Probabilistic Optimal Reactive Power Planning in Distribution Systems With Renewable Resources in Grid-Connected and Islanded Modes

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***Abstract*—Reactive power planning has always been a key research area in power distribution engineering; technically and economically. However, the problem needs to be revisited to consider several aspects of modern distribution systems, such as a high penetration level of renewable resources with intermittent nature; the microgrid concept and the possibility of system operation in grid-connected or isolated single microgrid mode, or isolated multiple microgrids; and probabilistic or hourly load profile. Motivated by these needs and considering all these aspects, this paper presents a generalized approach for probabilistic optimal reactive power planning in modern distribution systems. A new index is defined to probabilistically assess the success of microgrids in terms of real and reactive power adequacy and voltage limit constraints. Afterward, the reactive power planning is performed to reduce the annual energy losses of the grid-connected system and increase the defined microgrid success index. The problem formulation and solution algorithms are presented in this paper. The well-known PG&E 69-bus distribution system is selected as a test case, and through several sensitivity studies, the effect of optimization coefficients on the design and the robustness of the algorithm are investigated. A cost–benefit case study is also presented to determine the optimum total size of distributed reactive sources for the system under study.**

***Index Terms*—Energy losses, microgrid success, optimal allocation, reactive power planning, Tabu search (TS).**

I. Introduction

DISTRIBUTED REACTIVE SOURCES (DRSs) have been used in distribution systems for energy loss reduction, voltage profile improvement, power factor correction, and system capacity increase. Optimal reactive power planning or, as a specific case, optimal capacitor placement in distribution systems has been regularly performed by distribution engineers with several objectives, varying from peak power, energy losses, and costs reduction, to enhancing the reliability of distribution systems [1]–[3]. Several methods have also been proposed for this purpose, ranging from formerly used analytical and interactive methods [4]–[6] to recently proposed heuristic and intelligent methods [7], [8].

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In recent years, the structure of power systems has been changed significantly [9]–[11]. Environmental reasons and technical issues, such as the increase in the rate of electricity consumption, the need for reducing system losses, enhancement of system reliability, and deferment of system upgrades, have motivated the utility companies for local connection of renewable energy resources at the distribution level [12], [13]. This can transform conventional distribution systems into multiple modern interconnected distribution systems, i.e., *microgrids*. Microgrids are constructed from a set of distributed generators (DGs), storage units, and controllable loads, which are connected to a low-voltage system and can operate in grid-connected or islanded mode [14]. During the last decade, several efforts have been made to standardize microgrids [15], and several studies have been presented in this context. Microgrids have been under study from several aspects, including distribution loss minimization [16], distributed energy resource management [10], [14], [17], [18], control and protection of distribution networks [19], [20], reactive power compensation [21], voltage unbalance compensation [22], and design of advanced control strategies for intelligent microgrids [23]–[26].

Changing the structure of the distribution system itself by introducing the microgrids, the probabilistic nature of newly added DGs, as well as their ability to generate reactive power, manifests the need for new planning and operation strategies for current distribution systems. In this paper, the traditional optimal sizing and siting of reactive sources have been revisited considering the new system conditions. For this purpose, the reactive power planning problem for distribution systems is formulated by considering several aspects of modern distribution systems, such as: 1) the high penetration level of renewable resources with intermittent nature; 2) the microgrid concept and the possibility of system operation in grid-connected or isolated single microgrid mode, or isolated multiple microgrids; and 3) probabilistic or hourly load profile. These characteristics have not been seen or addressed properly in the existing reactive power planning studies in literature [1]–[11]. Two different objective functions are considered in this paper for optimization. The first objective is to minimize the annual energy losses in the grid-connected mode. The location and sizes of DRSs such as capacitor banks, which have the lowest cost among different reactive resources, can have significant impacts on the amount of annual energy losses. The second objective is to maximize a newly defined index for the successful islanded operation under supply-loss conditions. Successful operation of islanded microgrids, in case of emergencies, can prevent load interruption within that microgrid and consequently reduce the cost of interruption or power outage for the utility and customers. Some necessary conditions for a microgrid to be successful are its ability to operate with sufficient amounts of real and reactive power and, at the same time, to satisfy the voltage limit constraints to ensure voltage reliability. The defined probabilistic microgrid success index determines the success rate of microgrids in the system in terms of all these conditions. Optimal allocation of DRSs in the system increases the microgrid success index by: 1) affecting the real power adequacy of microgrids through reducing the losses; 2) significantly improving the reactive power adequacy; and 3) improving the voltage profile of the system. Therefore, both the grid-connected and islanded operation aspects can be considered in the reactive power planning in modern active distribution systems.

The main contributions of this paper to the research field are related to the probabilistic optimal reactive power planning in modern distribution systems as follows:

1) considering probabilistic nature of renewable resources in reactive power planning;
2) considering the typical fuel mix of DG units, e.g., wind turbines, photovoltaic (PV) modules, and biomass generators in the reactive power planning problem;
3) considering the hourly load profile for the reactive power planning;
4) defining a new probabilistic index for assessing the success rate of islanded microgrids (either a single islanded microgrid or multiple islanded microgrids) in terms of real and reactive power adequacy and voltage limit constraints;
5) probabilistic optimum reactive power planning considering the successful operation of existing microgrids in the system;
6) simultaneous consideration of annual energy losses in grid-connected mode and microgrid success index for probabilistic optimal reactive power planning.

This paper is organized as follows. Section II presents the models used for the system components, including loads and generators. The problem formulation is explained in Section III. Section IV explains the solution algorithms, and Section V presents the reactive power planning and sensitivity studies for the well-known PG&E 69-bus distribution system. In Section VI, the robustness of the algorithm to variation of load and DG penetration level is investigated. A sample case study for cost analysis is presented in Section VII; and finally, this paper is concluded in Section VIII.

