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Distribution System Restoration by Reconfiguration and MG Formation Considering Post-Restoration Failure Probability

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ABSTRACT

Recent weather-related disasters experienced worldwide with considerable damages to the interconnected power infrastructure have highlighted the importance and urgency of enhancing the resiliency of the distribution grid. A Resilient distribution grid can withstand and recover from such rare events. Resiliency against extreme events is conceptualized in three distinct stages: prior, during, and after the event. Rapid recovery is a feature of after the event stage. In this paper, restoration strategies to restore maximum loads as quickly as possible are investigated. The proposed approach attempts to restore the critical loads by using tie-switches to reconfigure the network. In the case of isolated areas without the possibility of using upstream utility grid, sectionalizing the grid into several microgrids (MGs) is proposed to improve the system resiliency. The number of isolated MGs is an issue that is required to be correctly determined. So, a new approach is proposed to compromise between amount and reliability of supplied load to find the optimum number of MGs. The proposed method is simulated on the unbalanced IEEE-123 and 37-bus distribution grid with random locations for DERs.

1. Introduction

Catastrophic weather events have been experienced worldwide in recent years with massive damage to the power system infrastructure. These kinds of events have a low probability of occurring with high impacts. Therefore, power system resiliency is gaining progressive attention to mitigate the severe consequences of such extreme weather events. The severity of extreme events ranges from simultaneous/sequential multiple faults to the total loss of the upstream utility grid supplying the distribution system [1].

Sectionalizing a distribution system into several MGs is a comprehensive operation scheme to improve distribution system resilience. In [2], an optimization algorithm based on maximum load restoration and voltage stability in the isolated part of the network is presented to form MGs. However, practical usage of the tie-switches in the restoration process before establishing MGs is not well exploited. In [3], a mixed-integer linear programming method is proposed that dynamically forms MGs to achieve a resilient distribution system. In [4], an MG formation plan is proposed that adopts a three-phase network model to represent unbalanced distribution networks. The unbalanced operation constraint of synchronous Generators (SGs) is included in the formulation to prevent unbalanced operations that might

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trip SGs. In addition, a linear approximation of the unbalanced operation constraint is also developed to handle more extensive networks.

The number of MGs in the isolated part of the network is an important issue. Reducing or increasing the number of MGs each has its advantages and disadvantages that have been discussed in various papers so far. In [5], it was presented that multiple sources in the network can be integrated by reducing the number of MGs (forming larger MGs), and more loads can be supplied. Also, the sources with limited power generation capability, like diesel generators, can be optimally allocated to critical loads. In [6], it was presented that different types of resources can be optimally coordinated by reducing the number of MGs. In [7], it was stated that reducing the number of MGs allows the uncertainty of renewable resources to be optimally managed. Based on IEEE standard 1547.4 [8], the operation and reliability of the distribution networks will increase if the grid could be split into multiple MGs (increase number of MGs) [7]. In [9], presented that the reliability of each MG is relevant to their included components. Therefore, increasing the number of MGs will result in fewer components in each MG and more reliability. In [10], presented that based on the amount of supplied load and MGs average repair time per year, the number of MGs should be detected by solving an optimization problem.

Reconfiguration of the distribution system before/after a natural disaster has been presented as one of the approaches to improving resiliency. Reconfiguration can be done with different purposes like bringing out the worn-out lines, connecting critical loads to resources, etc. In [11], an algorithm for system reconfiguration before a natural disaster is presented. This algorithm uses the fragility curve of different network lines, and the lines with a high probability of damage will replace with less probability of failure ones. In [12], reconfiguration of the system coordinated with MG formation after natural disasters is presented.

A comprehensive algorithm to increase the resiliency of the distribution system is an algorithm that considers:

- The potential of tie switches to connect loads to upstream network as much as possible. The reason is that there is an assurance of supplying loads when connected to the upstream network. And in this situation, the resiliency of the network will increase significantly.
- The algorithm should be suitable in unbalanced networks. Because of the limitations of unbalanced networks, the algorithms that are suitable for unbalanced networks can be applied to balanced ones, but the opposite is not possible.
- Specify the number of MGs before solving the optimization problem will take the answer away from the optimal global solution. So, in a suitable algorithm, the number of MGs is one of the problem variables.
- To consider the general case, a suitable algorithm should be useful for single or multiple faults. In other words, the network will separate into a connected and an isolated part in the general situation. So, a comprehensive algorithm should be organized for this situation.

