Optimum Microgrid Design for Enhancing Reliability and Supply-Security

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***Abstract*—Microgrids are known as clusters of distributed energy resources serving a group of distributed loads in grid-connected and isolated grid modes. Nowadays, the concept of microgrids has become a key subject in the smart grid area, demanding a systematic procedure for their optimal construction. According to the IEEE Std 1547.4, large distribution systems can be clustered into a number of microgrids to facilitate powerful control and operation infrastructure in future distribution systems. However, clustering large systems into a set of microgrids with high reliability and security is not reported in current literature. To fill-out this gap, this paper presents a systematic and optimized approach for designing microgrids taking into account system reliability- and supply-security-related aspects. The optimum design considers sustained and temporary faults, for system reliability via a combined probabilistic reliability index, and real and reactive power balance, for supply security. The loads are assumed to be variable and different distributed generation (DG) technologies are considered. Conceptual design, problem formulation and solution algorithms are presented in this paper. The well-known PG&E 69-bus distribution system is selected as the test system. The effect of optimization coefficients on the design and the robustness of the algorithm are investigated using sensitivity studies.**

***Index Terms*—Graph partitioning, microgrid, power imbalance, reliability, supply-security, tabu search.**

I. Introduction

THE STRUCTURE of power systems has been changed significantly resulting in new challenges for power systems' planners and operators [1]. Several objectives including system upgrade deferral, energy and power losses reduction and system reliability enhancements, have motivated utility companies for local connection of renewable energy resources and storage units at the distribution level. This can transfer the conventional distribution systems into multiple modern, interconnected distribution systems, so called *microgrids*. Microgrids are small distribution systems connecting a group of electricity consumers to a number of distributed generators and storage units, which in some cases, are interfaced by power electronic converters [2]. There are several papers in literature related to microgrids and their potential benefits for the utility and customers [3]–[6]; however, the concept of how to construct multiple interconnected microgrids and what factors are to be considered in their design have not been addressed properly.

Reliability of distribution systems has always been an important objective for the design and operation of power systems [7]. Recently, it has become even more important from both technical and economic point of views, especially for network operators because of the recent introduction of performance-based regulations in some countries [8]. In the smart grid environment or specifically in microgrid design, considering the reliability-related issues will also have several technical and economic benefits for utilities and customers. Several papers have discussed the reliability assessment and evaluation in a distribution system including distributed generations [8]–[11]; however, they have not been considered at the planning stage. In other words, reliability can be considered at the planning stage, as the number of components in a segment or a microgrid will affect the failure rate and average repair time per year for that microgrid; on the other hand, less number of components in a microgrid will result in larger number of microgrids and less generation or storage units per microgrid. This will also increase the average repair time per year for the microgrids. Therefore, the optimum microgrid infrastructure should be determined by solving an optimization problem.

Furthermore, designing microgrids for having optimum supply-security requires special attention to facilitate successful islanded operation and a powerful infrastructure for self-healing control under the smart grid environment [12]. The less the generation-load imbalance within the microgrids, the more self-sufficient and supply-secure the microgrids will be. Thus, more loads can be supplied in case of autonomous-mode of operation of microgrids in the distribution system and the energy losses on power lines connecting the microgrids will be minimized. Therefore, minimization of the power imbalance in microgrids is another important factor in construction of microgrids.

In this paper, a systematic approach is presented for optimal construction of microgrids considering the importance of both reliability and supply-security aspects. For this purpose, initially, a sample system is built up by optimum allocation of different kinds of distributed generation (DG), storage units and reactive power sources in a distribution system. A typical DG fuel-mix composed of wind turbines, photovoltaic (PV) modules and biomass generators as representatives of constant power dispatchable DGs, is considered. After the optimal

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allocation of energy resources, as a utility action, the system is divided into microgrids by optimizing only the reliability indices of the whole system. Then, the system is partitioned through optimizing only the supply security of microgrids; and finally both reliability and supply-security of the microgrids are considered for the system design. Such design approach will ensure that the whole system has optimum reliability indices and supply-security. Therefore, under fault conditions or operation in autonomous mode, more loads can be supplied through DG units in each microgrid. The proposed design is also aligned with the recently developed IEEE Std. 1547.4–2011, which presented the microgrid structure as the building blocks of active distribution systems [13].

The main contributions of this paper to the research field are related to the optimum design of reliable and supply-secure multi-microgrids-based distribution system that will benefit utilities, DG owners and electricity consumers. Such contributions can be summarized as follows:

- The development of a systematic strategy for constructing reliable microgrids considering temporary and sustained faults,
- The development of a systematic strategy for constructing supply-secure microgrids considering both real and reactive power self-sufficiency,
- Simultaneous consideration of reliability indices and real and reactive supply security for the construction of optimum microgrids,
- Taking into account the uncertainty in the characteristics of the DG units and loads for constructing a set of reliable and supply-secure microgrids.