II. Modeling of System Components

To find the optimum locations of DRSs in microgrids in a distribution system, the loads and DG units should be modeled properly. For this purpose, the loads are modeled with hourly shape using the IEEE Reliability Test System [27], and DG units are modeled as typical combination of three types of DGs, including PV modules, wind turbines, and biomass generators. The nature of wind and PV resources are probabilistic; therefore, the solar irradiance and wind speed for each hour of the day are modeled by beta and Weibull probability density functions (pdfs), respectively, by using historical data [28], [29]. Since the pdfs determine the generation level of DGs in power flow calculations, they should be as accurate as possible to have the optimum planning results. The pdfs can be obtained in several forms. For instance, in the areas that there is not much difference in the wind speed and solar irradiance during the seasons, four days of the year can be selected as representatives of four seasons. Moreover, in the areas with large variation of wind speed and solar irradiance, more than one day per season or an average of the days could be selected to obtain the pdfs. It is clear that, by using a higher number of selected days, higher accuracy and more computation efforts and time are yielded [28], [29]. The day representing each season is further divided into 24-hour time segments, each having a pdf for solar irradiance and wind speed. In order to integrate the output power of PV modules and wind turbines as multistate variables in the formulations, the continuous pdf of each is divided into different states. In this paper, the output power of the wind turbine and PV modules for each hour of the day is divided into twelve segments. Therefore, the probability of any combination of the load and generation is obtained by convolving the two probabilities. Assuming that solar irradiance and wind speed states are independent, for each hour, there are 144 (12×12) states with different probabilities, and for each day, there are 3456 (24×144) states. In order to get the annual energy losses for the system, the deterministic power flow is run for each state, and the results are accumulated considering the probability of each state. In this paper, the biomass generators are assumed to be firm generators with constant output power, and the PV modules and wind turbines are modeled as explained in [28] and [29].

III. Problem Formulation

The formulations of the objective functions, which are annual energy losses and islanded microgrid success index, are explained in this section. For this paper, the reactive power of DRSs is presented in a general format; however, they can be considered capacitor banks, which are usually very cost-effective, or an ancillary service provided by the DGs as well. In cases that the ancillary services are used with power electronic converters or that the capacitors are switchable, the same formulations, algorithm, and analysis are still applicable. The only difference is that the capacity of DRSs will be variable for all generation-load states, and at the end, the maximum calculated capacity of DRSs for the states, at each location, will be considered the optimum capacity of the DRS for that specific location.

A. Annual Energy Losses

The annual energy losses can be minimized by optimally allocating DRSs in a distribution system. As the distribution system works mainly in the grid-connected mode, minimizing annual energy losses while maintaining the voltage profile within the permissible band can be an important objective for utility planners, particularly under the intermittent nature of DG units and probabilistic load profile. In this paper, the probabilistic nature of DG units and load profile are considered in the annual energy loss minimization problem. Considering the different load-generation states, explained in Section II, and their probabilities for a one-year period, the objective function for this part can be defined as

$$F_1 = \text{Annual Energy Losses} = \sum_{n=1}^{N} P_{\text{Loss}_n} \times \rho_n \times h_n \quad (1)$$

where N is number of states for a year, P_{Loss_n} is the system losses for that specific hour of the year, ρ_n is the probability of the related state, and h_n is the time segment of the related state, which is 1 h in this paper. Minimizing the total energy losses of the system is achieved by optimally sizing and allocating the DRSs in the system.

B. Microgrid Success Index

To enhance distribution system reliability, islanded microgrids can be created to serve critical loads when the main supply is not available. Therefore, improving the success of islanded microgrids' operation can be an important factor for utility planners. The main challenge for successful operation of microgrids is the intermittent nature of distributed resources. DRSs, e.g., capacitors, can be a cost-effective solution to increase the success rate of islanded microgrids. In this paper, a new microgrid success index is defined to determine the percentage of times during a year that the microgrids can operate in islanded mode with normal conditions. Unlike previous studies [30], [31], which consider only active power matching as an index for successful islanded operation of microgrids, a comprehensive success index is defined and used in this paper. The proposed index combines three probabilistic indexes to account for real power adequacy, reactive power adequacy, and satisfaction of the voltage constraints, as necessary conditions for normal operation of microgrids. In some cases, the stability issues may need to be considered as well, which are out of the scope of the long-term planning problem considered in this paper. One necessary condition for an island to be successful is

$$P_{\text{DG}} \geq P_{\text{Load}} + P_{\text{Loss}} \quad (2)$$

where P_{DG} is the generated power of the DGs within the microgrid, P_{Load} is the load power of the island, and P_{Loss} is the power losses of the island and is assumed to be 5% of the current load [31]. On the other hand, according to [30], for an islanding operation of a microgrid, the penetration level of dispatchable DG units should be at least 60% of the total peak load demand at the time of islanding. For this paper, it assumed that biomass DG units are dispatchable; therefore, the second necessary condition for successful operation of microgrid is

$$P_{\text{BM}} \geq 0.6 \times P_{\text{DG}} \quad (3)$$

where P_{BM} is the generated power of biomass DGs in the microgrid. Equations (2) and (3) are two necessary conditions for successful operation of microgrids and can be satisfied by shedding the loads according to their requested reliability. In this paper, the load shedding starts from smaller loads to larger ones until the conditions are satisfied. These conditions may satisfy the real power adequacy of microgrids; however, the reactive power adequacy and voltage constraints should be also satisfied for a successful microgrid.

