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Combined Firm and Renewable Distributed Generation and Reactive Power Planning

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ABSTRACT The benefits of integrating Distributed Generation (DG) into the distribution networks depend on the characteristics of different types of DG units, loads and Reactive Power Sources (RPS). These benefits can be optimized if the firm DG units such as biomass energy and renewable DG units such as photovoltaic (PV) and wind system are optimally sized, located and coordinated with reactive power sources. In this paper, by assuming that the Distribution System Operator (DSO) has got the ownership and operation of DG units and RPS, a new planning strategy is proposed for determining the optimal placement and rating of DG units and RPS. This strategy overcomes the challenge of intermittency of renewable production in order that this planning will assist the system operators in defining the better integration strategies of firm and intermittent energy systems and reactive power sources in distribution networks. The proposed planning is based on single objective optimization so that it optimizes one of the following objective functions every time: the system energy losses, voltage stability margin, self-adequacy of microgrids defined on the distribution system and exchange of active and reactive powers between the distribution system and upstream network. The proposed technique accounts for the uncertainties associated with solar irradiance, wind speed and demand through a probabilistic optimization. The formulation of each planning problem is presented and applied to the 69-bus distribution system. The results of different planning strategies are compared and analyzed. Furthermore, the impact of the planning with each objective function on other indices is evaluated.

INDEX TERMS Combined planning, firm distributed generation, reactive power sources, renewable distributed generation.

NOMENCLATURE

INDICES AND SETS

i, j	Indices of buses
c	Set of candidate buses
m	Set of microgrids
n_m	Buses of microgrid m
h	Index/set of hours
s	Index/set of scenarios
y	Index/set of years
N_{bus}	Total number of buses in the system

PARAMETERS

n_y	Number of planning years
$Pr_{s,h}$	Probability of scenario s at hour h
G_{ij}	Conductance of line ij
B_{ij}	Susceptance of line ij
Y_{ij}, θ_{ij}	Magnitude and phase of the admittance matrix
P_{Di}, Q_{Di}	Peak active and reactive load at bus i
LS_h	Load states/levels of hour h
$PS_{s.h}^{W}.PS_{s.h}^{S}.$ $PS_{s.h}^{B}$	Wind, solar and biomass output power states of scenario s at hour h respectively (as a percentage of rated power)
V_{min}, V_{max}	Minimum and maximum voltage of bus i
$CF_W, CF_S,$ CF_B	Capacity Factor of wind, solar and biomass units respectively
x	Maximum penetration of DG in the system
$P_{DGmax\,i}$	Maximum penetration allowable on bus i
P_{DGunit}	Available ratings of the DG units
$k_{i,h}$	Weighting factor for load bus i at hour h
g	Annual load growth in percentage

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VARIABLES AND FUNCTIONS

$V_{i,s,h,y}$, $\delta_{i,s,h,y}$	Voltage magnitude and phase at bus i, scenario s, hour h and year y
P^{W}_{DGi}.P^{S}_{DGi}. P^{B}_{DGi}	Rated power of the wind, solar and biomass DG unit connected at bus i
$Q_{DER\,i}$	Reactive power sources connected at bus i
$P^{loss}_{s.h.y}$, $Q^{loss}_{s.h.y}$	Total power losses in the system during scenario s, hour h and year y
$Vp_{s.h.y}$	Voltage profile of the system during scenario s, hour h and year y
P_l	Network energy losses
V_{index}	Voltage stability margin index
SA	Supply adequacy of microgrids
EP	Exchanged power with the upstream network

I. INTRODUCTION

A. MOTIVATIONS

With increasing the penetration of distributed generation, especially renewable resources as one of the main requirements of smart grid development, the planning of the renewable resources along with the firm ones has been getting great importance. The aim of DG planning is to determine the location and capacity of the dispersed resources on a distribution system. DG planning is based on defining an optimization problem taking into account different techno-economic objectives and constraints. Utilizing the benefits of DGs in distribution networks and minimizing their adverse effects depends on the proper planning of these resources in the network. Since the consumption and production patterns at an active distribution system, including non-dispatchable generation, do not commonly match, attaining the planning goals while maintaining network constraints is more difficult.

In addition to DG planning, the concept of integration of DG planning with the planning of reactive power sources has been presented to determine the optimal location and capacity of both resources simultaneously. The joint planning of DGs and RPSs can considerably enhance their benefits for distribution networks, especially when there are variable DGs. Each distribution network operator emphasizes one or some of the objective functions for planning the active or/and reactive resources according to their network problems and priorities. Multi-objective optimization for considering conflicting objectives is a difficult task in view of selecting a suitable solution algorithm and decision for selecting the final solution among Pareto solutions, especially when there are many objective functions. In addition, some objectives are not conflicting, and optimizing one of them improves other objectives. Therefore, considering only an objective function and using a single objective optimization formulation is an advantage and a more practical method so that many researchers have been focused on only an objective function [1], [2]. This paper intends to emphasize the importance and practicality of single objective DG and reactive power planning, especially when the problem is a probabilistic one with many states of load and generation through investigating different selected objective functions on results of defined probabilistic planning for simultaneous renewable and firm DG and reactive power.

B. LITERATURE REVIEW

DG planning has been performed with various objective functions, constraints, and optimization methods [3], [4]. A comprehensive and meaningful survey of these studies is summarized in Table 1. The objective functions include technical objectives such as system's annual energy losses [1], [5]–[8], renewable generation capacity, voltage stability [9]–[11], voltage profile [10], [11] and reliability [12], [13]; and economic objectives such as deferral of upgrade investments [14], cost of energy losses [14], [15], cost of interruption [14], installation cost of DGs [16], total cost [17]–[19] and investment and operational costs [20].

DG planning problem has also been considered for the wind-based distributed generation [5], for different types of DG resources including wind, solar, and biomass [6], [11]–[13], [18], for the integration of dispatchable and non-dispatchable renewable DG units [8], [9], [14] and dispatchable DG units [15], [21].

Probabilistic load-generation model [5], [6] and Monte-Carlo simulation (MCS) [17] have been used for considering the stochastic nature of renewable energy resources and other uncertainties such as load growth, fuel price and output power of a Plug-in Electric Vehicle (PEV) in DG planning. Chance Constrained Programming (CCP) is one of the stochastic programming methods for dealing with uncertainties [17], [19].

In some studies, only one objective function is considered [1], [5]–[9], [17], [18], [20], but in some studies, distributed generation planning is defined as a multi-objective problem [11], [14], [16], [19], [21].

The DG planning has been solved by Mixed Integer Non-Linear Programming (MINLP) [5], [6], [9], Ant Lion Optimization Algorithm (ALOA) [10], Genetic Algorithm (GA) [14], [17], [20], Non-dominated Sorting Genetic Algorithm II (NSGA-II) [16], [19], Particle Swarm Optimization (PSO) [8], [11], [21], Tribe-PSO and Ordinal Optimization (OO) [18] and Tabu Search (TS) [12], [13], [15], [20].