This paper presents a comprehensive algorithm for restoring maximum possible loads after a natural disaster. In this algorithm, a configuration to connect all loads to the upstream network is presented. In addition, MGs should be formed in isolated areas in case of unavailability of a configuration to connect all network parts to the upstream network. So, there is the need for an index to determine the optimum number of MGs based on the amount of supplied loads and reliability of MGs. In general, the contributions of this paper include:

- Maximum possible load restoration is obtained by fully exploiting the potential of tie-switches before attempting to form isolated MGs.
- A strategy to obtain the maximum possible formable MGs in an unbalanced, isolated network is presented.
- A new index based on a compromise between the reliability of the formed MGs and the amount restored loads is proposed.

The proposed method is simulated on the IEEE-37 bus and IEEE-123 bus distribution networks with random locations for DERs and critical loads. These sample grids are unbalanced, so a three-phase power flow should be used to find the voltages and line flows. However, in some papers, the IEEE-123 sample network is treated as a balanced three-phase system with different simulation results.

This paper is organized as follows: section 2 describes the approach overview; section 3 provides restoration strategy, section 4 provides the numerical results and section 5 includes the paper and present the future research work.

2. Approach Overview

When a natural disaster occurs, some equipment will be damaged, and a part of the network will become isolated from the upstream network. In the first step of the proposed strategy, a reconfiguration will be performed to connect the isolated area to the upstream network if possible. The objective function for the reconfiguration is presented in section 3.1. But in some cases, with changing the configuration of the network, it is not possible to connect all the isolated areas to the upstream network. So, in this situation, forming MGs is recommended. Forming MGs can be performed with different objective functions. For example, the most popular objective function is maximizing the amount of restored critical loads. But because of probable secondary faults, this objective function will not be the best choice. So, in the next part of the proposed method, an objective function is proposed that is shown in section 3.2.2. Because the proposed objective function consists of different parts with a diverse range of change, in this section normalization approach of the proposed objective function is also presented. After proposing the objective function, it should be used with operational constraints to obtain feasible answers. The proposed objective function with operational constraints presented in section 3.2.3, should be performed for every possible number of MGs obtained with the method shown in section 3.2.1 to find optimum number and configuration of MGs among all possible configurations.

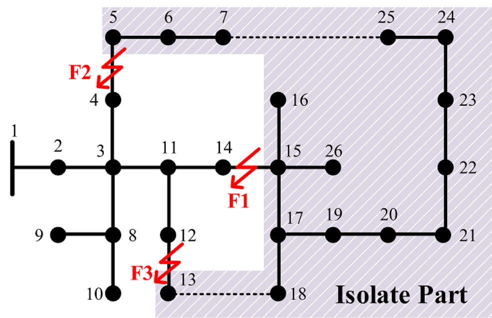

Fig. 1. An example of a network with different faults

3. Restoration Strategy

Distribution systems are loop/mesh designed but radially operated using tie-switches. In this paper, load restoration is done first by applying tie-switches. Whenever a fault occurs, automatic switches are used to isolate the fault. Next, the restoration process is triggered by using tie-switches. If multiple simultaneous/sequential faults occur, a large part of the network may be de-energized. Here, an isolated part would be established that could not be supplied by the upstream utility network. For example, consider Fig. 1 with the fault F1 on section 14-15. A de-energized part is established upon isolating the fault. Restoration of the isolated parts is possible either by closing tie-switch 7-25 or 13-18 depending on the optimization problem results, which will be presented in the preceding sections. Here, no load shedding is required. Two simultaneous faults, F1 and F2, on sections 4-5 and 14-15 are cleared by opening the relevant switches. Here, the concurrent closing of the tie-switches 7- 25 and 13-18 could only restore the isolated area, so it is not required to shed any load and the network is restored by using the tie-switches. For three simultaneous faults, i.e., F1, F2, and F3, the faulty sections 4-5, 12-13, and 14-15 are removed by opening the relevant switches. However, closing any of the tie-switches 7-25/13-18 could not restore the isolated area, so it is required to form autonomous MGs using the available resources in the isolated area.

