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Service Restoration Through Microgrid Formation in Distribution Networks: A Review

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ABSTRACT Microgrid formation is a promising solution to enhance resiliency of distribution networks. The self-adequacy feature of a microgrid enables continuity of power supply through distributed generation (DG) units during severe faults and natural disasters. In this paper, different methods commonly used to partition a distribution network into multiple microgrids are presented, including the graph theory, heuristic rule-based algorithm, cluster-based technique, and mixed integer programming. Advantages and disadvantages of these techniques and future research directions are presented. This review provides an excellent summary on service restoration through micrgrid formation, and offers a valuable reference for researchers working on grid modernization of distribution networks.

INDEX TERMS Distribution networks, microgrid formation, resiliency, reliability, service restoration.

I. INTRODUCTION

The resiliency improvement of power systems against extreme events is an essential aspect of the system design and operation [1], [2]. Extreme events can be either natural disasters or cyber-attacks, which not only affect the continuity of electrical service for a considerable number of consumers, but may also cause significant financial losses. For example, more than 50,000 electricity customers were knocked out of service due to weather disasters in the United States [1], and over \$1 billion financial losses were caused by eight weather disasters (i.e., flooding, storms, and hurricanes) during the first half of 2016. In August 2017, the hurricane Harvey caused a total of \$180 billion losses, and many towns were left without power for several weeks [3]. Other extreme weather events are shown in Table 1, which have caused catastrophic damages to power systems, resulting in massive power outages [1], [4]–[6]. These blackouts within bulk power networks across the globe indicate vulnerability of power systems, and their resiliency improvement is a fundamental task for power system operators.

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TABLE 1. **Major blackouts across the globe.**

Country	Date	Reference
Australia	2016	[40]
Ukraine	2015	[41]
India	2012	[42]
US	2012	[1]
China	2008	[43]

Resiliency is defined as the power grid's capability to withstand and recover quickly from severe incidents, react properly to changing conditions, and prevent future events [2]. Fig. 1 illustrates the performance of a resilient system and a conventional system under extreme events [4].

The power supply of the system is P_0 at time t_1 when a severe incidence happens. At time t_2, the power supply of the system quickly decreases to its minimum amount (P_{min-R} for a resilient system and P_{min-C} for a conventional system). The restoration is started for resilient and conventional systems at time t_3 and t_4, respectively. The normal power supply P_0 is resumed for resilient and conventional systems at time t_5 and t_6, respectively. Therefore, a resilient system equipped with resiliency-boosted strategies shows better performance in terms of load restoration.

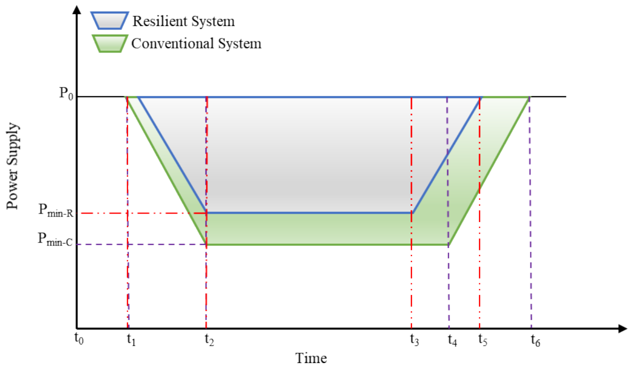


FIGURE 1. **A resilience performance curve [4].**

The system's resiliency and resilience-based models have been recently investigated in [5]–[7]. In [8], a theoretical tutorial system is proposed to train distribution system operators to effectively respond to emergencies. The study in [9] proposes a cooperative agents-based system for service restoration through artificial intelligence methods. In [10], a framework using a fuzzy logic is developed to manage outages. In [11], weather data are used to examine the probability of blackouts. The duration and frequency of occurrences have also been projected by selecting appropriate disaster response approaches.

Based on our literature review, techniques and strategies to improve the resiliency of distribution networks from both planning and operation point of view are provided in Fig. 2(a).

An effective planning must be conducted prior to undesirable incidents to prepare for and lessen the impact of upcoming disasters. The disaster-specific planning may include hardening schemes [12], resource allocation [13], [14], prediction [15], repair crews [16], and switch design [17], [18].

Hardening of distribution networks refers to making the infrastructure sturdier and consequently more durable to failure, so that serious damages due to natural disasters can be minimized, and the restoration time can be reduced accordingly [12]. The system recovery capability can be improved by availability of spare and reliable resources, and their pre-event allocation [14]. Prediction models are used to forecast power outages, possible damages and restoration time; utilities can use these models to plan corrective actions prior to incidences [15]. Repair crews play a prominent role in recovering power systems after extreme events, proper management and optimal number of repair crews can improve the system resiliency [16].

After a power outage occurs, the imperative mission for system operators is to restore distribution networks as fast as possible to support critical loads and minimize financial losses to customers. Load restoration can be generally divided into conventional techniques [19], [20], automation [21], [22], and microgrid formation [23]–[25].

In conventional technique, the load from the off-outage area is transferred to the adjacent feeder through tie-lines and tie-switches [19]. Automation in distribution networks realized through sensors, communication networks, and remotely controlled switches can help distribution network operators to detect and separate faulty areas and recover unsupplied load by opening or closing remotely controlled switches after severe events [21].

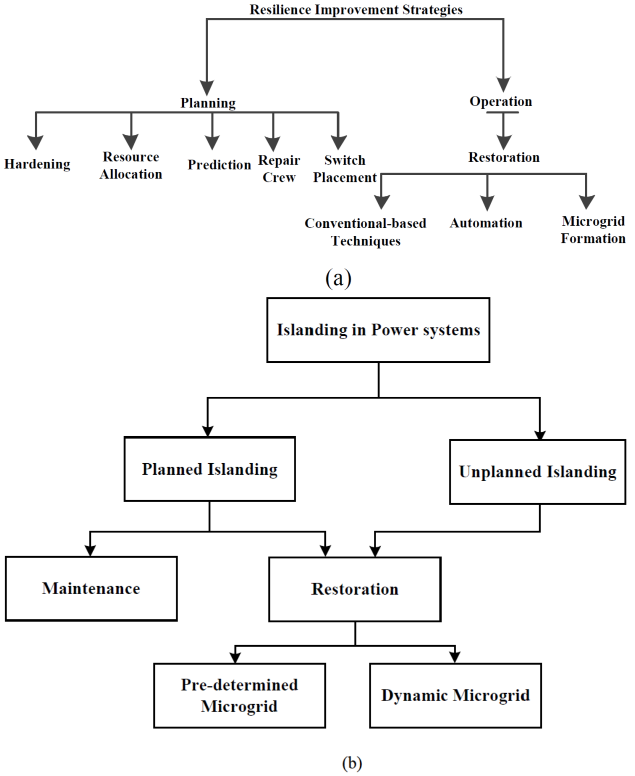


FIGURE 2. **(a) Resiliency improvement strategies in distribution networks, (b) Islanding in power systems.**

Optimal implementation of switches in distribution networks aim to enhance service restoration process by designing an efficient sequence of switching operations [17]. The study of optimal placement of sectionalizer in radial distribution networks is conducted in [18], and an algorithm based on tree structure and dynamic programming is proposed to find sectionalizing switch locations while minimizing the cost of outages and improving reliability of the system. Ref [17] studies upgrading manual switches to remotely controlled switches to improve service restoration in distribution networks, where a greedy rule-based algorithm is used to maximize load restoration and minimize the investment cost.