Reactive power planning is an important economic and technical issue in the distribution system. Optimal reactive power planning in distribution systems has been done by researchers with several objective functions varying from energy losses and costs reduction to enhancing the reliability of distribution systems. Since simultaneous DG and reactive power planning/operation leads to many benefits, some studies such as [11]–[13], [15], [20], [22] consider DG and reactive power sources at the same time.

C. CONTRIBUTION AND ORGANIZATION OF THE PAPER

Two important challenges of renewable DG planning are:

1) The production pattern of the renewable generation is usually different from the load pattern depending on weather

TABLE 1. Taxonomy of the reviewed DG planning.

Refs	Types of energy sources	Decision variables	Objective function(s)	Algorithm
[1]	Wind, firm	Location, size and PF of DGs, voltage transformer tap changer	Annual energy losses	Multi-period ACOPF
[5]	Wind	Location and size of DGs	Annual energy losses	MINLP
[6]	PV, wind ,biomass	Location and size of DGs	Annual energy losses	MINLP
[7]	biomass, wind	Size and Power Factor (PF) of DGs	Annual energy losses	Analytical Algorithms
[8]	PV, wind, micro-turbine, dispatchable	Size and PF of DGs	Annual energy losses	PSO
[9]	PV, wind, dispatchable	Location and size of DGs	Voltage stability margin	MINLP
[10]	PV, wind	Location and size of DGs	Power losses and voltage profiles and stability	ALOA
[11],[22]	PV, wind, biomass, RPS	Location and size of DGs and RPS	Power loss, voltage deviation and voltage stability	PSO
[12]	PV, wind, biomass, energy storage, RPS	Location and size of DGs and RPS	Reliability and supply-adequacy	TS
[13]	PV, wind, biomass, RPS	Location and size of DGs and RPS	Annual energy losses and microgrid success index	TS
[14]	Wind, dispatchable (natural gas)	Location and size of DGs	Deferral of upgrade investments, cost of energy losses and interruption cost	GA
[15]	Dispatchable DG, RPS	Location and size of DGs and RPS, tap positions of voltage regulators and sectionalizing switches	Costs of power and energy losses and total reactive power	TS
[16]	PV, wind	Location and size of DGs	Lines losses and installing costs of DGs	NSGA-II using OpenCL
[17]	PV, wind, PEV, fueled	Location and size of DGs	Total costs	CCP , GA-embedded Monte Carlo simulation
[18]	PV, wind ,biomass	Location, size and PF of DGs	Total costs	Tribe-PSO, OO
[19]	PV, wind, micro-turbine	Location and size of DGs	Annual total costs and risk	CCP , NSGA-II
[20]	Wind, dispatchable, RPS	Location and size of DGs and RPS	Investment and operational costs	TS-GA
[21]	Dispatchable DG	Location and size of DGs and contract price	DG owner's and distribution company's profits	PSO
This paper	PV, wind, biomass, RPS	Location and size of DGs	Annual energy losses, voltage stability margin, self-adequacy of microgrids and active and reactive power exchanged	NLP

conditions and economic and social conditions of consumers of distribution system and type of the connected loads. In addition, the difference between generation and consumption patterns varies with the variation of seasons and years. Therefore, renewable DG planning may give no feasible solution or nonacceptable solutions. Using the firm DG units along with the renewable ones and simultaneous planning of these units is a basic way to encounter this challenge. Another technique to get the maximum benefits from renewable DG planning is simultaneous planning of DG and distributed reactive power sources. The proposed planning formulation in this paper considers simultaneous planning of firm and variable DG and reactive power sources to reach the planning objectives.

2) Each distribution network operator emphasizes one or some of the objective functions for planning the active or/and reactive power sources according to their network problems and priorities. Multi-objective optimization for considering conflicting objectives is a difficult task in view of selecting a suitable solution algorithm and decision for selecting the final solution among Pareto solutions. In addition, some objectives do not conflict, and optimizing one of them improves other objectives. Therefore, considering only an objective function and using a single objective optimization formulation for DG and reactive power planning is an advantage for the distribution network operator. For this purpose, the paper proposes a DG and reactive power planning with only an objective function. In addition, the proposed planning problem is solved for four individual objective functions defined from different perspectives by Distribution Network Operators (DNOs), and the impact of optimization of each objective function on indices associated with other objectives is investigated.

The main contributions in this paper are:

- Investigating importance and practicality of single objective DG and reactive power planning, especially when the problem is a probabilistic one with many states of load and generation by defining a joint planning problem for renewable distributed generation (firm and variable) and reactive power sources on the multi-year planning horizon
- Investigating two important and known objective functions, system energy losses and voltage stability margin, along with two new objective functions defined in this paper based on the new paradigm of constructing microgrid in the distribution system, self-adequacy of microgrids, and the active and reactive power exchanged between the distribution network and the upstream network

- Introducing a methodology for reduction of concerned objective functions by each distribution utility to convert the complex planning problem to a single objective problem or a multi-objective problem with minimum objective functions through solving the optimization problem with only one objective function and investigating the optimal solution for each objective function on other objective functions to specify correlated or conflicting objective functions

The rest of the paper is organized as follows. The problem formulation is explained in Section II. The test system and case studies are introduced in Section III. Section IV presents the results and discussion. Finally, section V concludes the paper.

II. PROBLEM FORMULATION

This section presents the probabilistic formulation for the objective functions and constraints of the proposed DG and reactive power planning. The used methodology is based on generating a probabilistic generation-load model [6] to solve the planning problem, including firm and volatile distributed generation resources and reactive power sources. The model is obtained by listing all possible combinations of renewable DG output power with their probabilities and the load for the whole year. In this method, Beta and Weibull probability density functions (pdf) are respectively generated for solar irradiance and wind speed of each hour of a typical day for each season of one year (four seasons) in order to represent the random behavior of the different renewable resources during each period.

The mathematical model described in the paper, including considered objective functions and constraints, has been formulated as non-linear programming (NLP) on a GAMS environment and solved by solvers KNITRO and CONOPT.

A. OBJECTIVE FUNCTIONS

1) MINIMIZING ENERGY LOSSES

The network energy losses changes with the introduction of DG to the distribution network through variation of active and reactive power flows. One of the common objectives in the DG planning is to maximize the utility profit by reducing the system energy losses during the planning period. Reducing energy losses can have such positive environmental and economic impacts as relieving the feeders and transformers as well as improving the voltage profile. On the other hand, an improperly allocated DG can give rise to excessive losses. Therefore, the objective function of the planning problem can be defined as minimizing the energy losses in the distribution system on the planning horizon considering load and renewable generation scenarios and annual load growth.

$$\min P_l = 90 \sum_{s,h,y} P^{loss}_{s,h,y} pr_{s,h} \tag{1}$$

where h, s and y are hour, scenario and year indices, respectively. The network energy loss, energy losses associated with each scenario s, hour h and year y and probability of scenario s at hour h are indicated by P_l, $P^{loss}_{s.h.y}$ and $pr_{s,h}$ respectively. According to the load and generation modeling, there are 90 similar hours per season. The network losses for each s, h and y is calculated by

$$P^{loss}_{s,h,y} = 0.5 \sum_{i=1}^{N_{bus}} \sum_{j=1}^{N_{bus}} G_{ij}[V^2_{i,s,h,y} + V^2_{j,s,h,y} - 2V_{i,s,h,y}V_{j,s,h,y}\cos(\delta_{j,s,h,y} - \delta_{i,s,h,y})] \tag{2}$$

where N_{bus} and G_{ij} denote the number of network buses and real component of admittance of line ij respectively. The magnitude and angle phase of voltage of bus i at scenario s, hour h and year y are denoted by $V_{i,s,h,y}$ and $\delta_{i,s,h,y}$ respectively.