Probabilistic load flow approaches, graph-related theories, and Tabu search optimization technique are used to conduct this research. The paper is organized as follows: Section II explains the motivations and design concepts; the generation and load models are explained in Section III and the problem is formulated in Section IV; Section V explains the solution algorithms and Section VI discusses implementation and sensitivity studies; in Section VII, the robustness of the design to variation of system parameters is investigated and lastly, the conclusions are drawn in Section VIII.

II. Motivations and Concepts of Design

This paper proposes a methodology for optimum design of multiple microgrids in a smart distribution system. The motivations for developing such design as well as reliability-related and supply-security-related aspects of the design are explained in this section.

A. Motivations for the Proposed Design

The problem defined in this paper is a planning problem; therefore, the audience and user of the proposed approach will be the utilities planners. It should be also noted that since the research in this paper is a long-term planning problem, therefore, system transients and dynamics which may occur in grid-connected or islanded microgrids are out of the scope of this paper. However, supply-adequacy is a necessary condition for stability of islanded microgrids; this condition can be ensured by the proposed planning approach. With the expected high penetration levels of distributed energy resources (DGs, storage and reactive sources) in future distribution systems, splitting the system into clusters of generation and load units, so called microgrids, will be beneficial for both customers and utilities from several aspects [13]. Therefore, using microgrids as building blocks for smart distribution systems is recently proposed in IEEE Std. 1547.4 [13]. From the communication and control point of view, other than the improvements in reliability and latency of the communication network, in a decentralized approach, the system can be operated more conveniently when clustered into a set of microgrids [14]. Construction of microgrids will also improve the efficiency of the automatic fault location detection techniques used in distribution systems. This will improve the self-healing control actions [15]. Finally, from self-healing point of view, as each microgrid is designed with maximum supply security, minimum number of actions will be required to achieve the self-healing capability of distribution networks and the disconnected microgrids can operate in autonomous mode with less amount of load shedding.

Reliability and supply-security related aspects will be explained in more details in the following sub-sections.

B. Reliability-Related Aspects

Microgrids in a distribution system are usually modeled as segments in terms of reliability. From the reliability point of view, this means that the whole system is modeled as segments or microgrids and not components [16]. The number of components in a segment or a microgrid affects the failure rate and average repair time per year for that microgrid. On the other hand, less number of components in a microgrid will result in a larger number of microgrids and less generation or storage units per microgrid. This will also increase the average repair time per year for the microgrids. Therefore, the optimum microgrid infrastructure should be determined by solving an optimization problem.

By using the proposed design in this research, the constructed microgrids and subsequently the whole distribution system will have optimized reliability indices. Usually, utilities use standard indices to evaluate distribution system reliability. These indices include SAIFI and SAIDI which are system average interruption frequency index and system average interruption duration index, respectively [17]. As the temporary faults are getting more important, in recent years, the MAIFIe index which measures the number of momentary interruptions per customer has also been used by utilities to evaluate the reliability of the system [16]. In order to consider the importance of both sustained and temporary faults, all the reliability indices, SAIFI, SAIDI, and MAIFIe are used, via a combined reliability index, for designing the proposed optimum microgrids. Other reliability indices could also be considered in a similar approach.

C. Supply -Security-Related Aspects

In response to disturbances, a self-healing system reconfiguration that splits a power network into self-sufficient and supply-secure microgrids can stop the propagation of disturbances and avoid cascading events. Thus, an optimum microgrid design is the one with maximum supply security. When the microgrids

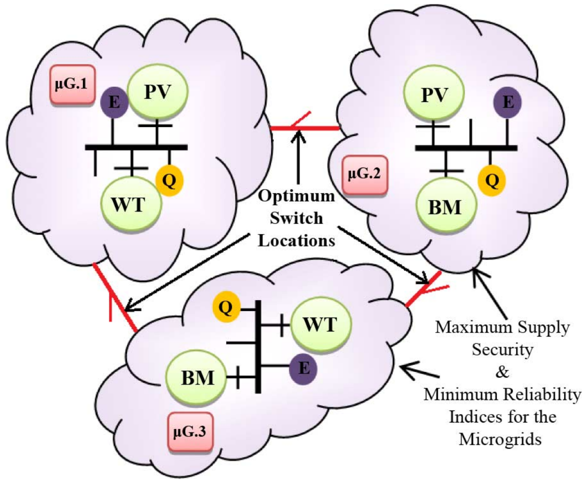

Fig. 1. Main design concepts and the virtual microgrids.

are constructed in a distribution system with maximum supply-security, more loads can be supplied in case of autonomous-mode operation and also the energy losses on power lines connecting the microgrids will be minimized. Traditionally, only the real power has been considered in system partitioning [18]. However, by considering the reactive power in supporting the voltage profile, both real and reactive power balance can be considered in designing the microgrids [19].

In such design, each microgrid may operate in grid-connected or islanded mode, with minimum interactions from other parts of the system. A sample distribution system with three constructed microgrids is shown in Fig. 1. With the proposed design in this research, the constructed microgrids will not only be reliable but also they will have secure supply in case of islanding and separation from the main substation.