However, during natural disasters, the distribution network may lose its connection with the main grid, and is not able to supply loads. In this case, traditional restoration techniques may not work properly. To address this issue, microgrid formation/islanding can be a promising solution because loads can be fed through local distributed generators within microgrids [23].

Fig. 2(b) shows different types of islanding in power systems, which can be categorized into two groups [26]: planned islanding and unplanned islanding. Planned islanding, also known as intentional islanding, is initiated by power system operators or supervisory control and data acquisition (SCADA) systems; while unplanned islanding usually occurs due to faults in the system [27]. Sudden unplanned islanding should be detected quickly, it may trigger all control operations to maintain power generation and delivery despite islanding separation [26].

Both planned and unplanned islanding operations could be used in service restoration for distribution networks during severe events to supply load in their original or extended boundary. Based on their boundary [28]: microgrids can be divided into pre-determined microgrids and dynamic microgrids.

A pre-determined microgrid has a fixed boundary, which is determined based on the supply adequacy, maximum distribution coverage, and reliability indices [29]–[32]. In [29], a systematic approach is proposed to sectionalize a distribution network into several virtual microgrids with optimized self-adequacy. An optimum design of microgrids in distribution networks based on reliability index, and active power and reactive power balance for the supply-security purpose is proposed in [30], [31]. In [32], the maximum coverage criterion, and optimized communication and control infrastructure are used to partition a distribution network into several microgrids.

A dynamic microgrid has boundaries that can be expanded or shrunk, while still maintains a balance between power generation and load demand. To avoid imbalance between local distributed generation (DG) units and loads, or to maximize the load pick-up during extreme events are main reasons that microgrids have dynamic boundaries. In [33], microgrid formation with flexible boundaries is proposed to improve reliability and resiliency of distribution networks.

To solve optimization problems associated with microgrid formation, the genetic algorithm and mixed integer linear programming can be used. In [34], smart switches are used as automatic sectionalizers to determine flexible boundaries of microgrids during natural disasters. In [35], adaptive self-adequate microgrids using dynamic boundaries is proposed, where clusters of nodes based on self-adequacy measures are built first, each cluster is then assigned with an agent with the capability of supervisory control of all power generation sources within the cluster, communication with customers' smart meters within the cluster, and communication with neighbors' agents. Afterward, desirable adaptive microgrids can be formed by merging a group of clusters. Ref [2] proposes the formation of adaptive microgrids using graph theory and load switching sequence. Microgrid formation based on time and location of faults using mixed integer programming is presented in [36].

Planned microgrid formation/islanding can be used to supply load for expected conditions, such as maintenance in upstream grids [27]. Microgrids in island mode can provide electricity to remote communities, where the expansion of power systems is not economical [37]. Islanded microgrids can also improve energy security for critical load demands of industrials and militaries [38], reduce power losses, and improve voltage profile, power quality, and reliability [39].

In this paper, a comprehensive literature review is conducted on service restoration through microgrid formation techniques in distribution networks. The main contribution of the paper includes:

1) Various microgrid formation methods and their advantages and disadvantages are discussed.
2) Control and economic prospects of microgrids are summarized.
3) Future research directions are recommended.

The paper is arranged as follows: microgrid construction models and microgrid control are provided in Sections II and III. Section IV introduces microgrid economic prospect. Section V discusses advantages and disadvantages of microgrid formation algorithms and future research directions. The conclusion is drawn in Section VI.

II. MICROGRID CONSTRUCTION MODELS

The most challenging aspect of the distribution network's partitioning is to form an optimal microgrid while maintain operational constraints, such as power balance and voltage limits at each node [44], [45]. Existing microgrid formation strategies can be broadly categorized into four techniques as shown in Fig. 3 [12]: heuristic rule-based strategy [46], mixed integer linear programming (MILP) [14], [47], graph theory [48], and cluster-based models [49]. The cluster-based models can be categorized into 1) spectral clustering, 2) hierarchical algorithms, and 3) K-Means approach.

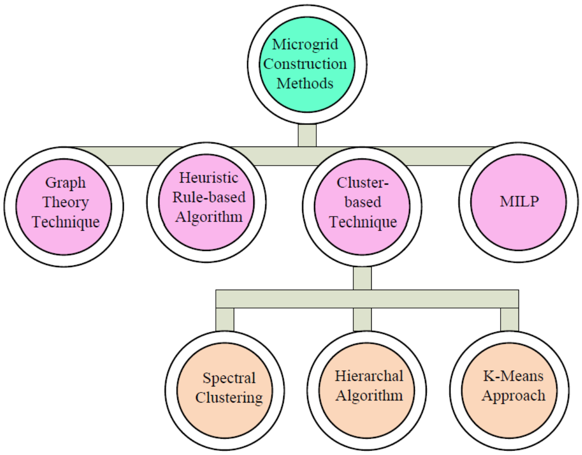


FIGURE 3. The summary of microgrid formation techniques.

A. GRAPH THEORY-BASED TECHNIQUE

Graph theory employs mathematical formulations to specify pair-wise relations between objects. Each graph is composed of vertices and edges, which are also known as nodes and links, respectively. In power distribution networks, the graph-based concepts, such as graph partitioning, spanning tree, and spanning forest, are used to form microgrids in two different topologies: 1) loop-based microgrid topology, and 2) radial-based microgrid topology. In [2], both radial and loop-based microgrid topologies are considered as part of the load restoration strategy. The linearized DisFlow model is employed to consider power flow and voltage characteristics in each constructed microgrid. In [50], spanning tree and spanning forest concepts are applied to form post-disturbance radial-based microgrids energized by DGs. The LinDistFlow model is also used to satisfy operational constraints. In [51], the graph partitioning technique and linear integer programming are proposed to form an optimal loop-based microgrid to improve system reliability. In the following subsections, radial- and loop-based models are discussed.