3.1. Utility-grid Connected Network/Sub-network

In some cases, there is more than one configuration to connect the isolated part to the upstream network. In this situation, because of the assurance of supplying all loads, the optimum solution is a configuration with less switching and power loss as below:

$$Minimize \left(\left(\frac{N_{sw}}{N_m} \right) \times \left(\frac{P_{loss}}{P_{total}} \right) \right) \quad (1)$$

In some cases, no configuration can connect all the isolated parts to the upstream network because of the severity of the disaster or network topology. In this situation, the amount of restored loads is more important than the number of switching and power loss. Therefore, the optimum solution is the configuration that restores more amount of load as below:

$$Maximize \left(\frac{P_{res}}{P_{total}} \right) \quad (2)$$

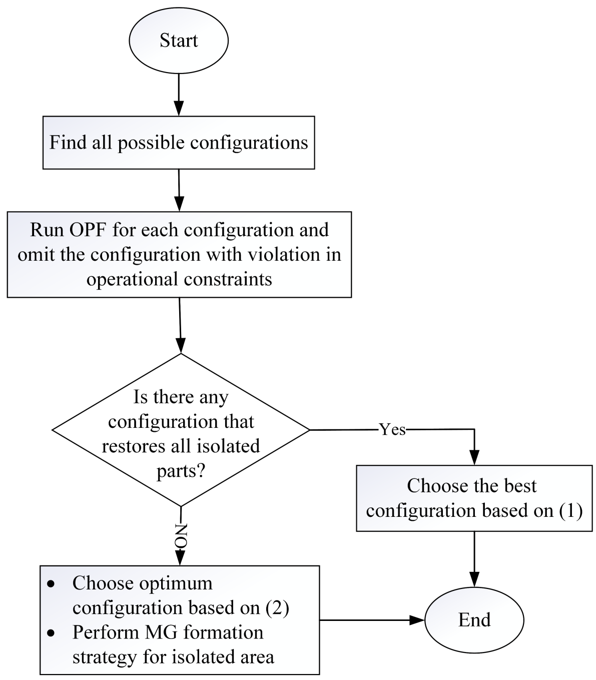

Fig. 2. Flow chart of the proposed method

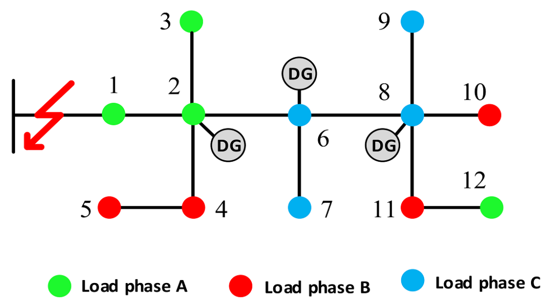

Fig. 3. Sample unbalanced network

After identifying the objective functions, the algorithm to find different configurations should be identified. In [13-14] spanning-tree search algorithm is presented to find all possible configurations in different situations. Therefore, when the network divides into connected and isolated parts, spanning tree algorithm can be used to identify the optimum configuration. The flowchart of the proposed strategy is presented in Fig. 2.

3.2. MG Formation Strategy

The MG formation strategy presented in this paper has three general sections. The first section is an algorithm to obtain the maximum number of formable MGs in the isolated part. The second section presents the objective function to determine the optimum number of MGs among all possible configurations (obtained in the first section). Finally, the third section presents mathematical formulation and constraints for MG formation.

3.2.1. Maximum formable MGs

MG formation methods are well documented in the literature. For example, in [2-3], the objective function maximizes the restored loads based on their priority in the isolated area. The assumption is the availability of one DG per MG that means the number of MGs is equal to the number of DGs. However, it is not always possible to

	1	2	3	4	5	6	7	8	9	10	11	12	*A*	*B*	*C*	*DG*
1	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0
2	1	0	1	1	0	1	0	0	0	0	0	0	1	0	0	1
3	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0
4	0	1	0	0	1	0	0	0	0	0	0	0	0	1	0	0
5	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0
6	0	1	0	0	0	0	1	1	0	0	0	0	0	0	1	1
7	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0
8	0	0	0	0	0	1	0	0	1	1	1	0	0	0	1	1
9	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0
10	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0
11	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0
12	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0

(3)

fulfill this task due to the constraint of the specified threshold for phase imbalance of the synchronous generators. This constraint asserts that the output powers of different phases of a synchronous generator should not violate a defined threshold. For example, the single-phase loads in the vicinity of the DG at bus 2 in the network presented Fig. 3 are mainly connected to phase A and B, and there is no load at phase C. Since the output power of phase C of DG_2 is zero, the output power of the other phases should remain near zero. It means that in such a condition, it is not possible to use this DG to establish a MG, so the MG needs to be formed with two DGs (DGs at bus 2 and 6) within one MG.