III. Modeling of Loads and Distributed Resources

Proper modeling of DGs and loads is essential to develop optimum microgrids design in a distribution system. For this purpose, models of a combination of three typical DG technologies are considered in this study, including PV modules, wind turbines and biomass generators. PV and wind renewable 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 (PDF), respectively, by using historical data [12]. To develop the PDFs for a selected period of one year, four days are selected as representatives of the four seasons of the year. The day representing each season is further divided into 24-hour time segments, each having a probability density function for solar irradiance and wind speed. The load is also modeled as an hourly shape load using IEEE-RTS [20]. In order to integrate the output power of PV modules and wind turbines as multi-state variables in the formulations, the continuous PDF of each is divided into different states. The selected number of states affects the accuracy and complexity of the formulation. In this research, the output power of the wind turbine and PV modules for each hour of the day is divided into twelve segments with different probabilities. Assuming that solar irradiance and wind speed states are independent, the probability of any combination of the load and generation is obtained by convolving the two probabilities. Therefore for each hour one has $144(12 \times 12)$ states with different probabilities and for each day there are $3456(24 \times 144)$ states and for each year, $1\,261\,440(365 \times 3456)$ states including different time periods (day and night), with different penetration level of DGs. In order to calculate the supply security of microgrids as well as the probability of having successful microgrids to calculate reliability indices, each state is assessed separately and the results are accumulated considering the probability of each state. Further details on modeling different DG types, storage units and reactive sources are explained in [12].

IV. Problem Formulation

The objective function which includes maximization of reliability and supply security of constructed microgrids, are formulated in this section.

A. Reliability Index Calculations

As explained in Section II, three typical reliability indices are used in this study, namely SAIFI, SAIDI, and MAIFIe. These indices are calculated for a distribution system using annual failure rate (λ_i), annual outage duration (U_i) and momentary failure rate (λ_{mi}), respectively, at each load point as follows:

$$SAIFI = \frac{\sum_{i=1}^{NoL} N_{Li} \times \lambda_i}{\sum_{i=1}^{NoL} N_{Li}} \tag{1}$$

$$SAIDI = \frac{\sum_{i=1}^{NoL} N_{Li} \times U_i}{\sum_{i=1}^{NoL} N_{Li}} \tag{2}$$

$$MAIFIe = \frac{\sum_{i=1}^{NoL} N_{Li} \times \lambda_{mi}}{\sum_{i=1}^{NoL} N_{Li}} \tag{3}$$

where NoL is the number of load points, N_{Li} is the number of customers connected to load point i, λ_i is the annual failure rate of the i^{th} load point, U_i is the annual outage duration of the i^{th} load point and λ_{mi} is the momentary failure rate of the i^{th} load point. These indices can be used in the same format for a distribution system without any distributed generation; however, for a distribution system including several microgrids with distributed energy resources, the two indices, SAIFI and SAIDI should be recalculated. For assessment of reliability indices, each microgrid is considered as a segment including a group of components and the whole distribution system is modeled as segments or microgrids. If there is a fault in a microgrid, the microgrid and all its loads will be disconnected. This fault will cause service interruption for the downstream microgrids unless there is enough distributed generation in the downstream microgrids to support the loads for the duration of service interruption. In such case, if the output power of the generators within the microgrid is sufficient to supply the local microgrid's loads, the number and duration of interruptions for that microgrid will decrease. Thus, both SAIFI and SAIDI will be lower for that microgrid comparing to the base-case without any DGs. Therefore, for reliability-based clustering, the SAIFI and SAIDI for each microgrid in a smart distribution grid can be calculated as shown in (4) and (5),

$$SAIFI_{\mu G} = SAIFI_{\mu G}|_{self} + (1 - P_{\mu G}) \times \sum SAIFI_{\mu G_{Upstream}} \quad (4)$$

$$SAIDI_{\mu G} = SAIDI_{\mu G}|_{self} + (1 - P_{\mu G}) \times \sum SAIDI_{\mu G_{Upstream}} \quad (5)$$

where the subscript *"self"* shows the index for that microgrid without considering other parts of the system; P_{uG} is the probability that shows the percentage of times in a year that the generation in a microgrid exceeds the loads in that microgrid and is calculated by accumulating the probability of each state having more generation than loads over a one year period in a microgrid. As two extreme cases, if P_{uG} is zero which means the generation never exceeds the loads in the microgrid, then the index calculated for the microgrid is the summation of the index for the microgrid and all upstream ones. If P_{uG} is one which means that all the times, the generation level is higher than the load in the microgrid, the indices of upstream microgrids do not have any effect on the reliability of that microgrid. It is clear that for using (4) and (5) to calculate the reliability indices for a microgrid, the calculations should be started from the upstream microgrids and be initiated from the ones connected to the main feeder. After calculating the reliability indices for each microgrid, the reliability indices of the whole system can be calculated as weighted summation of the indices based on the number of customers in each microgrid as shown in (6).

$$R_{index} = \frac{\sum_{i=1}^{NoM} N_{Li} \times R_{index_{\mu G}}}{\sum_{i=1}^{NoL} N_{Li}} \quad (6)$$

where R_{index} can be replaced by SAIFI, SAIDI, or MAIFIe. The three indices or objective functions can be minimized individually or as a weighted summation single objective function to consider both sustained and momentary indices. Since these indices may have different values, the weighted summation of the indices should be normalized using the target or the optimum value for each index as shown in (7). The optimum value for each index is the optimum result when the objective function includes that index only.