1) LOOP-BASED MODEL

The graph partitioning concept, which is employed to determine potential loops based on existing DG units, sectionalizes a graph G with the vertex set V and the edge set E into the Q subset $(V_{1,...,.}V_{i,...}, V_Q)$, so that $Vi \subset V$, $Vi \cap Vj = \emptyset$ for $i \neq j$. In distribution systems, energized buses and distribution lines are defined as the vertex set and the edge set of the graph, respectively. Objective functions may include the maximization of load pick-up, minimization of switching operations, generation-load balancing, minimization of neighboring loops interactions, and combinations of the above. The graph partitioning is composed of three stages, 1) coarsening, 2) partitioning, and 3) uncoarsening [52].

a: STAGE1: COARSENING

The coarsening stage iteratively simplifies the distribution network graph until it can no longer be partitioned. The Shortest Edge Machine (SEM) is widely employed in this process. An initial node is firstly selected randomly and matched with the nearest adjacent node. Afterward, the nodes are combined into a single node and the process is repeated until all possible matches in the graph have been achieved. This process will end when the number of nodes reaches an established percentage of the original number. The graphs shown in Figs. 4 and 5 demonstrate the coarsening process using the IEEE 37-bus distribution network. Fig. 4(a) indicates the coarsening first iteration, where each red line indicates that the two nodes should be merged according to the SEM strategy. The outcome of the first iteration is shown in Fig. 4(b), in which the number of nodes is decreased from 37 to 23. The second iteration of coarsening is illustrated in Fig. 5(a), and its outcome is shown in Fig. 5(b). The coarsening process will end in the second iteration because the number of nodes is decreased to 16, which meets the termination criterion (obtaining less than 50% of the original number of nodes of the graph) [52].

b: STAGE2: PARTITIONING

In partitioning stage, the graph obtained in the last iteration of coarsening process is partitioned into Q parts. The heuristic approaches, such as Kernighan-Lin (KL) and Greedy Graph Growing Partitioning (GGGP) algorithms, are used in [52]. With the GGGP algorithms, the solution is found by selecting the initial vertex and expanding it to comprise a large part of the graph. Since the main goal of service restoration is to form microgrids with self-healing capabilities, the potential cluster is expanded around controllable DGs. Power mismatches and the distance between nodes are employed to ensure that growing loops satisfy power balancing and the nearest nodes are used [52]. The partitioning stops when all nodes are covered by the loops. This process is shown in Fig. 6, which includes three iterations, and the ultimate outcome is shown in Fig. 6(c). Since four controllable DG sources are present, four potential microgrids are formed, and four points evolve autonomously from those sources in Fig. 6(a). The process terminates once all nodes are covered by one of the loops in Fig. 6(c).

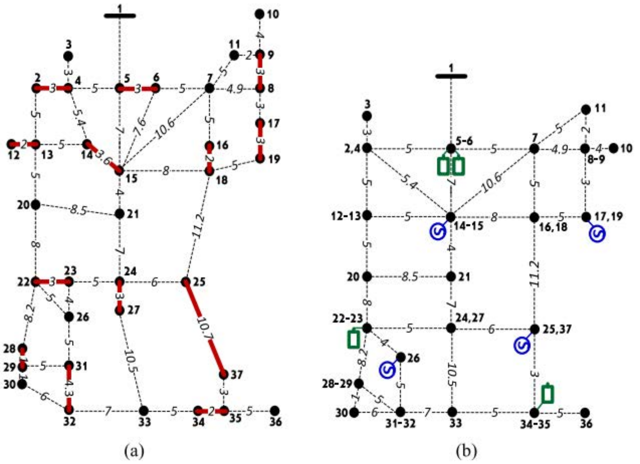


FIGURE 4. The coarsening first iteration in the graph partitioning technique [52].

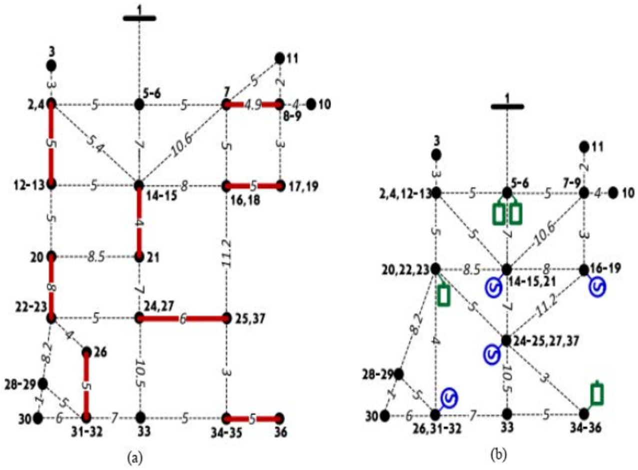


FIGURE 5. The coarsening second iteration in the graph partitioning technique [52].

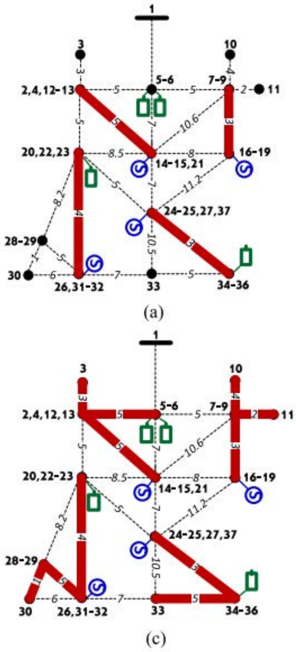


FIGURE 6. **The partitioning stage in the graph partitioning technique [52].**

c: STAGE 3: UNCOARSENING

In uncoarsening stage, the partitions obtained in previous stage should be reversed into the original graph based on the sequence of coarsening process. Refinement strategies, such as KL algorithm, should be employed. In this algorithm, the edge weight serves as a criterion to transfer a vertex between neighboring loops. However, it is more logical to consider power balancing criterion in microgrid formation to transfer nodes between adjacent loops. This modification should be implemented for refinement when used in microgrid formation [52].

Fig. 7 illustrates the uncoarsening process, which also contains two iterations because the graph coarsening is also performed in two iterations. The first and second iterations of uncoarsening are demonstrated in Figs. 7(a) and 7(c), respectively; the refinement is shown in Figs. 7(b) and 7(d) based on the power mismatch amount in per unit. In the first iteration of the refinement, Node 20 is transferred from the lower left loop to the upper left loop to balance the power.

B. RADIAL-BASED MODEL

The radial topology in distribution networks can be defined as a graph, where all nodes are put together into one energy source node without any loops. Two graph-based concepts, spanning tree and spanning forest, are used to model the radiality constraint in the microgrid formation problem. A spanning tree is a graph connecting all nodes with links without forming any loops. A spanning forest is a graph, whose connected constituents are spanning trees.