2) MAXIMIZING VOLTAGE STABILITY MARGIN

The long feeders with heavy loading in the distribution network suffer small voltage stability margins. Thus, DG and reactive power sources planning can be defined to enhance the voltage stability margin of the distribution network. Maximizing the objective function V_{index} defined in (3) leads to an increase of the system voltage stability because it maximizes the network voltage profile weighted by load level at system buses. In other words, the voltage stability margin is enhanced by giving more importance to the improvement of voltages in the buses that have high power demand. The weighted voltage magnitudes of the network buses related to before and after planning are shown by $V^{withoutDG}_{Ps.h.y}$ and $V^{withDG}_{Ps.h.y}$ respectively. The number of planning years, the installed active power at bus i, the percentage of the installed active power (load state), which is connected at hour h of year y, and the weighting coefficient of load i at hour h of year y are denoted by n_y, P_{Di}, $LS_{h,y}$ and $k_{i,h,y}$ respectively.

$$\max \mathrm{V}_{index} = \sum_{s,h,y} \frac{Vp^{withDG}_{s,h,y}}{Vp^{withoutDG}_{s,h,y}} \cdot \frac{pr_{s,h}}{96n_y} \tag{3}$$

where

$$Vp_{s,h,y} = \sum_{i=1}^{N_{bus}} V_{i,s,h,y} P_{D_i} k_{i,h,y} \tag{4}$$

And

$$k_{i,h,y} = \frac{P_{D_i} LS_{h,y}}{\sum_{i=1}^{N_{bus}} P_{D_i}} \tag{5}$$

If the value of V_{index} is more than unity, using DG units and reactive power sources has a positive impact on the voltage index. Thus, maximizing V_{index} leads to the best location for installing the DG units and reactive power sources to improve voltage stability.

3) MAXIMIZING SUPPLY ADEQUACY OF MICROGRIDS

One of the new paradigms in smart distribution networks is to take advantage of integrating the DG units and reactive power sources to form microgrids in the distribution network. Hence, it can continue to supply important loads autonomously and separately from the network in the case of an emergency. A microgrid is a small electrical distribution network including loads, distributed energy sources and some control systems to control loads and energy sources. Microgrid must have active and reactive supply adequacy to continue its service in the islanding mode with the least load interruption when it disconnects from the upstream system. In other words, a more self-sufficient and more self-healing microgrid is a result of the less generation-load imbalance within it. In addition, active and reactive supply adequacy help make appropriate infrastructure for fast and efficient restoration of the smart electrical grid after a blackout in the power system. Thus, DG and reactive power sources planning can be performed in a way to attain the best condition in view of the active and reactive supply adequacy of constructed microgrids in the distribution system.

A probabilistic index for both active and reactive supply adequacy is defined based on the load-generation scenarios by (6) to evaluate the supply adequacy of the constructed microgrids within the distribution system. The index is calculated by summation of the weighted square of the mismatch between generation and consumption plus losses for both active and reactive powers and all load-generation scenarios and all microgrids during the planning horizon. Supply adequacy of microgrids, active power adequacy of microgrids and reactive power adequacy of microgrids are denoted by SA, F_P and F_Q respectively.

$$\begin{aligned}\min\ SA &= F_P + F_Q \\ &= \sum_{m}\sum_{s,h,y}\left|\sum_{n_m}(P_{Gn,s,h,y,m} - P_{Dn,s,h,y,m}) - P^{loss}_{s,h,y,m}\right|^2 pr_{s,h} \\ &\quad + \sum_{m}\sum_{s,h,y}\left|\sum_{n_m}(Q_{Gn,s,h,y,m} - Q_{Dn,s,h,y,m}) - Q^{loss}_{s,h,y,m}\right|^2 pr_{s,h}\end{aligned} \tag{6}$$

where

$$P^{loss}_{s,h,y,m} = 0.5\sum_{i\in m}\sum_{j\in m} G_{ij}[V^2_{i,s,h,y} + V^2_{j,s,h,y} - 2V_{i,s,h,y}V_{j,s,h,y}\cos(\delta_{j,s,h,y} - \delta_{i,s,h,y})] \tag{7}$$

$$Q^{loss}_{s,h,y,m} = -0.5\sum_{i\in m}\sum_{j\in m} B_{ij}[V^2_{i,s,h,y} + V^2_{j,s,h,y} - 2V_{i,s,h,y}V_{j,s,h,y}\cos(\delta_{j,s,h,y} - \delta_{i,s,h,y})] \tag{8}$$

where m and n_m are the number of microgrids constructed in the distribution system and the number of buses belonged to microgrid m, respectively. $P_{Gn.s.h.y.m}$ and $Q_{Gn.s.h.y.m}$ are active and reactive generated power, and $P_{Dn.s.h.y.m}$ and $Q_{Dn.s.h.y.m}$ are active and reactive load at bus n in microgrid m, scenario s, hour h and year y, respectively. The active power losses and reactive power losses of microgrid m associated with each scenario s, hour h and year y are denoted by $P^{loss}_{s.h.y.m}$ and $Q^{loss}_{s.h.y.m}$ respectively. B_{ij} denotes the imaginary component of admittance of line ij.

4) MINIMIZING EXCHANGED POWER WITH THE UPSTREAM NETWORK

When the distribution network includes one microgrid only, the well-matched distribution system and self-sufficiency of the microgrid can be attained by minimizing the exchange of active and reactive powers between the distribution network and the upstream network. Thus, dependency of the distribution system to the main system and the adverse effects of the distribution network on the upstream network and vice versa are reduced. Consequently, when the distribution system is disconnected from the upstream system due to some problems in the power system or distribution system, the load supply can be continued with minimum difficulty by providing some control facility and disconnecting some non-sensitive or insignificant loads. In addition, reducing the exchanges of active and reactive powers between the distribution network and the upstream network can lead to a reduction of energy losses and occupied capacity of the feeder connecting the distribution system to the main power system.

A probabilistic index based on the load-generation scenarios is defined as (9) to attain this objective. The index calculates the summation of the weighted square of the exchanged active and reactive powers between the distribution and upstream systems for all load-generation scenarios during the planning horizon.

$$\min\ \mathrm{EP} = \sum_{s,h,y}\left[P^2_{SL,s,h,y} + Q^2_{SL,s,h,y}\right]pr_{s,h} \tag{9}$$

where EP, SL, $P_{SL,s,h,y}$ and $Q_{SL,s,h,y}$ denote exchanged power index, slack bus (the connection point of distribution system to the main system), and the exchanged active and reactive powers between the distribution and upstream system in scenario s, hour h and year y respectively.

B. CONSTRAINTS

Network constraints are presented in (10-16), and distributed generation constraints are considered in (17-18).