$$F_1 = W_1 \times \frac{SAIFI - SAIFI_{Opt}}{SAIFI_{Opt}} + W_2 \times \frac{SAIDI - SAIDI_{Opt}}{SAIDI_{Opt}} + W_3 \times \frac{MAIFIe - MAIFIe_{Opt}}{MAIFIe_{Opt}}. \quad (7)$$

The above formulations are related to a specific system with allocated switches and designed microgrid structure. However, as changes in the switches' locations in the system changes the components in the microgrids only, the reliability indices for the new design can be calculated in a similar approach. It should also be noted that in this paper, it is assumed that the locations of DGs are fixed in the system and the switches are allocated to optimize the system's reliability and supply security indices. If the DGs locations vary for any reason, then the problem should be formulated and solved considering the new DG configuration and the reliability indices can be calculated similarly. The effects of considering each index as the objective function, on the constructed microgrids, are presented in Section VI.

B. Supply-Security Index Calculations

The supply-security of the constructed microgrids is examined by defining a probabilistic adequacy index. When the microgrids are created in a distribution system with maximum supply-security, more loads can be supplied in case of autonomous-mode operation. In order to test the adequacy of both real power and reactive power in the system, the objective function is defined as shown in (8). Selection of K_{2p} and K_{2q} will define the real power supply-security, reactive power supply-security or the combination of both, as the objective function, and depends on the system requirement for balancing the load-generation in the microgrids. Traditionally, only the active power has been considered in system partitioning which means $K_{2p} = 1$ and $K_{2q} = 0$. However, by considering the reactive power as an important role player in supporting the voltage profile and knowing that a significant mismatch of reactive power supply and demand causes high or low voltage conditions within microgrids, both real and reactive power balance should be considered in system partitioning [12]. In other words, for the microgrids without any reactive power compensators in the system, the coefficients should be set equally as 0.5 each.

Since there are several probabilistic generation and variable loads in the system, the multi-state generation-load model is used for calculation of indices in the microgrids. For each generation-load state, the index is calculated by subtracting the load level and losses from the generation at that state. The real and reactive power losses in the microgrid are assumed to be 5% of the real and reactive load at each state [21]. The supply-security index for microgrid i is defined as an accumulated index considering the probability of each generation-load state. Finally the supply-security index for the whole system is defined by the summation of the real and reactive power supply security indices for the constructed microgrids and shown in (8).

$$\begin{aligned} F_2 &= K_{2p} \times F_{2P} + K_{2q} \times F_{2Q} \\ &= K_{2p} \times \sum_{i=1}^{NoM} \sum_{j=1}^{N} \sum_{k=1}^{nbus_i} \Big| P_{G_{i,j,k}} - P_{L_{i,j,k}}(1 + 0.05) \Big|^2 \times \rho_i \\ &\quad + K_{2q} \times \sum_{i=1}^{NoM} \sum_{j=1}^{N} \sum_{k=1}^{nbus_i} \Big| Q_{G_{i,j,k}} - Q_{L_{i,j,k}}(1 + 0.05) \Big|^2 \times \rho_i \end{aligned} \quad (8)$$

where N is the number of generation-load states, NoM is the number of microgrids, $nbus_i$ is the number of buses in microgrid i, $P_{Gi,j,k}$, $P_{Li,j,k}$, $Q_{Gi,j,k}$ and $Q_{Li,j,k}$ are the real and reactive generated power and the load in state j, microgrid i and at bus k. Selection of K_{2p} and K_{2q} affects the constructed microgrids as will be shown in Section VI.

C. Combined Objective Function

Both reliability and supply-security indices can be considered for the construction of microgrids. For this purpose, the two objective functions are combined by weighting coefficients to form a single objective optimization problem as shown in (9).

$$Min\,(F)\,,\quad F = K_1F_1 + K_2F_2. \tag{9}$$

Selection of K_1 and K_2 will determine the target of the objective function and whether it is the system reliability, supply-security, or a combination of both. K_1 and K_2 can also be selected so that the objective function represents the total costs. For this purpose, K_1 can represent the cost of interruption (low reliability) in the system and K_2 can represent the costs related to lack of supply security for the loads in the microgrids. In case of importance of both F_1 and F_2, they can be set as 0.5 each; however, in order to have more realistic and cost beneficial design, the coefficients should be set by performing cost-benefit analysis for the systems' reliability and supply-security, which is out of the scope of this paper.

Since the optimum values of the two objective functions are different, they are normalized in (9) with the same approach presented in (7).

D. Optimization Constraints

Two important constraints should be satisfied to guarantee the security of supply for the constructed microgrids. They are the voltage magnitude limits on all system buses as well as maximum line currents which are formulated as follows.