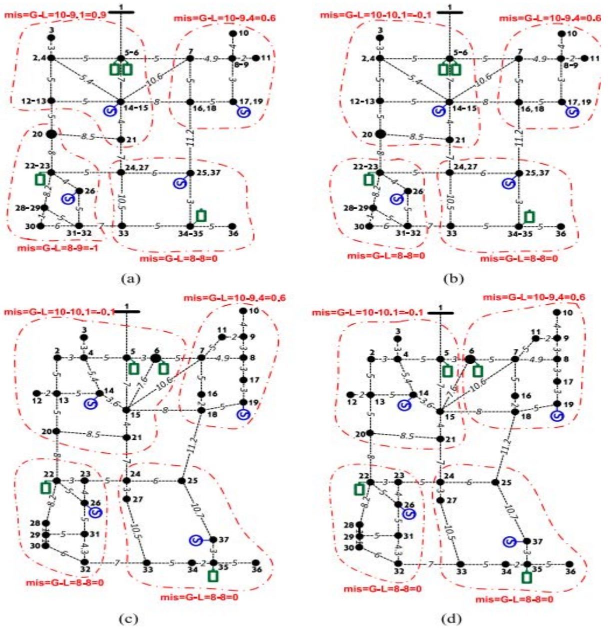


FIGURE 7. **Uncoarsening stage in the graph partitioning technique [52].**

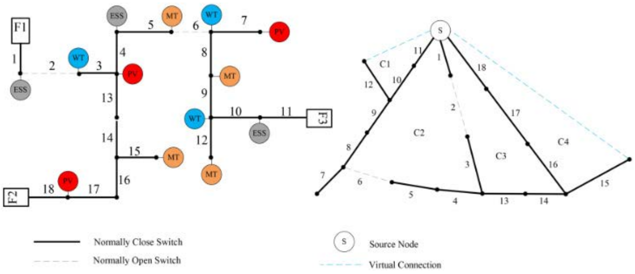


FIGURE 8. **The distribution network graph in a normal mode [53].**

Distribution networks may be modelled with graphs consisting of vertexes and edges as shown in Fig. 8 [53]. There are controllable switches at the edges of this graph, and the source nodes have feeders connected to the main grid, or to DG units. The fundamental loops of a graph defined by vectors, whose values are edges of the constructed loops, should be specified.

In Fig. 9, there are four loops, C1 to C4, defined by the following vectors:

$$V1 = \{10, 11, 12\}$$
$$V2 = \{1, 2, 3, 4, 5, 6, 8, 9, 10, 11\}$$
$$V3 = \{1, 2, 3, 13, 14, 16, 17, 18\}$$
$$V4 = \{15, 16, 17, 18\}.$$

These fundamental loops can be categorized as real loops (C2 and C3) and virtual loops (C1 and C4). The virtual loops are those with DG units and the frequency control capability. The frequency control is one fundamental requirement for power systems operation. In island mode, microgrids must be able to realize voltage and frequency control through their controllers. DGs are usually connected to power systems with interfacing power electronics converters, which enables advanced controllers to be designed to realize frequency control [54]. Frequency control has been widely studied for DGs

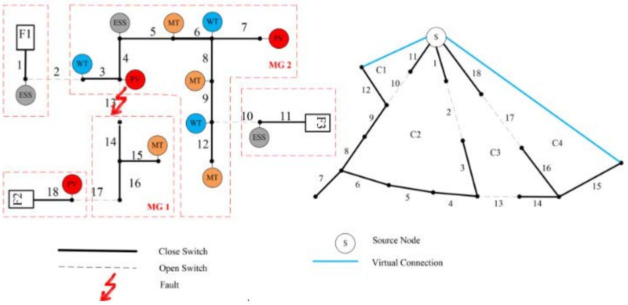


FIGURE 9. The distribution network graph in a self-healing mode [53].

in microgrids [55], [56]. In [55], a dual-stage fractional order proportional–integral–derivative (PID) controller is used to improve the frequency control of microgrids when operating in island mode, and the imperialist competitive algorithm is implemented to optimize the PID gains. The Fuzzy tilt integral derivative using a filter and the double integral control are employed for frequency control of DGs in [56], and coefficients of the controller are optimized through the Whale optimization algorithm.

Following the designation of fundamental loops, spanning tree and spanning forest algorithms are employed to determine microgrid formation, taking into account the radiality constraint and the load supply. The spanning tree in a graph is not used with all nodes connected, thus some edges should be eliminated. A spanning forest, which is a graph with several trees, is used to model a distribution network [50]. To create a spanning forest and ensure the radiality of the network, it is sufficient to open only one switch in each loop that is not shared with any adjacent loop. In addition, if the switch is selected from virtual loops, a microgrid energized by DGs is formed. For instance, if switches 10 and 17 are opened, two microgrids (MG1 and MG2) are formed (Fig. 9). Accordingly, by considering the switch status as a decision variable in the optimization problem, optimal microgrids are formed in load restoration process.

C. HEURISTIC RULE-BASED ALGORITHM

Heuristic rule-based algorithms employ heuristics or rules to find solutions. The goal of this method is to solve the problem within an acceptable time frame. The solution may not be the best, but it is near the optimal one. As this algorithm is computationally efficient, it can be used in the optimization problem with many decision variables. The microgrid formation problem based on the heuristic rule-based algorithm utilizes rules to achieve solutions.

In [46], a post-disturbance microgrid construction solution is proposed for medium to large distribution networks using the heuristic algorithm in three steps. In the first step, DG units are placed optimally without considering microgrid formation constraints. Load dispatch, nodal balance, line flow, generation placement, and voltage constraints are considered in the optimization problem with the objective of maximizing the load pick-up. Locations of DGs are provided in the first step. In the second step, the non-isolated nodes are clustered into microgrids using k-means method and DG nodes are considered as centroids. The network configuration for the constructed microgrids must meet the total load demand. In the third step, the dispatch assessment is implemented, where the capacity of the constructed microgrids is evaluated based on power system operation constraints. Fig. 10 illustrates the heuristic method process in microgrid formation.

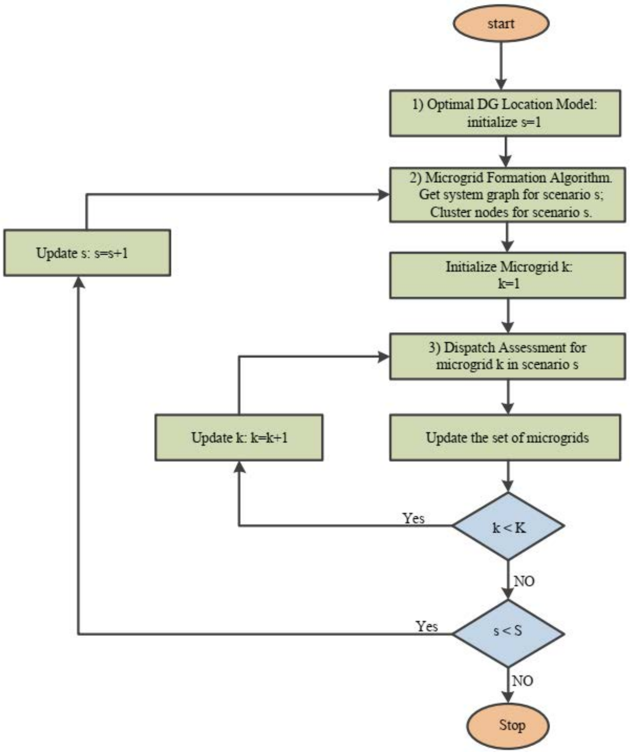


FIGURE 10. The flowchart of microgrid construction using the heuristic method [46].