1) POWER FLOW EQUATIONS

Constraints presented in (10) and (11) satisfy the active and reactive power balance at each bus of the network, respectively. The annual load growth (g) in the planning problem is taken into account by (12).

$$PS^W_{s,h}P^W_{DG_i} + PS^S_{s,h}P^S_{DG_i} + PS^B_{s,h}P^B_{DG_i} - LS_{h,y}P_{D_i} = \sum_{j=1}^{N_{bus}} V_{i,s,h,y}V_{j,s,h,y}Y_{ij}\cos(\theta_{ij} + \delta_{j,s,h,y} - \delta_{i,s,h,y}) \tag{10}$$

$$Q_{DER_i} - LS_{h,y}Q_{D_i} = -\sum_{j=1}^{N_{bus}} V_{i,s,h,y}V_{j,s,h,y}Y_{ij}\sin(\theta_{ij} + \delta_{j,s,h,y} - \delta_{i,s,h,y}) \tag{11}$$

$$LS_{h,y} = LS_h(1 + \frac{g}{100})^{y-1} \tag{12}$$

where $PS^W_{s.h}$, $PS^S_{s.h}$, $PS^B_{s.h}$ are the ratios of generation of wind, solar and biomass DGs at scenario s and hour h to their installed capacities, respectively, and $LS_{h,y}$ is the load level at hour h and year y. The capacity of wind, solar and biomass DGs and reactive power sources installed at bus i are denoted by P^W_{DGi}, P^S_{DGi}, P^B_{DGi} and Q_{DERi} respectively. P_{Di} and Q_{Di} are peak active and reactive load at bus i. Y_{ij} and θ_{ij} show the magnitude and phase angle of element ij of the nodal admittance matrix.

2) VOLTAGE LIMITS

The slack bus voltage and the allowable range of magnitude and phase of the bus voltage are as follows.

$$V_{SL,s,h,y} = 1 \tag{13}$$

$$\delta_{SL,s,h,y} = 0 \tag{14}$$

$$V_{\min} \le V_{i,s,h,y} \le V_{\max} \tag{15}$$

$$-\pi \le \delta_{i,s,h,y} \le \pi \tag{16}$$

3) MAXIMUM PENETRATION OF DG UNITS

Constraints of the maximum installable capacity of DG (P_{DGmaxi}) at each bus and allowable penetration of DG in the system ($x \sum P_{Di}$) are expressed by (17) and (18), respectively. CF_W, CF_S and CF_B are capacity factors of wind, solar and biomass DGs, respectively.

$$P^W_{DG_i} + P^S_{DG_i} + P^B_{DG_i} \le P_{DG\max_i}, \quad \forall i \in c \tag{17}$$

$$\sum_{i\in c} CF_W P^W_{DG_i} + \sum_{i\in c} CF_S P^S_{DG_i} + \sum_{i\in c} CF_B P^B_{DG_i} \le x \sum_{i=1}^{N_{bus}} P_{D_i} \tag{18}$$

III. TEST SYSTEM

This section presents the general data and other required data related to the formulated problem for the test system. The well-known PG&E 69-bus distribution system is selected as the test system for studying the defined planning problems. The system data can be found in [23]. For this study, the candidate buses for connecting the DG units are {20, 46, 49,50, 53} according to [15]. The candidate buses for connecting the reactive power sources have been also selected as {10, 31, 49, 50, 51, 52, 53, 54, 55, 57, 59} by using the sensitivity analysis. It is assumed that the DG units operate at a unity power factor and all buses in the system have the same wind profile and solar irradiance. The hourly solar irradiance and wind speed data have been utilized from historical data, and biomass energy is considered a firm generation. The hourly load data given in [6] and the annual peak load for the system under study [23] are used to obtain the hourly load model for the typical day of each year season. A maximum limit for DG capacity equal to 1200 kW and a maximum limit for reactive power sources capacity equal to 1200 kVAr are assumed for each candidate bus. The maximum penetration of DG units is assumed equal to 50% of the peak load. When the objective is maximizing the supply adequacy of microgrids, the defined microgrids on the test system are shown in Fig. 1. The microgrids have been chosen according to the results obtained in [12].

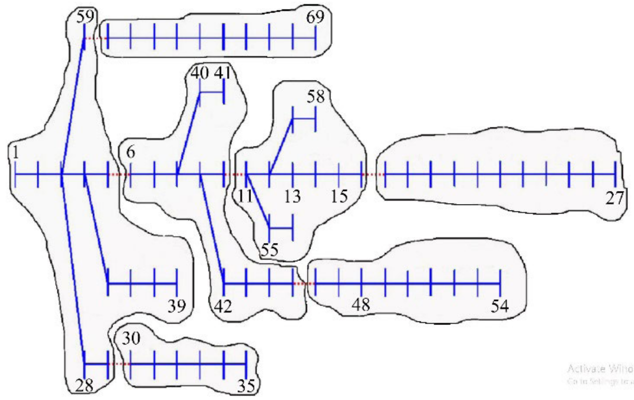

FIGURE 1. Structure of defined microgrids on the test system.

To study the proposed DG and reactive power planning defined in this paper, 2 scenarios and 16 cases for each scenario are proposed as follows.

Scenario 1: $n_y = 1$

Scenario 2: $n_y = 5$ and annual load growth rate = %4

Case 1: base case, without DG and reactive power sources;

Case 2: reactive power sources (Q);

Case 3: biomass DG units (B);

Case 4: wind-based DG (W);

Case 5: solar DG units (S);

Case 6: biomass DG with reactive power sources (BQ);

Case 7: wind-based DG with reactive power sources (WQ);

Case 8: solar DG units with reactive power sources (SQ);

Case 9: biomass DG with wind-based DG (BW);

Case 10: biomass DG with solar DG (BS);

Case 11: wind-based DG with solar DG (WS);

Case 12: biomass, wind-based DG and RPS (BWQ);

Case 13: biomass, solar DG and RPS (BSQ);

Case 14: wind-based, solar DG and RPS (WSQ);

Case 15: a mix of biomass, wind-based and solar DG (BWS);

Case 16: a mix of biomass, wind-based and solar DG with RPS (BWSQ);

The proposed mathematical models are formulated as NLP on a GAMS environment.

IV. RESULTS AND DISCUSSION

A. SCENARIO 1

Fig. 2 shows the values of index P_l for all cases in scenario 1 when the objective function of the planning problem is annual energy losses. It is observed that annual energy losses reduce in all 15 cases (2-16) with respect to the base case. When active and reactive distributed generation sources are utilized in the distribution network, the loads are supplied close to where the energy is consumed instead of thoroughly demanding the loads from the upstream network. Hence, feeder capacities are less occupied, and the system energy losses

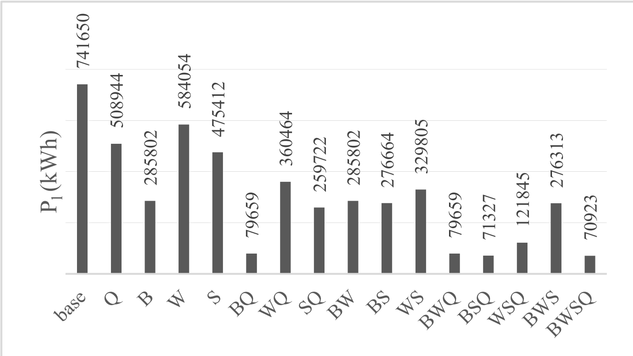

FIGURE 2. Optimal annual energy losses for all cases in scenario 1.

reduce. The most reduction occurs in case 16 (BWSQ) that biomass, wind, PV and reactive power sources are present at the same time. Case 13 (BSQ) also leads to annual energy losses near to that of case 16. It is obvious that reactive power sources have a profound impact on reducing energy losses. Generally, the impact of biomass energy on the reduction of losses is more than wind and solar-based DGs due to their intermittent production. The wind-based DG has the least impact on the loss reduction with respect to other sources; however, its impact is magnified when wind system is used along with solar or/and reactive power sources.