As explained in Section II, due to the probabilistic nature of generation units and variation of loads in the system for a one-year period, there would be 3456 × 365 number of states with different probabilities for each state. In order to calculate the defined index for each microgrid, each state is evaluated separately, and a number of zero or one is assigned to it, as shown in the following:

$$\rho_{\mu G_i} = \begin{cases} 1 & P_{G_i} \geq P_{L_i} \ \&\ Q_{G_i} \geq Q_{L_i} \ \&\ V_{\min_i} \leq V_i \leq V_{\max_i} \\ 0 & \text{otherwise} \end{cases} \quad (4)$$

where G_i represents the total generation and L_i represents the total consumption for real and reactive power at state i, including losses, V_i represents the voltage of all buses at the microgrid during state i; they are all determined by performing conventional load flow in the microgrids. It should be noted that, since this paper is related to the planning stage, the conventional load flow is performed for the steady-state conditions. After calculating the index for each state, they are accumulated by using the probability of each state, as shown in the following to get the success index for the microgrid:

$$\rho_{\mu G} = \sum_{i=1}^{N} \rho_{\mu G_i} \times \rho_i \quad (5)$$

where ρ_i is the probability of the related state. The calculated index in (5) is for the system with one microgrid only; however, for the systems including several microgrids, the success index can be defined as weighted summation of indexes for microgrids based on the number/amounts of loads, as shown in the following:

$$F_2 = \text{Microgrids Success Index} = \frac{\left(\sum_{k=1}^{\text{NoM}} \rho_{\mu G_k} \times N_{L_k}\right)}{\sum_{k=1}^{\text{NoM}} N_{L_k}} \quad (6)$$

where NoM is the number of microgrids, and N_{Lk} is the number/amounts of loads in a microgrid k. In this paper, maximizing the microgrid success index is achieved by optimally sizing and allocating the DRSs in the system.

C. Combined Objective Function

Since both annual energy losses and microgrid success index are important objectives in modern distribution systems, both of them can be considered simultaneously for probabilistic optimal allocation of DRSs in a distribution system. For this purpose, the two objective functions can be combined with weighting coefficients to form a single objective optimization problem, as shown in the following:

$$\min(F),\ F = K_1 F_1 + K_2(1 - F_2). \quad (7)$$

It should be noted that, in order to combine F_1 and F_2 and formulate a minimization problem, both F_1 and F_2 are normalized, and F_2 is modified to $(1 - F_2)$.

Selection of K_1 and K_2 will determine the objective function to be annual energy losses, a microgrid success index, or a combination of both depending on the importance of each. If the possibility of islanding is less, the annual energy losses will be more important, and K_1 should be larger than K_2 and vice versa. Since the optimum values of the two objective functions are different, they should be normalized using their optimum values, as will be explained in Section V-C. Sensitivity studies are performed in Section V to investigate the effect of selecting annual energy losses or microgrid success index as the objective function for probabilistic optimal sizing and allocating DRSs in the system.

D. Constraints of the Problem

There are several practical constraints for solving the problem defined in this paper. These constraints can be summarized as follows.

1) Power flow equations should be modified in order to consider the reactive power generated by the DRSs and the real power charged or discharged by the distributed energy storage resources (DESRs) if they exist in the system, as shown in the following:

$$P_{\mathrm{Sub}_t} + \sum P_{\mathrm{DG}_t} \pm \sum P_{\mathrm{DESRs}} - \sum P_{\mathrm{Load}_t} = \sum_{i=1}^{\mathrm{nbus}} V_{t,i} \times V_{t,j} \times Y_{i,j} \times \cos(\theta_{ij} + \delta_{t,j} - \delta_{t,i}) \quad \forall j, t \tag{8}$$

$$Q_{\mathrm{Sub}_t} + \sum Q_{\mathrm{DG}_t} + \sum Q_{\mathrm{DRSs}} - \sum Q_{\mathrm{Load}_t} = -\sum_{i=1}^{\mathrm{nbus}} V_{t,j} \times V_{i,j} \times Y_{i,j} \times \sin(\theta_{ij} + \delta_{t,j} - \delta_{t,j}) \quad \forall j, t \tag{9}$$

where subscripts Sub, DG, DESR, DRS and Load with P and Q represent the real and reactive power of substations, DGs, DESRs, DRSs, and loads, respectively. The power of DESR units is positive in the discharging period and negative in the charging period.

2) Voltage limits at all the system buses should be kept in the acceptable limits of $V_{\min}$ and $V_{\max}$, i.e.,

$$V_{\min} \le V_{t,i} \le V_{\max} \qquad \forall i \ne 1. \tag{10}$$

3) Feeder capacity limits should be maintained as follows:

$$P_{\mathrm{sub}_t} \le P_{\mathrm{rated}}. \tag{11}$$

4) The discrete sizes of DRSs should be considered as follows:

$$Q_{\mathrm{DRS\_}i} = k_{Q\_i} \times Q_{\mathrm{Step}} \qquad \forall i \tag{12}$$

where $Q_{\mathrm{DRS\_}i}$ is the reactive power capacity installed at bus i, Q_{Step} is the discrete size of DRS units, and k_{Q_i} is the number of DRS units installed at bus i.

5) The penetration level of DRSs at each bus may have a limit, which is shown in the following:

$$Q_{\mathrm{DRSs\_}i} \le Q_{\max} \qquad \forall i. \tag{13}$$

6) The last constraint is the total reactive power capacity of DRSs, i.e., Q_{DRS}, which is usually determined based on cost–benefit analysis, i.e.,

$$\sum_i Q_{\mathrm{DRSs\_}i} = Q_{\mathrm{DRS}}. \tag{14}$$

In practice, typical distribution systems' loads are usually imbalance. The IEEE standard 1159-2009 [33] limits the voltage imbalance in the range of 0.5%–2%, and this constraint limits the amount of load imbalance in the system. If the imbalance in the system is negligible, the same analysis could be done for the reactive power planning of the whole system, and if the imbalance is not negligible, the proposed algorithms are still applicable. In such cases, the single-phase power flow should be replaced with three-phase power flow, and the reactive power vector Q_{DRS} should include the system buses for each phase of the system. In the following, the algorithms used to solve the proposed optimization problem are explained.