In [57], [58], a decentralized multiagent system (MAS) strategy and the heuristic rule-based algorithm are employed to form microgrids using load priority and switching operations as objective functions. The following ten steps are proposed, and the controlled DG unit is used as the power source for critical load restoration [58]:

- Step 1: *entire nodes* = a set of all nodes, which is demanded by the DG agent for restoration.
- Step 2: *node to restore* = a set of the nodes to be restored is selected by calculating the objective function (i.e., load priority order) and following the branch current limits, voltage limits, and consumed power constraints.
- Step 3: *min priority load* = the least priority node in the node to restore set.
- Step 4: *lower priority nodes* = a set of nodes in the entire nodes with a priority less than *min priority node*.
- Step 5: new loads to restore are initialized as a set of the nodes from nodes to restore by removing the min *priority node.*

- Step 6: the new load to restore is chosen from *lower priority nodes*, based on the load priority objective and operational constraints.
- Step 7: *max priority node* = the highest priority node chosen from the new nodes to restore set.
- Step 8: *priority factor* = the priority order of *min priority node* divided by the priority order of *max priority node*.
- Step 9: Compute the number of switching operations for *nodes to restore* and *new nodes to restore* as X and Y, respectively.
- Step 10: If Y smaller than X multiplied by *priority factor*, then *nodes to restore* is *new nodes to restore* and go to Step 4. Else, *lower priority nodes* = *lower priority nodes* – *max priority nodes*. If *lower priority nodes* is an empty set, the algorithm ends, else go to Step 6.

Fig. 11 shows the islanding of the 119-bus test system using the above-mentioned heuristic rule-based algorithm. In out of service areas, each dispatchable DG unit with the assistance of other types of renewable-based DGs build an individual microgrid to restore critical loads with an optimum number of switching operations.

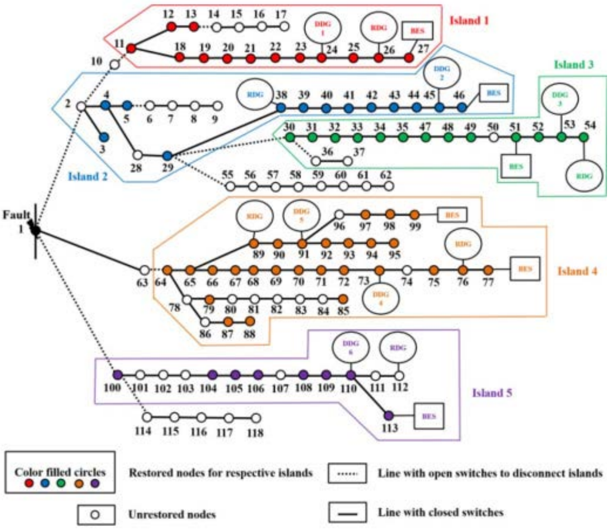


FIGURE 11. Microgrid formation of the 119-bust test system [57].

D. CLUSTERING ALGORITHM

The clustering analysis splits a set of objects into uniform groups based on similarity measures, so the similarity of objects in one constructed group is greater than that in another group. Three clustering algorithms including spectral clustering [59], hierarchical algorithm [60], and k-means method [61] are widely used in distribution network partitioning.

1) SPECTRAL CLUSTERING

Spectral clustering is a type of graph partitioning that uses the affinity between two components within the dataset, which is the computational coupling between two nodes in power systems [59]. Since this method clusters buses by using the affinity matrix, buses with a greater affinity become a cluster. It is required that the affinity matrix must be obtained with high accuracy. The affinity between any two nodes is determined by the Hessian matrix related to AC optimal power flow. The Hessian matrix is the second derivative of the Lagrange function, and a larger amount of entry in this matrix indicates a stronger coupling.

To calculate the Hessian matrix, AC optimal power flow must be performed. After computing the Hessian matrix, the spectral clustering method is used to group buses with greater affinity together. The process of partitioning a distribution network with B buses into N clusters using spectral clustering is given by [59] as follows:

- Determine the components of the affinity matrix based on $A_{i,j} = (1-w)\sum_{k=1}^{m}\sum_{l=1}^{n}|H_{k.l}| + w * Y_{i,j}$ if $i \neq j$ and set $A_{ii} = 0$.
- Form the diagonal matrix D based on $D_{i,i} = \sum_{n=1}^{B} A_{i,n}$ and build the matrix $P = D^{-1/2}AD^{-1/2}$.
- Specify the N largest eigenvalues associated with the matrix P and construct the matrix V by stacking the eigenvectors in columns. To have unit length, normalize the V's rows.
- Consider each row of V as a data point and group these data points into N partitions using an algorithm, such as k-means or hierarchical.
- Give bus i to cluster A if row i of V was given to cluster A.

$Y_{i,j}$ is the component of the admittance matrix, and w is the affinity weight.

In [62], an adaptive spectral splitting technique is proposed. The primary splitting of the distribution network is achieved through the spectral clustering strategy first. When the primary partitioning is obtained, the boundary nodes/buses transfer from the present location to the neighboring partition in every iteration to acquire the corresponding power balance ratio of each partition, which is defined as a ratio of the total power demand to the total generation capacity, while maintaining power balance constraints.

2) HIERARCHICAL ALGORITHM

In hierarchical clustering, nodes are grouped into hierarchical structures based on power system specifications of the line including average power flow or line impedance (admittance), and the obtained results are known as tree or dendrogram. A dendrogram's root point corresponds to the entire set of nodes, whereas each leaf represents a separate node. To what degree the nodes are similar to each other is shown by intermediate points. The distance between clusters or objects can be determined by the dendrogram height. Dendrograms can be cut at various levels to gain the final clustering results [63]. Fig. 12 depicts the dendrogram related to IEEE 39-bus test system in which at the height level one, the blue, green, yellow and red clusters are formed; cutting

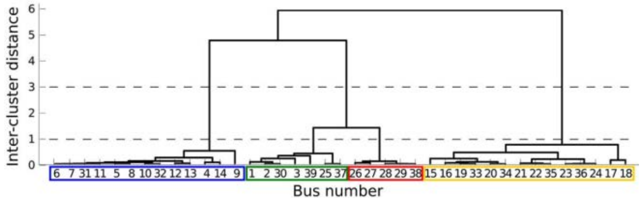


FIGURE 12. **Hierarchical algorithm, the dendrogram of IEEE 39-bus test system [49].**

dendrogram at the height level three will result in combining the green and red clusters and forming three islands.