Fig. 3 shows the values of V_{index} for 16 cases in scenario 1 when the objective function of the planning problem is the voltage stability function. Utilizing DG and RPS, especially in high load demand buses, causes a reduction in buses voltage drop and, as a result, an increase in voltage stability margin. For instance, the voltage magnitude of bus 55 at the peak hour is 0.909 PU in the base case, while it reaches 0.994 PU at the same hour in case 6. As observed, the impact of reactive power sources is more than that of active power sources. Reactive power sources and biomass units lead to the most improvement in the voltage stability index so that the most increase in V_{index} is obtained in case 13 (BSQ).

FIGURE 3. Optimal voltage stability index for all cases in scenario 1.

Fig. 4 shows the values of SA for 16 cases in scenario 1 when the objective function of the planning problem is supply adequacy of microgrids. Placement of DG units and RPS reduces the load-generation imbalance in microgrids

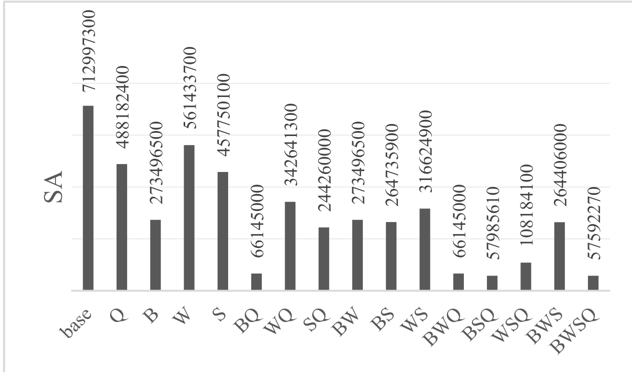

FIGURE 4. Optimal supply adequacy of microgrids in scenario 1.

by adding active and reactive power generation close to the consumers in the constructed microgrids; therefore, the SA index improves. As it is observed, biomass and reactive power sources have the most impact on the supply adequacy index. When all kinds of DG units are added to reactive power sources, the index reaches the least value.

Fig. 5 shows the values of EP for 16 cases in scenario 1 when the objective function of the planning problem is the exchanged power with the upstream network. Utilizing DGs and RPS in the distribution network reduces power received from the upstream network. The most reduction in EP occurs in case 16 (BSWQ) that there are biomass, wind, PV and reactive power sources. Case 13 (BSQ) also leads to a low value for EP. The impact of biomass energy on the reduction of EP is more than wind and photovoltaic DGs. The wind-based DG has the least impact on the index EP with respect to other sources; however, its impact is magnified when wind system is used along with solar, biomass and reactive power sources.

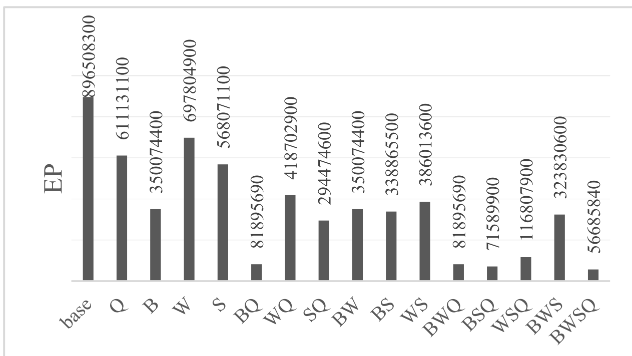

FIGURE 5. Optimal exchanged power with upstream in scenario 1.

Wind-based DG has less impact on all objective functions than other sources because the profile of wind production is different from the profile of load in the performed studies. Simultaneous use of renewable sources, including PV and wind systems, considerably improves the indices with respect to exploiting only wind or solar energy. The best result of DG planning is related to the simultaneous use of biomass and solar energy, while the best result is obtained for all indices by simultaneous planning of biomass, solar and reactive power sources.

Fig. 6 compares the variation of annual energy losses for cases 2, 3, 6, 11, 13 and 16 to the base case when the planning problem is solved by considering different objective functions. It is observed that the annual energy losses seriously increase in cases 2, 6, 13 and 16 when the objective function of the planning is voltage stability index. Due to the overuse of reactive power sources to improve voltage profile, the reactive current of feeders increases considerably. Therefore, considering V_{index} as an objective function in planning reactive power sources will dramatically increase energy losses, SA index and EP index. The common feature of cases 2, 6, 13 and 16 is accompanying reactive power planning with DG planning. Applying V_{index} as an objective function does not cause a significant variation in the energy losses in case 11; however, it has a suitable impact on reducing energy losses in the case 3 (biomass DG planning). As expected, the most reduction of annual energy losses is related to objective function P_l. Using objective function SA can also lead to a considerable reduction of energy losses near to results obtained by objective function P_l while using objective function EP presents a moderate impact on the reduction of energy losses. Similarly, Figs 7 to 9 compare the variation of voltage stability index, supply adequacy index and exchanged power with the upstream network with respect to those in the base case for cases 2, 3, 6, 11, 13 and 16 when the planning problem is solved by considering different objective functions.

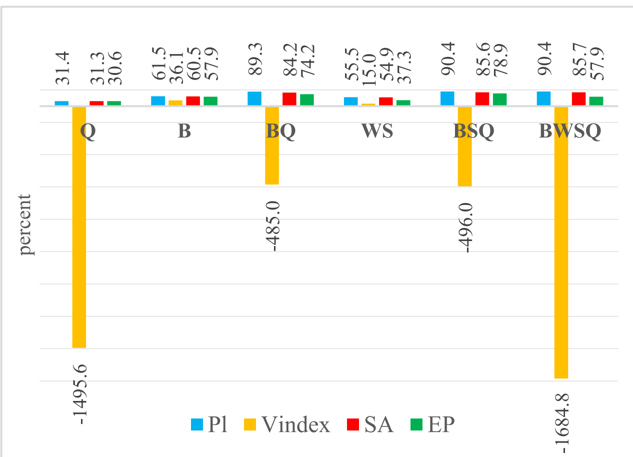

FIGURE 6. Normalized variation of annual energy losses with respect to base case losses for some cases when different objective functions are optimized.

Fig. 7 demonstrates that using all defined objective functions positively impacts V_{index}. After the objective function of the voltage stability, objective functions PE, SA and P_l have the most impact on V_{index} respectively. Figs. 8 and 9 qualitatively give similar results with Fig. 6.