IV. Solution Algorithm

The Tabu search (TS), [34], [35], which is an effective heuristic algorithm for solving optimization problems, is used in this paper for probabilistic optimal allocation of DRSs in the distribution systems. The TS is an iterative-based algorithm, which uses different memory structures to guide the search to the optimal solution. The optimal solution is a vector with the length of candidate buses for installing DRSs, as shown in the following:

$$Q_{\mathrm{DRS}} = [Q_{\mathrm{DRS\_1}} \cdots Q_{\mathrm{DRS\_}k} \cdots Q_{\mathrm{DRS\_}N_C}] \tag{15}$$

where $Q_{\mathrm{DRS\_}k}$ represents the capacity of DRSs, which is required to be installed on bus k, and N_C is the number of candidate buses. The TS starts by generating a trial solution and continues by moving in a neighborhood space. A trial solution is a vector similar to Q_{DRS} that contains the size of DRSs for each bus of the system. By changing the components of this vector, a set of candidate vectors, which is called neighborhood, will be obtained. The neighborhood can be defined in different ways. In this paper, it is defined by changing some components, e.g., 5, of the current trial solution. Afterward, the objective function is calculated for each trial solution in the neighborhood. Depending on the values of K_1 and K_2, the procedure will be as follows.

1) If $K_1 \ne 0$, F_1, which is the annual energy losses, should be calculated for the system in grid-connected mode. For this purpose, the conventional deterministic power flow is run for all load-generation states, defined in Section II, for a one-year period , and the energy losses for each state is

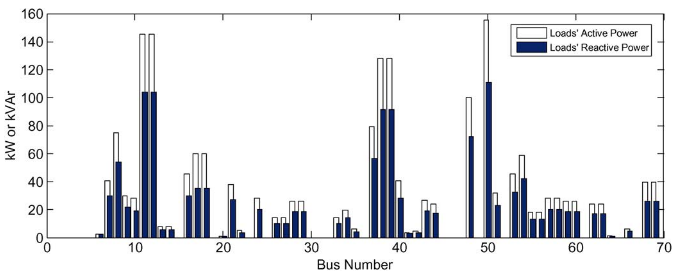

Fig. 1. 69-bus distribution system's loads.

TABLE I
OPTIMUM SELECTED BUSES FOR INSTALLING DGs

DG type	Locations in the System (Buses)	Rated Capacities (kW)
Wind Turbine	13,16,19,35,43,52	50,25,25,50,50,50
PV Module	30,36,50,56,58,62	25,25,25,25,25,25
Biomass DG	6,15,21,27,33,38, 42,45,54,57,68	25,50,25,50,75,50,50, 50,75,75,75

calculated. The calculated energy losses of the states are then accumulated using the probability of each state, and the resulted value is used to represent the annual energy losses of the system.

2) If $K_2 \neq 0$, F_2, which is the microgrid success index, should be calculated for the system in islanded mode of operation. For this purpose, after performing the load shedding, as explained in Section III-B, the conventional deterministic power flow is run for all load-generation states in each microgrid to check the real and reactive power adequacy and voltage constraints. The microgrid success index is then calculated using (4)–(6).

By calculating F_1 and F_2, the objective function F is calculated for all trial solutions in the neighborhood, and then, the search process continues by moving to the best neighbor. This procedure will be done until a certain criterion, which is usually the maximum number of iterations, is met. In order to avoid random search in the space, different memory structures including Tabu list, short-term memory, and long-term memory are used in this paper. The memory structures are implemented by using different vectors with the same length as Q_{DRS} (further explanations about the TS and its implementations can be found in [32], [33]). In the succeeding sections, the proposed algorithm is applied to a 69-bus distribution system.

V. IMPLEMENTATION AND SENSITIVITY STUDIES

The well-known PG&E 69-bus distribution system [1] is selected as the test system for implementation of the algorithm and sensitivity studies. The modified system's real power and reactive power of the loads are shown in Fig. 1. During normal operation of the system, without adding any distributed energy resources to the system, the annual energy losses of the system is 199.56 MWh. In order to have a sample test system, different types of DGs, including wind turbines, PV modules, and biomass generators, are allocated in the system. The optimum locations and rated capacities of different types of DGs are presented in Table I.

TABLE II
OPTIMUM DESIGNED MICROGRIDS

Microgrid	Buses in the Microgrid	Peak Loads (kVA)	Generation (kVA)
One	1,2,3,4,28,29,30,31,32, 33,34,35,36,37,38,39	427.0+j304.6	225.0+j41.1
Two	5,6,7,8,9,40,41,42,43,44	246.6+j178.9	125.0+24.7
Three	10,11,12,13,14, 15,55,56,57,58	426.0+j304	225.0+41.1
Four	16,17,18,19,20,21, 22,23,24,25,26,27	265.8+j171.1	125.0+24.6
Five	45,46,47,48,49, 50,51,52,53,54	391.9+280.4	200.0+41.1
Six	59,60,61,62,63,64, 65,66,67,68,69	185.6+129.0	100.0+24.6

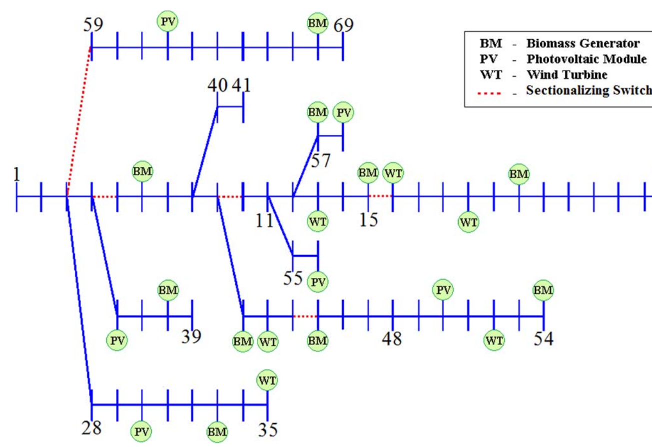

Fig. 2. 69-bus distribution system with DG locations.