- Voltage limits at all the system buses,

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

- Power line current limits,

$$I_i \le I_{\max,i} \quad \forall i. \tag{11}$$

The optimum microgrid design should satisfy these conditions in islanded mode of operation. In the next sections, the algorithms used to solve the proposed optimization problem are explained.

V. Solution Algorithms

The formulated problem in Section IV is a comprehensive problem with combinatorial nature that demands efficient solution algorithms. The problem has two different objective functions which are aggregated into a single objective function, by using pre-determined weighting coefficients, K_1 and K_2. Heuristic optimization techniques are well-suited for such optimization problems. Several heuristic optimization techniques have been proposed in literature for graph partitioning which cope with the combinatorial nature of the presented problem [22], [23]. In this paper, three different algorithms are used at different stages, including Tabu Search (TS), as the main optimization method; graph-theory-related techniques; and probabilistic power-flow methods. Since the main contribution of the paper is the new problem formulation that combines reliability and supply-security aspects and since the proposed mixed algorithms proposed in this paper is effective and sufficient for solving the defined problem, other optimization methods are not considered in this research.

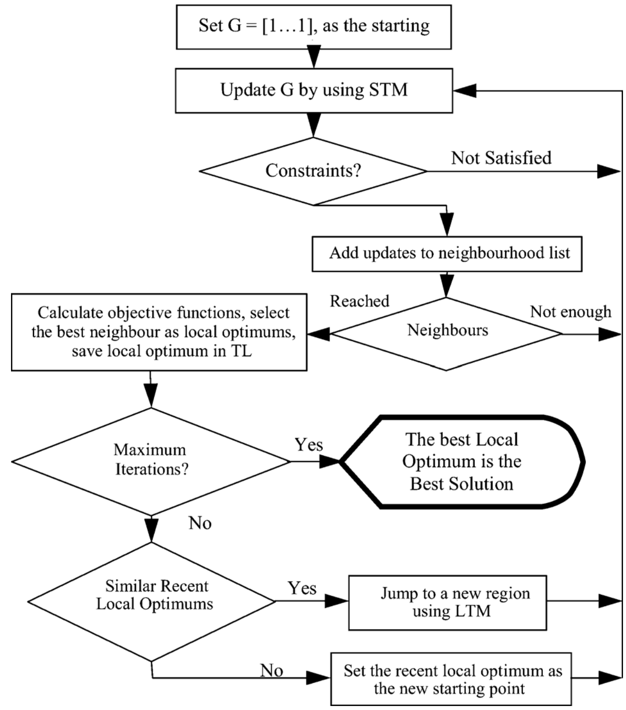

Fig. 2. Flowchart of the algorithms used for the design.

The flowchart of the algorithms is shown in Fig. 2. The optimization process starts by finding a feasible solution (G) and continues until certain criterion, which is usually the maximum iteration numbers, is reached. A feasible solution is an infrastructure constructed through virtually cutting some power lines in the network. The vector G which can be considered as control variable for each system can be represented as follows:

$$\mathrm{G} = [1 \quad 0 \quad 1 \quad 1 \quad 0\ldots1 \quad 0 \quad 1 \quad 1] \tag{12}$$

where the length of the vector is equal to the number of power lines which can be considered as cutting edges to construct the microgrids. Each component of the G vector represents one physical line in the system. The number "1" and "0" for each component of the G vector represents an inside or between microgrids line, respectively.

The next step is to make a set of neighbors for the starting point. A neighbor can be defined in several ways; each neighbor was selected by changing some components (e.g., 3 components) of the G from "0" to "1" or vice versa and checking the feasibility of the resulted infrastructure. To check the feasibility of the solutions, graph-related algorithms are implemented. These algorithms will check whether or not all the system buses are considered in different microgrids and if all the buses located in each microgrid are connected together as a tree. In order to answer these two questions, the shortest path algorithm can be used. The shortest path algorithm finds a path between two vertices (buses) in the system such that the sum of weights

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of its constituent edges is minimized [24]. The impedance of each branch is used as the weight of edges in this research and the undirected graph is generated from the distribution system topology. In order to check the connection between buses in each microgrid, the distance from every system bus to all system buses is checked for each suggested microgrid design. If for a specific bus there is at least one path to another bus of the system, then we can conclude that this specific bus is considered in a microgrid. If the same criterion applies for all system buses and there were no unconnected buses, then all the system buses are considered in different microgrids and also they are connected in each microgrid as a tree and the two conditions are satisfied. The next step is to calculate the objective function for all neighborhoods, set the best neighbor as the new starting point and then continue the process.