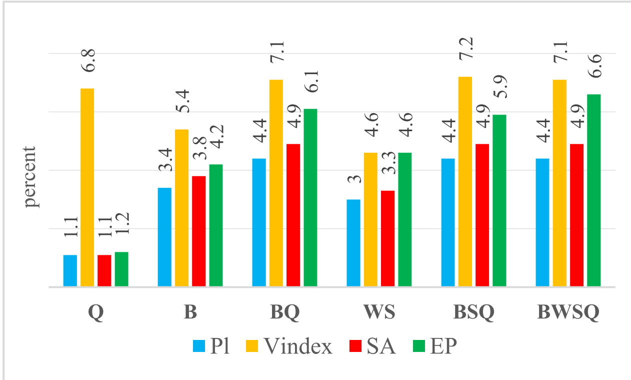

FIGURE 7. Normalized variation of voltage stability margin (V_{index}) with respect to base case for some cases when different objective functions are optimized.

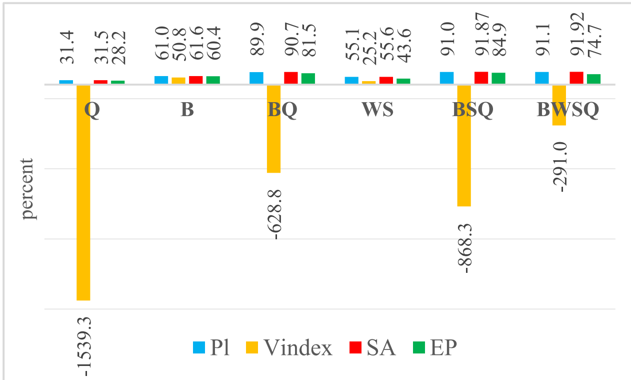

FIGURE 8. Normalized variation of supply adequacy (SA) with respect to base case for some cases when different objective functions are optimized.

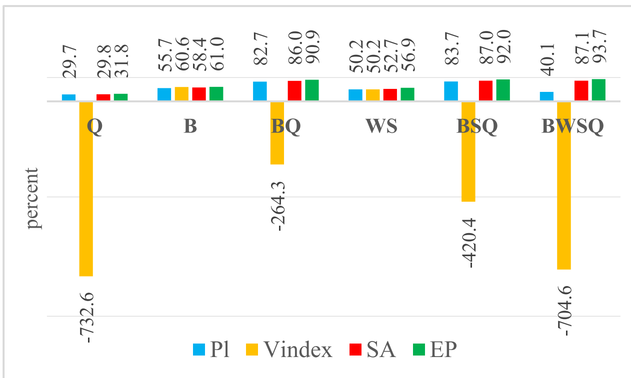

FIGURE 9. Normalized variation of exchanged power with the upstream network (EP) with respect to base case for some cases when different objective functions are optimized.

Tables 2 to 5 give optimal location and size of DG units and reactive power sources for the best case in view of different objective functions in scenario 1. It is observed that the most amount of reactive power is required for improvement of V_{index} which is mostly assigned to buses 10, 31, 49, 50, 51, 57 and 59. On the other hand, the most capacity of reactive

TABLE 2. Optimal location and size of DG Units and reactive power sources for the best case in view of index P_l in scenario 1 (case16).

Bus no.	P_{DG}^{B} (kW)	P_{DG}^{W} (kW)	P_{DG}^{S} (kW)	Bus no.	Q_{DER} (kVar)	Bus no.	Q_{DER} (kVar)
20	238	28	139	10	128	54	100
46	136	15	81	31	20	55	26
49	49	6	30	49	45	57	149
50	205	25	120	51	547	59	145
53	580	71	339	52	14		

TABLE 3. Optimal location and size of DG Units and reactive power sources for the best case in view of index V_{index} in scenario 1 (case13).

Bus no.	P_{DG}^{B} (kW)	P_{DG}^{S} (kW)	Bus no.	Q_{DER} (kVar)	Bus no.	Q_{DER} (kVar)
20	799	44	10	1200	52	102
46	623	0	31	1198	54	153
49	2	2	49	1200	55	79
50	418	107	50	1200	57	1200
53	0	56	51	1200	59	1200

TABLE 4. Optimal location and size of DG Units and reactive power sources for the best case in view of index SA in scenario 1 (case16).

Bus no.	P_{DG}^{B} (kW)	P_{DG}^{W} (kW)	P_{DG}^{S} (kW)	Bus no.	Q_{DER} (kVar)	Bus no.	Q_{DER} (kVar)
20	227	27	135	10	158	59	189
46	218	26	129	31	51		
49	0	0	0	54	476		
50	0	0	354	55	293		
53	918	108	174	57	40		

TABLE 5. Optimal location and size of DG Units and reactive power sources for the best case in view of index EP in scenario 1 (case16).

Bus no.	P_{DG}^{B} (kW)	P_{DG}^{W} (kW)	P_{DG}^{S} (kW)	Bus no.	Q_{DER} (kVar)
20	42	652	506	51	1146
46	0	0	586	54	174
49	0	0	0	55	63
50	290	40	0	59	274
53	1152	48	0		

power sources have been respectively assigned to buses 51, 54 and 59 when the objective function is P_l, SA or EP. It is also observed that the distribution of biomass, wind and PV production among the candidate buses considerably vary when different objective functions are used. For instance, the most capacity of biomass has been assigned to bus 53 in the case of using P_l as an objective function, while bus 20 should host the most biomass energy in the case of using objective function V_{index}. The most use of wind and solar energy is related to objective function EP, which mostly has been assigned to bus 20.

B. SCENARIO 2

Figs 10 to 13 respectively show percentage improvement of energy losses, voltage stability index, supply adequacy of micrograms and optimal exchanged power with the upstream network for all cases with respect to the base case in scenarios 1 and 2. The results of the proposed planning for scenario 2 and comparison of them with ones of scenario 1 demonstrates that the percent of the variation of each objective function in the 15 cases due to solving the single objective

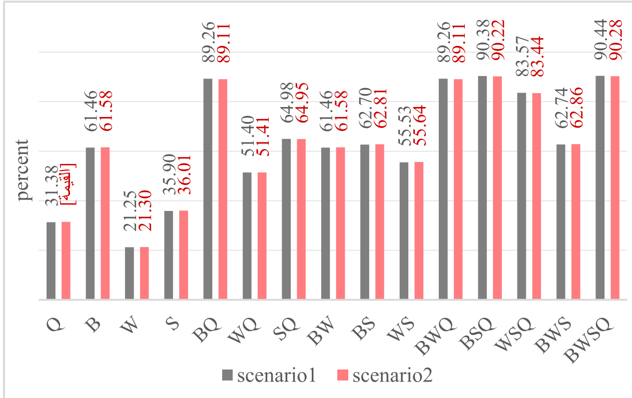

FIGURE 10. Percentage improvement of energy losses compared to the base case in scenarios 1 and 2.