The total rated capacities of wind turbines, PV modules, and biomass DGs are 250, 150, and 600 kW, respectively. It is assumed that the biomass DGs operate with 0.95 leading power factor. After adding the DGs to the system, the total annual energy losses reduced to 90.58 MWh. The system is then divided into six virtual microgrids with the objective of minimizing the real and reactive power imbalance in the microgrids according to [36] to provide a clustered system for better controllability and self-healing actions. The six microgrids, their total real and reactive loads, and the penetration level of DGs for each microgrid are presented in Table II.

The single-line diagram of the system with location of different types of DGs and the microgrids is also shown in Fig. 2. In the following, the DRSs are optimally allocated in the system, considering annual energy losses and the microgrids' success index as objective functions. The coefficients defined in the formulations may be different for different distribution systems depending on the economic conditions of the market. Based on the selection of the coefficients, the goal or objective function defined in this paper can represent real costs. A sample cost-based case study is given in Section VII.

A. Annual Energy Loss Objective Function Only

Here, only the annual energy loss objective function is considered for probabilistic optimal allocation of DRSs in the

TABLE III
DRSs, LOCATIONS, AND CAPACITIES FOR MINIMIZING ANNUAL ENERGY LOSSES

Total Capacity (kVAr)	DRS Buses	Rated Capacities (kVAr)	Annual Energy Losses (MWh)
100	3,24,53	25,25,50	78.93
150	3,18,24,51,52,53	25,25,25,25,25,25	72.43
200	4,17,23,50,53,54	25,50,25,50,25,25	66.88
250	3,17,19,21,50,52,53	25,50,25, 25,75,25,25	62.28
300	2,18,19,21, 50,51,53,57	25,50,25,25, 75,25,50,25	58.59
350	3,12,13,17,18, 24,50,52,53,58	25,25,25,25,50, 25,100,25,25,25	55.49
400	11,12,15,17,22, 27,50,51,52,53,57	25,50,25,50,25, 25,50,25,75,25,25	52.07
450	3,12,15,18,19,23,48, 50,51,53,54,55,57	25,50,25,50,25,25, 25,50,50,25,25,50,25	51.07

TABLE IV
DRSs, LOCATIONS, AND CAPACITIES FOR MAXIMIZING MICROGRID SUCCESS INDEX

Total Capacity (kVAr)	DRS Buses	Rated Capacities (kVAr)	Microgrid Success Index (%)
100	3,33,37,61	25,25,25,25	23.88
150	2,25,27,29,33,63	25,25,25,25,25,25	39.47
200	3,21,27,28,38,39,67	25,25,25,25,25,25,50	54.12
250	4,8,17,24,28,31, 38,42,59,61	25,25,25,25,25, 25,25,25,25,25	65.98
300	3,9,21,25,31,36,41, 46,51,53,63,69	25,25,25,25,25,25, 25,25,25,25,25,25	71.49
350	3,7,8,18,26,28,33,38, 44,45,48,53,63,65	25,25,25,25,25,25,25, 25,25,25,25,25,25,25	80.79
400	7,11,15,19,23,31,33, 35,39,43,47,51,62,67	25,50,25,25,25,25,25, 25,25,25,50,25,25,25	88.11
450	3,7,8,11,14,15,22,27, 28,31,38,43,47,51,54 ,58,63,64	25,25,25,25,25,25,25, 25,25,25,25,25,25,25, 25,25,25,25	94.90

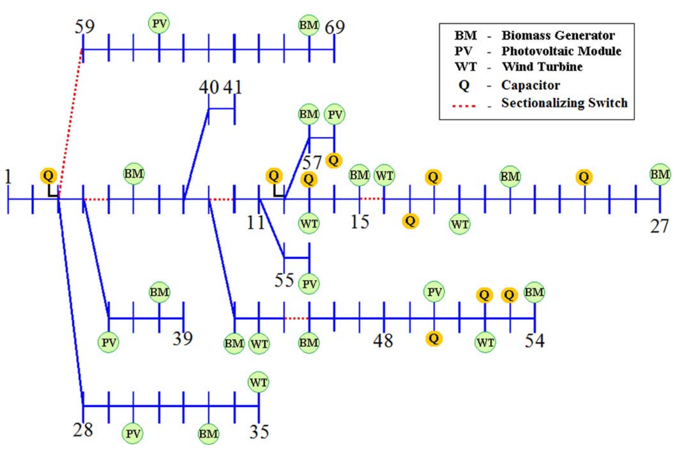

Fig. 3. DRSs' locations for annual energy losses objective function only.

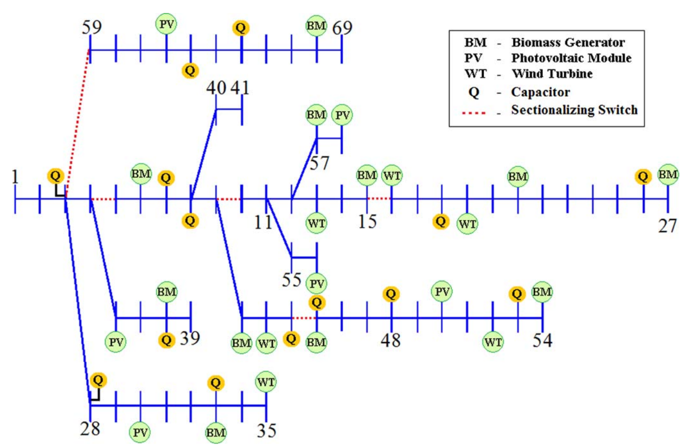

Fig. 4. DRSs' locations for microgrid success index objective function only.

system. In other words, $K_1 = 1$, and $K_2 = 0$. It is assumed that the predetermined total capacity of 100–450 kVAr in 25-kVAr steps is to be optimally allocated in the distribution system to minimize the annual energy losses. The optimization problem is solved for all the steps and the sizes of the DRSs, and their locations in the system are presented in Table III. Table III also shows the annual energy losses in the system when the DRSs are optimally allocated. It is shown that, by increasing the total size of DRSs from 100–450 kVAr, the annual energy losses decrease from 78.93 to 51.07 MWh. The locations of DRSs in the system for the case that the total size of DRSs is 350 kVAr, is shown in Fig. 3. By adding the DRSs to the system, for this case, the voltages of the buses improved from the range of [0.9651–1.0016] p.u. for all the states, over a year, to the range of [0.9931–1.0018] p.u.