3) K-MEANS METHOD

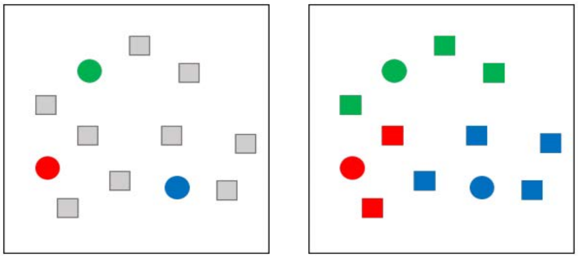
The K-means algorithm falls into centroid or distance-based algorithms, and the distances are computed to assign an object to a cluster with its own centroid point [61]. The purpose of K-means method is to partition the network with n nodes into k clusters and to ensure that the distances are minimal within each cluster. This strategy begins by selecting k nodes randomly as initial centroid points within the networks. The remaining nodes are assigned to the closest among them. After that, the centroids are repositioned from each cluster to ensure that there is a minimum distance between the centroid and any other node within the cluster. Afterward, the distance between each node and k points is calculated, and the node is assigned to a cluster with the nearest centroid.

In this method, k centroid points are moved in succession until they reach a minimal threshold, and a stable cluster is obtained. In the distribution network's partitioning, nodes with controllable DGs are regarded as centroid points, and the electrical distance is utilized for distance metric. The process of the K-means algorithm is illustrated in Fig. 13 [64].

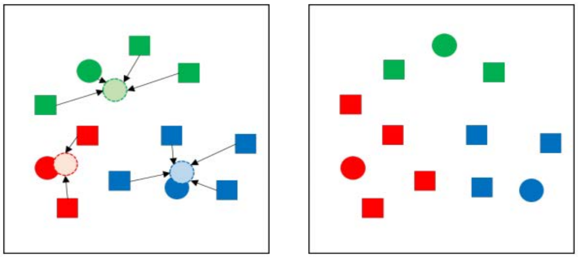
E. *MIXED INTEGER LINEAR PROGRAMMING*

Mixed integer linear programming (MILP) is a mathematical optimization problem with integer decision variables, linear objective functions and constraints. This approach is broadly used in load restoration and microgrid formation [23], [33], [65]. Ref. [21] develops a MILP to form a microgrid energized by DGs through controlling the status of remotely controlled switches after natural disasters, where critical load pick-up is maximized with self-adequacy and operational constraints satisfied.

In [65], a MILP-based method is proposed to form multiple microgrids to restore prioritized load in distribution networks after extreme events. Flexible microgrid formation is investigated in [33], where MILP is used to solve the optimization problem based on utility profits and customer satisfactions. Implementation of MILP-based microgrids requires a large number of control variables. To address this problem, a MILP with radiality constraints is proposed in [66]. In the MILP-based method, the following constraints must be satisfied when forming a microgrid:



(a) Initial random seeding process
(b) Datapoints clustered to closest centroid



(c) Mean of cluster determined as new centroid
(d) Steps (a), (b), (c) repeated until convergence is achieved

FIGURE 13. **The K-means algorithm [64].**

- Splitting constraints.
- Power system physical constraints.
- Subgraph connectivity constraints.

Mathematically, MILP optimization can be handled by branch-and-bound, branch-and-cut, or cutting plane approaches. Currently, several commercial optimizers, such as CPLEX, GUROBI, and MOSEK, are available to provide flexible, parallel-processing and high-performance solvers for MILP.

According to our literature review, a summary on microgrid formation for service restoration in distribution networks can be found in Table 2. Different studies are compared from application, information discovery, construction approach, objective function, and optimization problem aspects.

III. MICROGRID CONTROL

Renewable energy-based DG units in microgrids use interfacing power electronics converters to connect to the system, and controllers are designed and implemented on these power electronics converters to achieve power, voltage and frequency control of DGs and the microgid. In grid-connected mode, the voltage and frequency of microgrids are governed by the utility grid, controllers are used for real and reactive power or power factor control. In island mode, the microgrid must be able to control its voltage and frequency through advanced DG controllers. Hierarchical control techniques are extensively utilized for microgrid control and power management [70], [71].

A. *TRADITIONAL HIERARCHICAL CONTROL FOR MICROGRIDS*

The traditional hierarchical control framework is illustrated in Fig. 14, including primary, secondary, and tertiary control.

TABLE 2. Summary of literature review on microgrid formation for service restoration in distribution networks.

Reference Number		[2]	[16]	[23]	[57]	[25]	[50]	[67]	[29]	[30]	[33]	[46]	[49]	[51]	[59]	[60]	[68]	[69]
Application	Pre-determined Microgrid					*			*	*	*		*	*	*	*		*
	Dynamic Microgrid	*	*	*	*		*	*				*					*	
Information Discovery	Distributed MAS Scheme			*	*													
	Centralized Scheme	*																
Construction Approach	Graph Theory (Loop-Based)	*												*				
	Graph Theory (Radial-Based)	*	*				*		*		*						*	
	Heuristic Rule-Based				*						*	*					*	
	Spectral Clustering												*		*	*		
	Hierarchical Algorithm												*			*		
	K-Means Method											*						
	MILP		*	*		*		*		*							*	*
Objective Function	Supply-adequacy								*	*	*			*				
	Load Pickup	*	*	*	*		*	*				*						
	Switching Operation				*		*											
	Running Cost					*									*		*	*
	Power Exchange Between Microgrids								*	*				*				
	Islanding Success Probability										*							
	Subgraph Expansion												*					
Optimization Problem	Stochastic Problem	*			*							*				*		*
	Deterministic Problem		*	*		*	*	*	*	*	*		*	*	*		*	

The widely used primary control is droop control to adjust the local voltage and power, prevent system instability, and handle proper power sharing among DGs [70], [71]. The following well-recognized droop control technique is used to reach primary control objectives [71]:

$$\omega_{MG} = \omega^* - m.(P - P^*) \tag{1}$$

$$E_{MG} = E^* - n.(Q - Q^*) \tag{2}$$

where, the frequency and output voltage amplitude are detonated by ω_{MG} and E_{MG}, respectively. ω^* and E^* represent the reference frequency and voltage amplitude, respectively. Droop coefficients are represented by m and n.

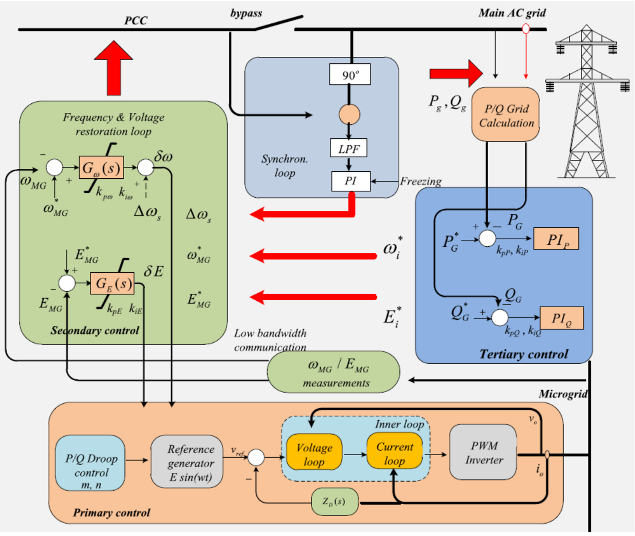


FIGURE 14. Traditional hierarchical control for microgrids [71].