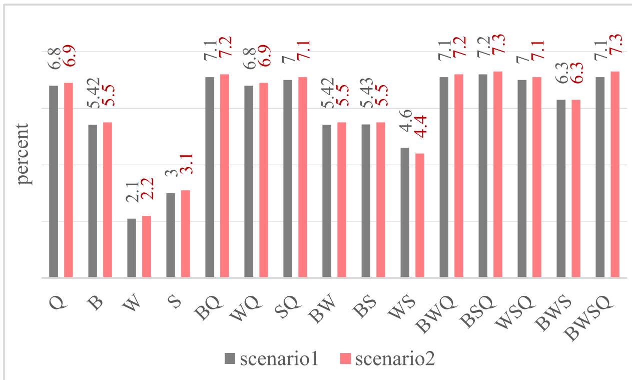

FIGURE 11. Percentage improvement of voltage stability margin compared to the base case in scenarios 1 and 2.

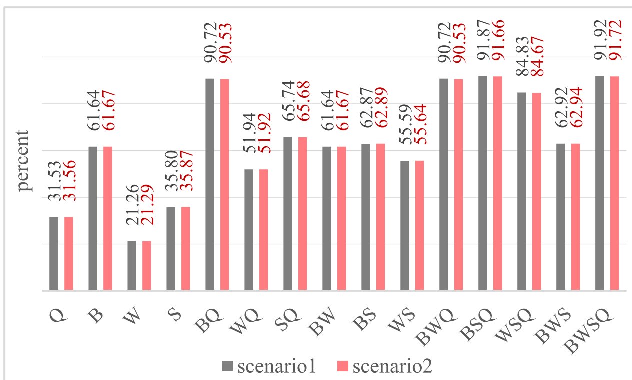

FIGURE 12. Percentage improvement of supply adequacy of microgrids index compared to the base case in scenarios 1 and 2.

optimization problems with respect to those in the base case are almost the same for both scenarios. Indeed, scenario 1 and scenario 2 correspond two different problems because although the used objective function is identical in both scenarios, scenario 1 considers load levels in one year, but scenario 2 studies more load levels regarding annual load growth during 5 years; in addition, renewable energy patterns are assumed the same for all years. Thus, it is natural that the assigned capacities of different types of sources are different in scenarios 1 and 2. In other words, we expect different

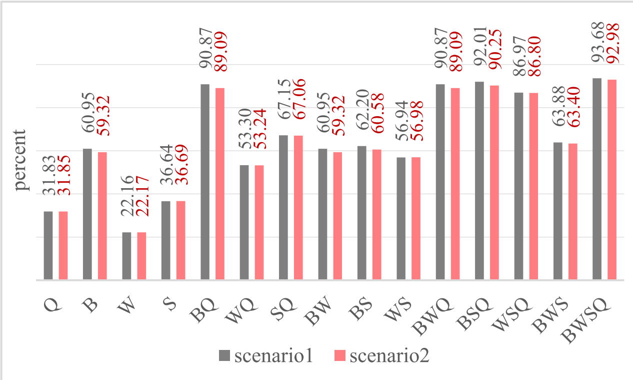

FIGURE 13. Percentage improvement of exchanged power with the upstream network compared to the base case in scenarios 1 and 2.

TABLE 6. Optimal location and size of DG Units and reactive power sources for the best case in view of index P_l in scenario 2 (case16).

Bus no.	P_{DG}^{B} (kW)	P_{DG}^{W} (kW)	P_{DG}^{S} (kW)	Bus no.	Q_{DER} (kVar)	Bus no.	Q_{DER} (kVar)
20	257	30	151	10	139	54	108
46	148	17	88	31	21	55	28
49	53	6	32	49	48	57	162
50	222	27	130	51	594	59	157
53	630	77	368	52	16		

TABLE 7. Optimal location and size of DG Units and reactive power sources for the best case in view of index V_{index} in scenario 2 (case13).

Bus no.	P_{DG}^{B} (kW)	P_{DG}^{S} (kW)	Bus no.	Q_{DER} (kVar)	Bus no.	Q_{DER} (kVar)
20	855	44	10	1200	52	102
46	0	0	31	1200	54	152
49	0	0	49	1200	55	79
50	645	108	50	1200	57	1200
53	0	56	51	1200	59	1200

patterns of capacities for different types of sources in two scenarios while attaining the optimal solution of the intended objective function, and the alteration of patterns is different for different objective functions.

Specifically, when the network energy losses is considered as the objective function of the planning problem, the pattern of the assigned capacities of different types of DG and reactive power sources in case 16 (the best case) is the same for both scenarios as shown in Table 6. However, the capacities of all resources in scenario 2 have been increased by about %8 with respect to those in scenario 1 due to the increase of system load during years 2, 3, 4 and 5 of the planning horizon. Similar results with the objective function of energy losses are obtained for objective function SA, as the total capacity allocated to each resource type has increased by 8% compared to scenario 1 (Table 8). For objective function V_{index}, the capacities of the resources are the same for both scenarios 1 and 2 except that the total capacity of biomass energy decreases from 1842 kW in scenario 1 to 1500 kW in scenario 2 due to assigning the zero capacity to bus 46 in scenario 2 as shown in Table 7. In the case of using EP as an objective function in the planning problem, the pattern of assigned resources to the candidate buses is approximately the same for both scenarios as shown in Table 9. Although the capacities of reactive power

TABLE 8. Optimal location and size of DG Units and reactive power sources for the best case in view of index SA in scenario 2 (case16).

Bus no.	P_{DG}^{B} (kW)	P_{DG}^{W} (kW)	P_{DG}^{S} (kW)	Bus no.	Q_{DER} (kVar)	Bus no.	Q_{DER} (kVar)
20	246	29	146	10	171	59	207
46	236	28	140	31	55		
49	0	0	0	54	541		
50	0	0	485	55	293		
53	996	117	87	57	41		

TABLE 9. Optimal location and size of DG Units and reactive power sources for the best case in view of index EP in scenario 2 (case16).

Bus no.	P_{DG}^{B} (kW)	P_{DG}^{W} (kW)	P_{DG}^{S} (kW)	Bus no.	Q_{DER} (kVar)	Bus no.	Q_{DER} (kVar)
20	42	1018	128	49	52	57	151
46	0	0	1052	50	9	59	279
49	0	0	0	51	1080		
50	270	13	0	54	163		
53	1095	0	0	55	59		

and solar energy have increased about %8 in scenario 2 with respect to scenario 1, the capacity of wind-based DGs has increased about 39 percent, and the capacity of biomass units has decreased about 5 percent.

V. CONCLUSION

This paper proposes a probabilistic joint firm and renewable DG and reactive power planning to overcome the challenge of non-compatibility of renewable generation and load patterns and maximize benefits of renewable DG units, including photovoltaic and wind systems. The proposed technique accounts for the uncertainties associated with solar irradiance, wind speed, and load growth during the planning horizon to plan a safe and optimal system. The paper intends to emphasize the importance and practicality of single objective DG and reactive power planning, especially when the problem is a probabilistic one with many states of load and generation. Two important ones are system energy losses and voltage stability margin, which have been studied on the well-known 69-bus test system along with two new objective functions defined in this paper based on the new paradigm of constructing microgrid in the distribution system, self-adequacy of microgrids defined on the distribution system and exchange of active and reactive powers between the distribution system and upstream network. This is done by solving the optimization problem with only one of four objective functions and investigating the optimal solution for each objective function on the other three objective functions to specify correlated or conflicting objective functions. Generally, the best results objective functions P_l, SA and EP are obtained when renewable DG units are used along with firm DGs and reactive power sources (case 16). Case 13 (BSQ) gives the best results for the objective function V_{index}. Based on the results of all scenarios and cases, it is concluded that objective functions P_l and SA and approximately EP are oriented ones while voltage stability index can be considered as an objective function that conflicts with other ones.