The objective function includes two parts F_1 and F_2. F_1 is determined as a weighted summation of normalized SAIFI, SAIDI, and MAIFIe which are determined in a probabilistic manner for a microgrid as explained in Section IV. F_2 is related to the real and reactive power supply-security. For every microgrid design infrastructure, all load-generation states are checked and the objective function is calculated by probabilistic accumulation of adequacy indices for each state. After calculating the objective function for all the points in the neighborhood, the best neighbor will be set as the new starting point and the algorithm continues. To avoid stopping at a local optimum, and to prevent cycling around it, the Tabu List (TL) is introduced which prevents visiting the best solutions that have been visited in previous moves. To construct the TL from the best recently visited solutions, a unique quantity for each vector G is used which is calculated in (13).

$$\sum_{i=1}^{n} G(i) \times 2^i. \quad (13)$$

The TS algorithm uses different memory structures to avoid random search, namely they are the short-term memory (STM) and the long-term memory (LTM) structures. The STM memorizes the common features of sub-optimal solutions for a number of iterations and tries to search for the solutions with similar features in that region. The LTM diversifies the search by jumping to new regions to find the global optimum. This long-term memory will keep track of the common features of all initial starting points in different regions to avoid restarting from similar previously used starting points. The two types of memories have been implemented by using two different vectors with the same length as G. In the next sections, the proposed algorithm is applied to a 69-bus distribution system.

VI. Implementation and Sensitivity Studies

The well-known PG&E 69-bus distribution system [25] is selected as the test system for the implementation of the algorithm and conducting the sensitivity studies. The modified system's real and reactive powers of the loads are shown in Fig. 3. In order to have a sample test system with DG units, distributed energy storage resources (DESRs) as well as distributed reactive sources (DRSs), are allocated in the system. The total rated capacities of DG units are 250 kW, 150 kW, and 600 kW, for

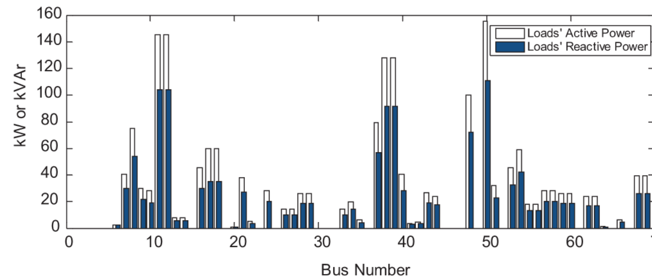

Fig. 3. The 69-bus distribution system's loads.

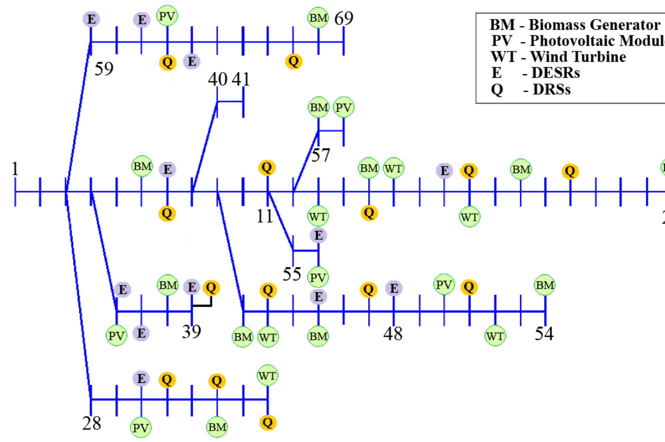

Fig. 4. The 69-bus distribution system with DGs' locations.

wind turbines, PV modules, and biomass DGs, respectively. The locations and rated capacities of different types of distributed generators are presented in Table I. The DESRs and DRSs with the total rated capacities of 450 kW and 400 kVAr are also installed in the system. The location and rated capacities of these resources are shown in Table II. It is clear that for a real distribution system with already interconnected resources, these steps will be neglected. The single-line diagram of the system with the optimum locations of DGs, DESRs, and DRSs is shown in Fig. 4. In the next sub-sections, the optimum microgrids are designed for this system considering reliability and supply-security as objective functions. The coefficients defined in the formulations may vary for different distribution systems depending on the economic conditions of the market. Depending on the selection of the coefficients, the goal or objective function defined in the paper can represent real costs.

A. Reliability-Related Objective Function Only

In this formulation, only the reliability-related objective function is considered, i.e., $K_1 = 1$ and $K_2 = 0$.

The reliability data of system components can be found in [26]. The reliability indices are SAIFI, SAIDI, and MAIFIe, as defined in Section IV. In order to gauge the effect of considering each reliability index as the objective function, on the optimum design, several cases have been considered by combining these indices. Table III shows the optimum switch locations for constructing the microgrids as well as the reliability indices of the microgrid infrastructure. In this table, the cut-set line j is the line between bus j and $j+1$, line *jei* is the i^{th} branch starting from bus j. The NoZ is the number of zones or constructed microgrids. It is observed that the constructed microgrids are

TABLE I
OPTIMUM DG LOCATIONS

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

TABLE II
OPTIMUM SELECTED BUSES FOR INSTALLING DESRS AND DRSS

Energy Resource type	Locations in the System (Buses)	Rated Capacities (kW-kVAr)
DESRs	7,18,30,36,37,39, 45,48,56,59,61,63	25,25,25,50,25,50,25, 25,25,75,50,50
DRSs	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

