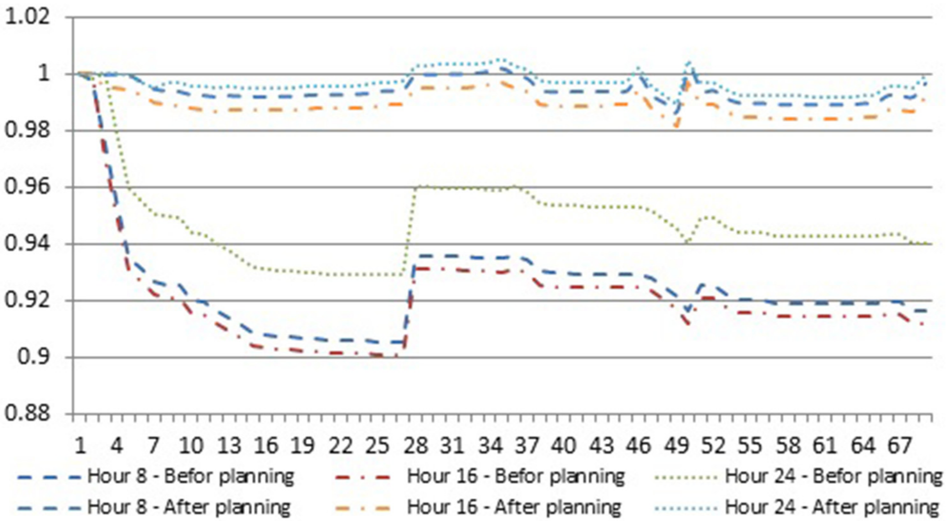

FIG. 9. Voltage profile of second case related to the last year of the planning.

V. CONCLUSIONS

In this paper, minimizing cost and maximizing profit as two different economic viewpoints and considering expected customer outage costs and minimizing the AIF and AID of the system as two different reliability viewpoints are provided. A new method for reliability evaluation based on the interruption of the distribution system by using the Markov model, which is integrated into the planning procedure, is proposed. Also, other reliability indices were considered by a new formulation including indices due to reactive power shortages, which are separated with those due to real power shortage. The proposed method was successfully applied on two standard power distribution systems with renewable DGs and time-varying loads. The results show the effectiveness of this method to consider the reliability of system and profit-based planning.

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