The deviation of output voltage and frequency caused by primary control can be eliminated by secondary control [72]. The frequency and voltage restoration controllers are demonstrated in Fig. 14 [71].

$$\delta_\omega = k_{pw}\left(\omega^*_{MG} - \omega_{MG}\right) + k_{iw}\int\left(\omega^*_{MG} - \omega_{MG}\right)dt + \Delta\omega_s \tag{3}$$

$$\delta E = k_{pE}\left(E^*_{MG} - E_{MG}\right) + k_{iE}\int\left(E^*_{MG} - E_{MG}\right)dt \tag{4}$$

The frequency and voltage amplitude values, ω_{MG} and E_{MG}, in a microgrid are identified and evaluated by references, ω^*_{MG} and E^*_{MG}, the obtained errors through compensators, δ_ω and δE, are send to each DG unit to adjust frequency and voltage. The secondary control parameters are represented by k_{pw}, k_{iw}, k_{pE}, and k_{iE}. $\Delta\omega_s$ indicates the synchronization term.

Centralized control [73], [74] and decentralized control [65], [76] are two major techniques used in secondary control. For centralized control, the main drawback is its high reliance on the microgrid control center and the bidirectional communication structure. When the microgrid control center is faulted or the communication system fails, the centralized control no longer works well. Accordingly, the stability of the microgrid is decreased and its cost is increased [77].

Decentralized control, on the other hand, can overcome above issues, errors caused by one DG will not cause a whole system's failure, and it does not rely on communication networks, and can be simply expanded to several DGs, which improves the system's scalability [78].

Tertiary control is employed to identify power flow to achieve optimal operation for economic and service restoration purposes [79]. In Fig. 14, by calculating P/Q via the static bypass switch, P_G and Q_G can be evaluated by the preferred references, P_G^* and Q_G^*.

$$\omega_{MG}^* = k_{pP}\left(P_G^* - P_G\right) + K_{iP}\int\left(P_G^* - P_G\right)dt \qquad (5)$$

$$E_{MG}^* = k_{pQ}\left(Q_G^* - Q_G\right) + K_{iQ}\int\left(Q_G^* - Q_G\right)dt \qquad (6)$$

The tertiary control parameters are represented by k_{pP}, K_{iP}, k_{pQ}, and K_{iQ}.

Power quality adjustment and economic operation can be achieved by the hierarchical control strategy, which enhances the flexibility of microgrids. The microgrid control center is utilized in this strategy to manage DGs and loads, which contributes to reliable operation of multiple microgrids [80].

B. MULTIAGENT SYSTEM-BASED DISTRIBUTED CONTROL

Multiagent control strategy splits a large system into a number of autonomous subsystems, which can communicate with each other [71]. Each agent has intelligent features [81], [82]. Using these intelligent agents, the multiagent system-based distributed control can achieve coordinated operation of the entire system. Fig. 15 demonstrates the structure of a multiagent control-based microgrid [71]. Various electrical components, such as wind turbine generation units, loads, gas turbines, and energy storage systems, are assigned to each agent. These agents observe control operations and the status of each electrical component, and the microgrid control center coordinates activities among all agents. Once there is a command from an agent, the microgrid control center notifies and coordinates all agents [83]. Communication and coordination are crucial during the entire decision-making process. Ref [84] uses the contact net protocol in such process.

Each agent generally contains two-level control blocks: the upper-level control block identifies the power supply reference and demand, and measures optimal increment cost; the lower-level control block applies the power reference tracking of related electrical components [85]. Accordingly, each agent controls local load and power generation, and exchanges information with other agents.

There are many reported multiagent system-based distributed control schemes in the literature [86]–[91]. A multiagent distributed control with a frequency control framework is proposed in [86] by employing consensus method. Power sharing among distributed energy resources in microgrids through a multiagent-based technique is suggested in [87]. Ref [90] can overcome the weakness of droop control by using multiagent distributed control, and realize voltage and frequency control and proportional reactive power sharing among DGs. Ref [91] can regulate frequency, where each local controller shares information with neighboring controllers.

IV. MICROGRID ECONOMICS

Economic benefits from microgrid formation is an essential feature to address. Microgrids have several economic benefits, such as load leveling and peak shaving [92], power export and net metering [93], loss and emission reduction [94], power quality improvement [95], and resiliency enhancement [96].

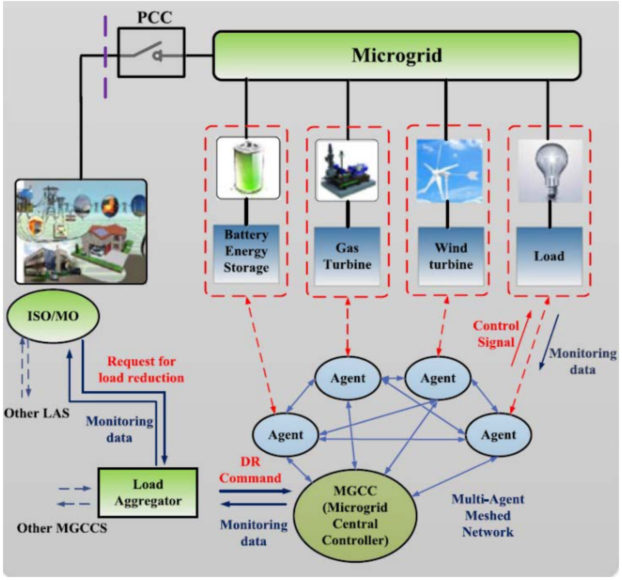


FIGURE 15. The structure of multiagent-based microgrid [71].

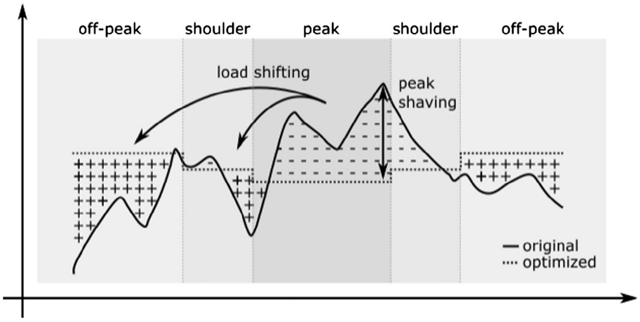


FIGURE 16. Peak shaving and load leveling [95].

DGs and energy storage along with advanced control technologies enables flexible power management within a microgrid. It can be especially economically influential when the utility's Time-of-Use tariff comprises power and volumetric charges [95]. This type of tariff is usually a powerful motivation to facilitate peak shaving and load leveling as shown in Fig. 16. In this example, an optimized load profile is achieved by implementing load shifting and peak shaving, which minimizes power demand and volumetric charges.