TABLE III
OPTIMUM MICROGRIDS- RELIABILITY-RELATED ASPECTS

W_1	W_2	W_3	Optimum Switch Locations	SAIFI	SAIDI	MAIFIe	GOAL
0	0	1	7,14,29,9e1,59	0.428	18.68	0.277	0.277
0	1	0	6,13,30,9e1,60	0.443	17.56	0.365	17.56
0	1	1	7,13,30,43,59	0.472	17.73	0.319	0.161
1	0	0	8,18,28,42,59	0.287	24.86	0.486	0.287
1	0	1	8,12,28,48,60	0.409	25.48	0.413	0.916
1	1	0	6,13,30,9e1,60	0.343	17.57	0.455	0.196
1	1	1	8,18,28,42,60	0.437	19.82	0.381	1.027

different based on the considered reliability indices in the objective function. In this table, the objective functions for the cases that consider SAIFI, SAIDI, or MAIFIe only are in failure/year, hour/year, and (momentary failure)/year, respectively. For the cases with the combined indices, the objective function is normalized as explained in Section IV.

B. Supply-Security-Related Objective Function Only

In this formulation, the supply-security-related objective function is only considered, i.e., $K_1 = 0$ and $K_2 = 1$. The objective function for optimizing the supply-security, defined in (8), depends on the two coefficients K_{2p} and K_{2q}. In this subsection, three case studies are presented to gauge the effects of these coefficients on the optimum constructed microgrids. The results of sensitivity studies are shown in Table IV. In this table, the goal, corresponds to the results presented in the first line, is to minimize the reactive power imbalance in the microgrids only and the dimension of objective function is kVAr while the goal, corresponds to the results presented in the last line, is to minimize the active power imbalance in the microgrids only and the dimension of objective function is kW. For the middle row of the table, the objective function is a combination of real and reactive power imbalance in kVA. As can be seen in Table IV, the constructed microgrids are different based on the selection of real or reactive power generation-load imbalance as the objective function.

TABLE IV
OPTIMUM MICROGRIDS-SUPPLY-SECURITY-RELATED ASPECTS

K_{2p}	K_{2q}	Optimum Switch Locations	F_{2p}	F_{2q}	GOAL (kVA)
0	1	4,10,15,49,3e1	32.40	18.74	18.74
0.5	0.5	6,10,15,48,3e1	31.90	18.90	25.4
1	0	6,10,15,44,3e1	30.90	19.23	30.90

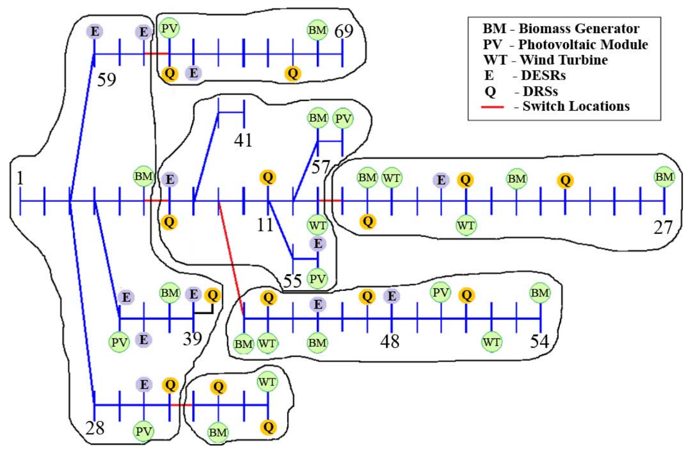

Fig. 5. Optimum switch locations for 69-bus system.

TABLE V
OPTIMUM MICROGRIDS-COMBINATION OF OBJECTIVES

K_1	K_2	Switch Locations	F_{2p}	F_{2q}	SAIFI	SAIDI	MAIFIe	Goal
0	1	6,10,15,44,3e1	31.90	18.90	0.87	45.88	0.73	2.44
0.1	0.9	6,9,15,44,3e1	32.24	19.27	0.87	45.81	0.74	2.56
0.3	0.7	8,15,3e1,44,59	45.23	27.12	0.51	26.41	0.50	1.25
0.5	0.5	6,13,30,9e1,61	51.01	29.83	0.48	24.86	0.49	1.08
0.7	0.3	8,18,28,42,59	56.10	34.36	0.46	22.73	0.45	0.74
0.9	0.1	7,15,30,9e1,59	58.31	32.27	0.45	20.12	0.42	0.29
1	0	8,18,28,42,60	58.64	35.74	0.43	19.82	0.38	1.027

C. Considering Both Objective Functions

Both reliability and supply-security-related objective functions are considered in this formulation. For this purpose, the algorithm is applied under different circumstances with different optimization coefficients and the optimum microgrids infrastructure is developed as presented in Table V. For the sensitivity studies, it is assumed that K_{2p} and K_{2q} are equal to 0.5 and W_1, W_2, and W_3 are all equal to one. By changing K_1 and K_2, the total objective function changes based on the importance of each of the objectives. It is seen that by increasing K_1 and decreasing K_2, the supply-security-related objective function increases and the reliability indices decrease. Table V shows that depending on the importance of reliability-related or supply-security-related aspects, the optimum microgrid infrastructure will vary. In this table, the goal of the objective function also varies with the variation of the K_1 and K_2 values. The optimum system infrastructure for the case where K_1 and K_2 are 0.5 and 0.5, respectively, is shown in Fig. 5. The optimum infrastructure in this case, divides the system into 6 microgrids, each having the optimum reliability and supply-security indices.