B. Microgrid Success Index Objective Function Only

Here, only the microgrid success index is considered the objective function for probabilistic optimal allocation of DRSs in the distribution system. In other words, $K_1 = 0$, and $K_2 = 1$. As explained in Section III, this index shows the probability of having successful islands in terms of real power adequacy, reactive power adequacy, and voltage constraints. For this part, it is assumed that the predetermined total capacity of 100–450 kVAr is supposed to be optimally allocated in the distribution system to maximize the microgrid success index. Table IV shows the microgrid success index for the whole system as well when the DRSs are optimally allocated. It is seen that, by increasing the total size of DRSs from 100–450 kVAr, the microgrid success index increases from %23.88 to %94.9. The locations of DRSs in the system for the case that the total size of DRSs is 350 kVAr is shown in Fig. 4. By comparing Figs. 3 and 4, one can see that, in spite of the same amount of total size of DRSs, the locations are different for the two cases.

C. Considering Both Objective Functions

Both annual energy losses and microgrid success index are considered here. For this purpose, the total size of DRSs is assumed to be 350 kVAr, and then the objective function has been

TABLE V
DRSs, LOCATIONS, AND CAPACITIES FOR MINIMIZING ANNUAL ENERGY LOSSES AND MAXIMIZING MICROGRID SUCCESS INDEX

K_1	K_2	DRS Buses	Rated Capacities (kVAr)	Objective Function (%)
0	1	3,7,8,18,26,28,33, 38,44,45,48,53,63,65	25,25,25,25,25,25,25, 25,25,25,25,25,25,25	0.0
0.1	0.9	3,23,28,30,38,43, 44,50,53,60,68	25,50,25,25,25, 25,50,25,50,25,25	0.0225
0.3	0.7	3,11,13,15,20,23, 28,33,38,43,63,68	25,50,25,25,25,25, 25,25,25,50,25,25	0.1076
0.4	0.6	3,21,24,28,31,36,43, 44,49,50,51,63,68	25,25,25,25,25,25, 50,25,25,25,25,25,25	0.0927
0.5	0.5	3,8,10,13,18,23, 33,38,43,58,60,64	25,25,25,50,25,25, 25,50,25,25,25,25	0.1582
0.6	0.4	3,11,14,15,18,20,28, 37,39,42,43,61,68	25,25,25,50,25,25, 25,25,25,25,25,25,25	0.1761
0.7	0.3	3,7,23,34,38, 43,51,54,63,68	25,25,50,25,50, 25,75,25,25,25	0.1502
0.9	0.1	3,12,13,14,19,23,42, 43,47,50,52,53,57,60	25,25,25,25,25,25,25, 25,25,25,25,25,25,25	0.1495
1	0	3,12,13,17,18, 24,50,52,53,58	25,25,25,25,50, 25,100,25,25,25	0.0

TABLE VI
DRSs, LOCATIONS, AND CAPACITIES IN THE CASE OF VARIATION OF LOAD AND GENERATION LEVELS

Load (%)	DG (%)	DRS Buses	Rated Capacities (kVAr)	Objective Function (%)
90	100	3,7,8,16,25,28,30,32, 43,46,48,63,68	25,25,25,25,25,25,25, 25,25,50,25,25,25	0.0515
100	100	3,8,10,13,18,23,33,38, 43,58,60,64	25,25,25,50,25,25, 25,50,25,25,25,25	0.1582
110	100	3,9,18,28,36,38,44, 51,52,53,63,68	25,25,50,25,25,25, 25,25,25,50,25,25	0.3307
130	100	3,17,22,30,38,39,42, 48,50,51,53,60,63	25,25,25,25,25,25,50, 25,25,25,25,25,25	0.8864
150	100	3,18,24,27,37,38,39,41, 48,50,53,65,68	25,25,25,25,25,25,25, 25,25,25,50,25,25	0.7635
100	90	3,13,15,23,38,39, 40,44,53,54	25,25,50,50,25, 50,25,25,50,25	0.1640
100	110	3,8,18,19,28,37,42, 44,51,53,62,68	25,25,25,25,50,25, 25,25,50,25,25,25	0.1687
100	130	3,8,19,23,30,31,34, 38,43,44,62,67	25,50,50,25,25,25, 25,25,25,25,25,25	0.3096
100	150	3,7,19,22,23,28, 33,40,63,66,68	25,25,25,25,25,25, 75,50,25,25,25	0.5294

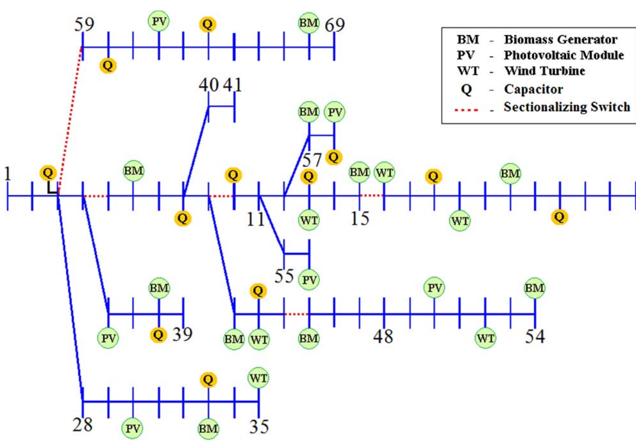

Fig. 5. DRSs' locations considering both objective functions.