Exporting electricity to power systems is one main source of income brought by microgrid formation [93]. Net metering and feed-in tariffs are two general methods used to specify surplus power generated by microgrids [95]. Net metering utilizes a bidirectional meter to calculate a customer's net power consumption [95]. If the generation is more than the consumption, the meter turns backward. In the feed-in tariff method, all power producers receive a payment when they inject power into the system [97].

As microgrids are located locally, power generation can be consumed locally, which avoids long distance transmitting electricity, and thus, power losses along the

TABLE 3. Cost details of various power generation technologies [100].

Generation Technology	Capital Cost ($/MW)	O & M Cost ($/M)	Fuel Cost ($/MWh)	Capacity Factor	Efficiency (%)	GHG Emission (tCO_2/MWh)	Renewable Potential (MW)	Life time (years)
Hydro	1260	28	-	0.46	85	-	1400	40
Wind	1620	43	-	0.37	30	-	2400	25
Solar	2160	27	-	0.25	30	-	6487	30
Geothermal	1200	30	-	0.7	20	-	3442	30
Coal Fired	1125	35	6.14	0.75	38	1.08	-	30
Coal IGCC (integrated gasification combined cycle)	1315	28	6.14	0.8	43	1.08	-	30
Gas Fired	810	21	30.7	0.85	47	0.5	-	30
Gas IGCC	510	8	30.7	0.8	57	0.5	-	25
Biomass	1900	43	5.86	0.75	35	0	4807	25
Nuclear	2070	45	3.07	0.85	33	-	-	40

feeders are reduced [98]. Power quality and the system's reliability can be also improved because the decentralized power supply can better match power supply and demand locally, and the influence due to transmission and generation outages can be reduced [99]. Due to increasing penetration of renewable energy-based DGs, microgrids can reduce greenhouse gas (GHG) emission compared to conventional power generation.

Table 3 provides a summary of cost details for various power generation technologies, including their technology cost, operation and maintenance (O & M) cost, capacity factor, fuel cost, efficiency, GHG emission, renewable potential, and the life time [100]. DGs in microgrids are mainly renewable energy sources, which makes microgrid formation economically viable.

In [101], the economic analysis is conducted for a microgrid with PV and battery storage in Northampton, Massachusetts, USA by considering the outage mitigation, emission reduction and resiliency improvement. The system is modeled using the battery storage evaluation tool for a one-year period, and its efficiency is demonstrated through historical data and randomly generated large outages.

A lifecycle analysis is conducted for a microgrid with wind turbines, PV, diesel generators, and energy storage to evaluate its commercial aspect in [102], and it shows significant reduction in costs of GHG emission and loss, and improvement in reliability indices. An industrial microgrid with PV in China is analyzed from the economic aspect in [103] regarding emission reduction costs, levelized energy costs, and the payback period. This study demonstrates the economic benefit gained by a PV-based microgrid through real microgrid output data. In [104], economic benefits of microgrids are assessed according to reliability improvement, emission reduction, power quality of services, and the lessened peak loading.

Participation in electricity market is considered one benefit behind microgrid formation [105]. In the restructured electricity market, microgrids can participate in both energy and ancillary service markets as autonomous entities. Power generated by microgrids can be traded in electricity markets. The microgrid control center conducts the optimal power management of the electricity market, and aims to satisfy local demand during the system operation through optimal allocation of local energy sources [106]. Microgrids with renewable energy sources and energy storage can also participate in the emission trading market, where the energy price and emission data are sent to the microgrid control center, and the microgrid will be paid based on these data.

V. ADVANTAGES AND DISADVANTAGES OF MICROGRID FORMATION ALGORITHMS, AND FUTURE RESEARCH DIRECTIONS

A. *ADVANTAGES AND DISADVANTAGES OF MICROGRID FORMATION ALGORITHMS*

A fast and effective service restoration strategy is vital to improve resiliency of distribution networks. Due to high penetration of DGs, microgrid formation can be an effective strategy to enhance the system's resiliency via critical load restoration during contingency. To form optimal microgrids, different algorithms have been reported in the literature. Each approach has its advantage and disadvantage, which will be discussed below:

- The mixed integer linear programming-based techniques can provide a complete picture of microgrid formation by modeling all components of a distribution network in details, but an optimal solution can be computationally expensive or practically infeasible when the size of the system is large.
- The heuristic rule-based algorithm can quickly find feasible microgrid formation after faults, but it needs problem-dependent information and may not guarantee an optimal solution.
- The graph theory can be successful to find optimal solution rapidly in a small system, however, its efficiency degrades for medium to large systems since the number of trees is increasing, and implementing the graph partitioning concept takes time to form a microgrid, which makes this method unattractive in the service restoration problem.
- In the spectral algorithm, to determine affinity between two components, the Hessian matrix needs to be calculated for AC power follow at a specific operating point.

Although this algorithm provides a reliable solution for a particular operating point, it may not be a promising solution for service restoration problem because the system operating condition varies and the partitioning should be run for many operating points.

- The hierarchical clustering technique employs structural characteristics of distribution networks rather than the operating point, which makes partitioning more reasonable than the spectral algorithm. K-means method clusters objects by minimizing the distance within each cluster, but it may not be able to guarantee radiality constraints of distribution networks.

Based on advantages and disadvantages of various algorithms for microgrid formation, the combination of different strategies may contribute to a more reliable solution for service restoration problem. For example, the combination of k-means method with mixed integer programming technique can result in less decision variables, which improves convergence speed of the optimization problem and satisfies operational constraints.

B. FUTURE RESEARCH DIRECTIONS

In the area of service restoration using microgrid formation, the distributed optimization technique can be a suitable method to tackle microgrid formation problem, as it decomposes a large optimization problem into several subproblems and handles them in a parallel fashion, and thus, the convergence speed increases and the global optimal solution is obtained.

To develop efficient service restoration strategies through microgrid formation, more realistic models of distribution networks are needed. For example, most distribution networks have unbalanced configurations, which has not been sufficiently investigated in microgrid formation. In addition, supplying power to different types of loads (static and dynamic loads) needs to be further investigated following outages as each constructed microgrid must have the capability to manage motor starting transients as an efficient service restoration strategy.

Artificial intelligent and machine learning-based methods can be developed in service restoration to realize intelligent control actions. For example, deep reinforcement learning has a big potential to realize microgrid formation and intelligent service restoration in distribution networks.

VI. CONCLUSION

In this paper, service restoration through microgrid formation techniques in the literature is extensively reviewed. Various approaches to construct mircorgrids are introduced, such as graph theory, heuristic rule-based algorithm, clustering algorithm, and mixed integer linear programming. Control and economic aspects of microgrids are summarized. The future research directions are recommended in the paper. The paper offers valuable information to engineers and researchers working on renewable energy sources and distribution system modernization.

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