TABLE VI
OPTIMUM MICROGRIDS—VARIATION OF LOAD AND GENERATION

Load(%)	DG(%)	Optimum Switch Locations	NoZ	Goal
90	100	8,15,3e1,44,59	6	1.35
100	100	6,13,30,9e1,61	6	1.08
110	100	4,10,15,44,3e2	6	1.23
130	100	4,10,15,44,3e2	6	2.01
150	100	5,10,15,44,3e2	6	1.97
100	90	4,10,15,44,3e2	6	1.49
100	110	8,15, 3e1,44,59	6	1.62
100	130	4,10,15,44, 3e2	6	1.72
100	150	7,15,30, 9e1,59	6	1.17

VII. ROBUSTNESS OF THE DESIGN

The research presented in this paper targets the planning stage which is of great importance to utility engineers. From the utility point of view, a microgrid infrastructure or any other long-term plan will be acceptable if it is optimal or near optimal, in case of variation of system conditions, for the designated long-term period.

Among the important characteristics of a distribution system are variation of loads, penetration level of DGs and adding new DGs to random buses of the system. How these changes will affect the optimum infrastructure and whether the planned microgrids infrastructure is still optimum or near optimum design are investigated in this section. For this purpose, several case studies are presented; firstly the effect of changing the loads and generation levels and then the effect of adding DGs to random buses are investigated. For the sensitivity studies in this section, it is assumed that both K_{2p} and K_{2q} are equal to 0.5, to consider both real and reactive power security supplies; each of W_1, W_2, and W_3 is equal to one, to consider all reliability indices. Finally, both K_1 and K_2 are considered to be equal to 0.5 in order to consider both reliability and supply-security objectives.

A. Load and Generation Levels

The load level or consumers of electric power in the system usually increases over a long period of time. The penetration level of DG units in the system also varies during a long term operating period depending on several factors, such as economic, environmental, and weather conditions. This subsection examines the effect of long-term variations in the load and generation levels on the optimum design.

For this purpose, it is assumed that the load and generation rated powers are changed from 90% to 150% for all system buses and the results are shown in Table VI. The sensitivity studies in this section show a little difference in the optimum designed microgrids in each case; in all cases, the number of microgrids and majority of virtual cut-sets are similar. This means that if for any reason the load or generation levels changed over a period of time for all or some of the system buses, the designed microgrids is still valid and close to optimum in terms of reliability and supply-security. It is clear that further increase in the load or penetration level of DGs will affect the optimum design. In such cases, the optimum designed microgrids should be updated accordingly.

TABLE VII
OPTIMUM MICROGRIDS—ADDING DGS TO RANDOM BUSES

DG(kW)	WSB	Optimum Switch Locations	NoZ	Goal
0	000	6,13,30,9e1,61	6	1.08
50	101	7,13,30,42,59	6	2.77
75	111	8,15,3e1,44,59	6	3.08
125	212	6,13,30,9e1,60	6	1.82
175	223	7,14,29,9e1,59	6	2.22
225	324	8,15,3e1,44,59	6	2.86
275	335	7,14,29,9e1,59	6	2.12
300	435	7,14,29,9e1,59	6	3.12

B. Adding DGs to Random Buses of the System

During a long-term period, the total number of distributed generators may increase in the system based on utilities' or DG owners' decision. In this subsection, it is assumed that different types of distributed generators including wind turbines, PV modules and biomass generators are randomly added to some of the system buses and the optimum microgrid infrastructure is designed and compared to the updated systems. The results are shown in Table VII. In this table, the total penetration level of DGs is increased from zero to 300 kW. The second column, WSB, represents the number of wind, solar and biomass DG units added to random buses of the system. For instance, "$\text{WSB} = 324$" means three units of 25 kW wind turbines, two units of 25 kW PV module 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 subsection reveal that the optimum designed microgrids 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 microgrid 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.

VIII. CONCLUSIONS

This paper presented a systematic and optimized strategy for designing microgrids in a distribution system. The new design takes into account both reliability and supply-security objectives as a weighted summation in the objective function. In the designed optimum infrastructure, the constructed microgrids have optimum reliability indices, whereas at the same time have optimum supply-security. Three probabilistic indices are defined to measure the reliability of the microgrids and two probabilistic indices are defined to measure their supply-security; which can be combined as one index. Several sensitivity studies are conducted on the modified PG&E 69-bus distribution system to evaluate the effects of weighting coefficients on the final constructed microgrids. The sensitivity studies show that the optimally designed microgrids depend on the weighting coefficients, which vary from one case to another for different system parameters. The robustness of the design to the variation of loads and DG penetration levels and adding new DGs to the system is also investigated. The results show that the final design is not very sensitive to the DG and load level as well as adding new DGs to the system. The proposed strategy for designing reliable and supply-secure microgrids in a distribution system is a step towards having a more reliable and cost efficient smart distribution network.

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