moved slowly from considering the microgrid success index only to considering annual energy losses only as the objective function. This has been done by gradually increasing K_1 and decreasing K_2. In order to have more feasible values and have the right dimensions to add the two objective functions, the two of them are normalized using their optimum values from Tables III and IV. In other words, the objective function for this case is calculated as follows:

$$F = \left[K_1 \times \left|\frac{F_1 - F_{1_{\mathrm{Opt}}}}{F_{1_{\mathrm{Opt}}}}\right| + K_2 \times \left|\frac{(1-F_2) - (1-F_{2_{\mathrm{Opt}}})}{(1-F_{2_{\mathrm{Opt}}})}\right|\right] \times 100. \quad (16)$$

The results of probabilistic optimal allocation of DRSs in the system are presented in Table V. As shown in Table V, the optimum locations and sizes of DRSs vary for different values of K_1 and K_2. The locations of DRSs in the system for the case that the total size of DRSs is 350 kVAr is shown in Fig. 5. Again, it is shown that the location of DRSs for this case is different than the ones in Figs. 3 and 4. This also confirms that the traditional DRS placement problem should be revisited again with the new objectives of today's modern distribution systems.

VI. ROBUSTNESS OF DESIGN

The research presented in this paper is related to the planning stage, and the audience of this paper are utility planners. This section presents some sensitivity studies to investigate the robustness of design in terms of variation of system characteristics. For this purpose, the effects of variation of load and generation, and variation of reactive power of the existing DGs, as well as adding new DGs to the system, on the optimum locations and sizes of DRSs are presented in this section. For the sensitivity studies in this section, any case mentioned in Table V can be used. As a sample case, here, it is assumed that K_1 and K_2 are both equal to 0.5, to consider both annual energy losses and microgrid success index in the sensitivity studies.

A. Load and Generation Levels

The load level and penetration level of DG units in the system usually varies during a long-term operating period depending on several factors, such as economic, environmental, and weather conditions. This part examines the effect of long-term variations in the load and generation on the optimum DRS placement problem. For this purpose, it is assumed that the load rated power and generation rated power are changed from 90% to 150%, and the results are shown in Table VI. The sensitivity studies in this section show that, if for any reason the load or generation levels changes over a period for all or some of the system buses, the probabilistic optimally allocated DRSs is still close to optimum in terms of the defined objective function. It is clear that further increase in the load or penetration level of DGs will affect the optimum locations and sizes of DRSs. In

TABLE VII
DRSs, LOCATIONS, AND CAPACITIES IN THE CASE OF VARIATION OF DGs' POWER FACTORS

DG Types	Power Factor	DRS Buses	Rated Capacities (kVAr)	Objective Function (%)
W	+0.9	3,18,23,28,29,33, 38,43,59,64,68	25,50,25,25,25,25, 25,75,25,25,25	0.5297
W	+0.95	3,6,8,17,23,29,33, 39,43,60,65,68	25,25,25,25,50,25, 25,50,25,25,25,25	0.5805
W	-0.95	3,18,23,24,26,33,36, 38,39,54,62,68,69	25,25,25,25,25,25, 25,25,50,25,25,25,25	0.9741
S	+0.9	3,18,23,29,38,39, 42,43,63,64,68	25,50,25,25,50, 25,25,50,25,25,25	0.6767
S	+0.95	3,17,18,27,28,33,37, 38,49,50,52,54,63,66	25,25,25,25,25,25,25, 25,25,25,25,25,25,25	0.8924
S	-0.95	3,8,17,23,27,37,38, 39,42,63,64,68	25,25,25,25,25, 25,50,25,50,25,2	0.8699
B	+0.9	3,12,18,19,21,37,38, 43,44,48,50,53,61	25,25,25,25,25,25,25, 25,25,25,25,50,25	0.0239
B	+0.95	3,8,10,13,18,23,33, 38,43,58,60,64	25,25,25,50,25,25, 25,50,25,25,25,25	0.1582
B	-0.95	3,18,23,26,27,29,30,34, 36,39,50,53	25,50,25,25,25,25, 25,25,25,50,25,25	1.4496

TABLE VIII
DRSs, LOCATIONS, AND CAPACITIES IN THE CASE OF ADDING DGs TO RANDOM BUSES

DG (kW)	WSB	DRS Buses	Rated Capacities (kVAr)	Objective Function (%)
0	000	3,8,10,13,18,23,33, 38,43,58,60,64	25,25,25,50,25,25, 25,50,25,25,25,25	0.1582
50	101	3,8,9,21,23,28,38,43, 48,53,54,63,67	25,25,25,25,25,25,50, 25,25,25,25,25,25	0.1874
75	111	3,23,26,34,37,39,42, 43,44,50,53,62,67	25,25,25,25,25,25, 25,25,25,25,50,25,25	0.1766
125	212	3,9,18,20,38,39,44, 50,51,52,54,63,64	25,25,25,25,50,25, 25,25,25,25,25,25,25	0.2342
175	223	3,9,15,18,26,38,39, 44,58,62,66	25,25,50,25,25,50, 50,25,25,25,25	0.3673
225	324	3,8,18,27,37,38,39, 43,48,49,53,60,68	25,25,25,25,50,25, 25,25,25,25,25,25,25	0.3729
275	335	3,21,23,33,37,38, 43,44,60,62,65	25,25,25,50,25,50, 50,25,25,25,25	0.5113
300	435	3,8,21,24,28,32, 38,39,44,53	25,25,25,25,25, 25,25,25,50,100	0.5277

such cases, the optimum locations and sizes should be updated accordingly.