It is recommended that each distribution company uses the proposed method as a general one regarding the especial problems of every network or/and national and local policies. The results of this method can lead to the reduction of concerned objective functions by the distribution utility and the complex planning problem to a single objective problem or a multi-objective problem with minimum objective functions.

REFERENCES

[1] L. F. Ochoa and G. P. Harrison, "Minimizing energy losses: Optimal accommodation and smart operation of renewable distributed generation," *IEEE Trans. Power Syst.*, vol. 26, no. 1, pp. 198–205, Feb. 2011.

[2] H. A. Hejazi, A. R. Araghi, B. Vahidi, S. H. Hosseinian, M. Abedi, and H. Mohsenian-Rad, "Independent distributed generation planning to profit both utility and DG investors," *IEEE Trans. Power Syst.*, vol. 28, no. 2, pp. 1170–1178, May 2013.

[3] P. S. Georgilakis and N. D. Hatziargyriou, "Optimal distributed generation placement in power distribution networks: Models, methods, and future research," *IEEE Trans. Power Syst.*, vol. 28, no. 3, pp. 3420–3428, Aug. 2013.

[4] P. H. A. Mahmoud, P. D. Huy, and V. K. Ramachandaramurthy, "A review of the optimal allocation of distributed generation: Objectives, constraints, methods, and algorithms," *Renew. Sustain. Energy Rev.*, vol. 75, pp. 293–312, Aug. 2017.

[5] Y. M. Atwa and E. F. El-Saadany, "Probabilistic approach for optimal allocation of wind-based distributed generation in distribution systems," *IET Renew. Power Gener.*, vol. 5, no. 1, pp. 79–88, 2011.

[6] Y. M. Atwa, E. F. El-Saadany, M. M. A. Salama, and R. Seethapathy, "Optimal renewable resources mix for distribution system energy loss minimization," *IEEE Trans. Power Syst.*, vol. 25, no. 1, pp. 360–370, Feb. 2010.

[7] D. Q. Hung, N. Mithulananthan, and Y. K. Lee, "Optimal placement of dispatchable and nondispatchable renewable DG units in distribution networks for minimizing energy loss," *Elect. Power Energy Syst.*, vol. 55, pp. 179–186, Feb. 2014.

[8] A. Nasri, M. E. H. Golshan, and S. M. S. Nejad, "Optimal planning of dispatchable and non-dispatchable distributed generation units for minimizing distribution system's energy loss using particle swarm optimization," *Int. Trans. Electr. Energy Syst.*, vol. 24, no. 4, pp. 504–519, Apr. 2014.

[9] R. S. Al Abri, E. F. El-Saadany, and Y. M. Atwa, "Optimal placement and sizing method to improve the voltage stability margin in a distribution system using distributed generation," *IEEE Trans. Power Syst.*, vol. 28, no. 1, pp. 326–334, Feb. 2013.

[10] E. S. Ali, S. M. A. Elazim, and A. Y. Abdelaziz, "Ant lion optimization algorithm for optimal location and sizing of renewable distributed generations," *Renew. Energy*, vol. 101, pp. 1311–1324, Feb. 2017.

[11] M. Kumar, P. Nallagownden, and I. Elamvazuthi, "Optimal placement and sizing of renewable distributed generations and capacitor banks into radial distribution systems," *Energies*, vol. 10, no. 6, p. 811, Jun. 2017.

[12] S. A. Arefifar and Y. A.-R. I. Mohamed, "DG mix, reactive sources and energy storage units for optimizing microgrid reliability and supply security," *IEEE Trans. Smart Grid*, vol. 5, no. 4, pp. 1835–1844, Jul. 2014.

[13] S. A. Arefifar and Y. A.-R. I. Mohamed, "Probabilistic optimal reactive power planning in distribution systems with renewable resources in grid-connected and islanded modes," *IEEE Trans. Ind. Electron.*, vol. 61, no. 11, pp. 5830–5839, Nov. 2014.

[14] M. F. Shaaban, Y. M. Atwa, and E. F. El-Saadany, "DG allocation for benefit maximization in distribution networks," *IEEE Trans. Power Syst.*, vol. 28, no. 2, pp. 639–649, May 2013.

[15] M. E. H. Golshan and S. A. Arefifar, "Distributed generation, reactive sources and network-configuration planning for power and energy-loss reduction," *IEE Proc.-Generat., Transmiss. Distrib.*, vol. 153, no. 2, pp. 127–136, Mar. 2006.

[16] M. Abdelaziz and M. Moradzadeh, "Monte-Carlo simulation based multi-objective optimum allocation of renewable distributed generation using OpenCL," *Electr. Power Syst. Res.*, vol. 170, pp. 81–91, May 2019.

[17] Z. Liu, F. Wen, and G. Ledwich, "Optimal siting and sizing of distributed generators in distribution systems considering uncertainties," *IEEE Trans. Power Del.*, vol. 26, no. 4, pp. 2541–2551, Oct. 2011.

[18] K. Zou, A. P. Agalgaonkar, K. M. Muttaqi, and S. Perera, "Distribution system planning with incorporating DG reactive capability and system uncertainties," *IEEE Trans. Sustain. Energy*, vol. 3, no. 1, pp. 112–123, Jan. 2012.

[19] S. Zhang, H. Cheng, K. Li, N. Tai, D. Wang, and F. Li, "Multi-objective distributed generation planning in distribution network considering correlations among uncertainties," *Appl. Energy*, vol. 226, pp. 743–755, Sep. 2018.

[20] B. R. Pereira, G. R. M. da Costa, J. Contreras, and J. R. S. Mantovani, "Optimal distributed generation and reactive power allocation in electrical distribution systems," *IEEE Trans. Sustain. Energy*, vol. 7, no. 3, pp. 975–984, Jul. 2016.

[21] A. Ameli, S. Bahrami, F. Khazaeli, and M.-R. Haghifam, "A multiobjective particle swarm optimization for sizing and placement of DGs from DG owner's and distribution company's viewpoints," *IEEE Trans. Power Del.*, vol. 29, no. 4, pp. 1831–1840, Aug. 2014.

[22] M. Z. Malik, M. Kumar, A. M. Soomro, M. H. Baloch, M. Farhan, M. Gul, and G. S. Kaloi, "Strategic planning of renewable distributed generation in radial distribution system using advanced MOPSO method," *Energy Rep.*, vol. 6, pp. 2872–2886, Nov. 2020.

[23] M. E. Baran and F. F. Wu, "Optimal capacitor placement on radial distribution systems," *IEEE Trans. Power Del.*, vol. 4, no. 1, pp. 725–734, Jan. 1989.

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