B. Variation of DGs' Power Factors

For the optimum DRS placement so far, it was assumed that only the biomass generators can generate reactive power with a 0.95 leading power factor. In this part, the effect of generating reactive power with different types of DGs on the optimum allocation of DRSs is investigated. For this purpose, several cases with different power factors for DGs are considered, and the problem of probabilistic optimal allocation of DRSs is solved for them.

The optimum locations and sizes of DRSs for all cases are shown in Table VII. In this Table, W, S, and B represent wind turbine generators, solar-based generators, and biomass generators, respectively. The positive sign stands for the leading power factor, and the negative sign is for lagging power factor. It is shown that the optimum results do not change significantly, which indicates that the optimally allocated DRSs are still optimum in terms of their locations and sizes.

C. Adding DGs to Random Buses of the System

During a long-term period, the total number of DGs may increase in the system based on utility and DG owners' decision. In this part of the paper, it is assumed that different types of DGs, including wind turbines, PV modules, and biomass generators, are randomly added to some of the system buses, and the optimum results are compared for the updated systems. The results related to this part are shown in Table VIII. In this table, the total penetration level of DGs is increased from 0 to 300 kW in 25-kW steps. The second column, WSB, represents the number of wind, solar, and biomass DG units added to some random buses of the system. For instance, WSB $= 324$ means three units of 25-kW wind turbines, two units of 25-kW PV modules, and four units of 25-kW biomass generators are added to nine $(3+2+4)$ random buses of the system.

The sensitivity studies in this section reveal that the optimum probabilistic DRS placement results are similar in all cases. This means that adding up to 300-kW new DGs to the system (%30 of existing DGs capacities) does not have significant impact on the optimum design. It should be noted that adding more DGs to the system may affect the optimum designed microgrids, and in such cases, the microgrids should be modified accordingly.

VII. Sample Case Study for Cost Analysis

In this section, the objective functions, including annual energy losses and microgrid success index, are modeled as real costs, and a case study is presented to determine the optimum total size of DRSs for the system under study. The price of energy losses is determined based on the price of electricity for each hour. In this paper, it is assumed that the price of energy losses for the peak load period is 0.12 $/kWh and for the light load period is 0.02 $/kWh [37], and it changes during the day with the same pattern presented in [37]. With this assumption, the cost of energy losses for a one-year period can be calculated. It is also assumed that the DGs are customer owned, and their operations' costs are paid by the customers and not the utilities.

The microgrid success index can be also modeled as real costs by modifications to represent the cost of interruptions in the system. Since F_2 is the success index, $1 - F_2$ is the failure index of the microgrid(s). Failure of microgrid(s) results in interruption, and the cost of interruption can be calculated based on the total hours of interruption [38]. The system average interruption duration index (SAIDI) for a set of microgrids can be calculated as explained in [39]; therefore, the objective function for this case can be easily represented as costs. Calculation of interruption duration for the microgrids can be calculated as outlined in [39]; therefore, the SAIDI for the system is estimated as 10 h/year. The 10 h/year is for the case without any DRSs, and for the other cases, this value has been adjusted

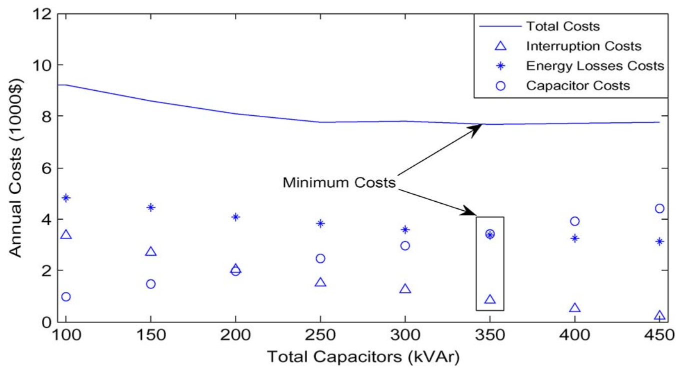

Fig. 6. Total costs and cost of interruption, energy losses, and capacitors.

using the microgrid success index values. Using the cost of interruptions and total hours of interruptions for a year, the microgrid failure index can be represented by real costs.

For the case study, the DRSs are assumed to be fixed capacitors. The cost of installation and maintenance of capacitors is also assumed to be 98 \$/kVAr with 10-year lifetime; therefore, the cost for one year will be 9.8 \$/kVAr. All the above calculated costs, including the sum of total costs, are shown in Fig. 6. As shown, the total costs reduces from 9769 to 7664.2 \$/year, and the minimum costs is for the case that the total size of capacitors is 350 kVAr. It should be noted that the cost is relatively small due to the small power ratings of the 69-bus system. For larger systems, significant cost, reliability, and technical performance enhancements can be obtained by optimum allocations of DRSs.

VIII. Conclusion

This paper has presented a systematic and optimized strategy for probabilistic optimal allocation of DRSs in microgrids. The problem is solved by using TS optimization algorithm considering two different objective functions. The first one is annual energy losses, and the second one is a newly defined index to evaluate the success of microgrids in terms of real and reactive power adequacy, as well as voltage constraints. Several sensitivity studies are performed to investigate the effect of considering each objective function on the optimum results. Sensitivity studies are also presented to investigate the robustness of the design during a long-term period. The sensitivities are performed under three different scenarios, which are variation of penetration level of DGs and loads, variation of DGs power factors, and adding new DGs to the system. The results show that the probabilistic optimum design is robust to variation of these parameters, Finally, a sample cost–benefit case study is presented.

The annual energy losses have been traditionally used for optimally allocating DRSs in the distribution system; however, through several case studies, this paper has shown that the DRS locations and sizes in the system have significant impact on the successful operation of microgrids. Therefore, this problem needs to be revisited for the current modern distribution systems that have intermittent DG units and can operate in islanded mode.

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