In balanced networks, the maximum number of MGs equals the number of synchronous generators. However, in unbalanced networks based on the network condition, the number of MGs does not follow a particular rule. For this reason, an algorithm will be presented to obtain the maximum number of MGs in the isolated part.

A feasible AC MG consists of three-phase loads with at least one synchronous generator. So, to determine the maximum number of formable MGs, the isolated part of the network should separate into the least sections with three-phase loads and synchronous generator(s). So, in the proposed algorithm, the network will simplify to three-phase nodes consisting of the synchronous generator(s). Finally, these nodes represent the maximum number of formable MGs. An essential point about the maximum formable MGs algorithm is that there is no guarantee about the feasibility of all numbers of MGs obtained in this algorithm. In other words, this algorithm will guarantee that more MGs than obtained MGs are undoubtedly impossible, but fewer MGs may be possible to be formed. So, the optimization algorithm and constraints will determine their feasibility.

In the proposed algorithm to obtain the maximum number of MGs, nodes with degree one (nodes that connect to one other node) will omit, and their load and generator will transfer to the neighbor bus. For this purpose, a network connection matrix will be formed. This matrix has three parts; the first is the connection part, the second is the phase part, and the third is the DGs part. For example, the connection matrix for the network presented in Fig.3 is shown in (3). To better explain this matrix, the first row of this matrix can be made as below:

- Node 1 just is connected to node 2, so just the second array of the first part of the matrix is equal to 1.
- Node 1 consists of load at phase A, so the first array of the second part of the matrix will be equal to 1.
- This node does not consist of DG, so the third part of the matrix equals 0.

It is clear from (3) that buses 1, 3, 5, 7, 9, 10, and 12 have degree 1. The new connection matrix will be like (4) by eliminating these buses.

	2	4	6	8	11	*A*	*B*	*C*	*DG*
2	0	1	1	0	0	1	0	0	1
4	0	1	0	0	0	0	1	0	0
6	1	0	0	1	0	0	0	1	1
8	0	0	1	0	1	0	1	1	1
11	0	0	0	1	0	1	1	0	0

(4)

It is clear from (4) that in this stage, buses 4 and 11 have degree 1. The new connection matrix will be like (5) by eliminating these buses. In (5), bus 8 has a three-phase load and contains a DG. So, this bus will stand for an MG, which will be omitted from considering in the connection matrix.

	2	6	8	*A*	*B*	*C*	*DG*
2	0	1	0	1	1	0	1
6	1	0	1	0	0	1	1
8	0	1	0	1	1	1	1

(5)

In (5), buses 2 and 6 are connected. By eliminating one and transferring the loads and generator to another, the connection matrix will be like (6).

	6	8	*A*	*B*	*C*	*DG*
6	0	1	1	1	1	1
8	1	0	1	1	1	1

(6)

In (6), two buses contain a three-phase load with a generator. So, in the network presented in Fig. 3, the maximum formable MGs is equal to 2. The first MG contains buses 1 to 7, and the second MG has buses 8 to 12.

3.2.2. *Index for the optimum number of MGs*

As presented, the number of MGs in isolated parts is essential while forming MGs. Generally, the amount of supplied loads and reliability of MGs will be affected by changing the number of MGs. By decreasing the number of MGs (forming larger MGs) as resources are pooled in the network, it is possible to supply more loads. In this situation, there will be more elements in each MG. Because the reliability of MGs is related to the reliability of the elements within them, their reliability will decrease as the number of MGs decreases. Another parameter that affects the reliability of the MGs is how loads are distributed between them. By specifying the number of MGs, they may be formed in different configurations for load distribution. For example, for the sample network presented in Fig. 4, if it is decided to form 3 MGs, it is possible to form them as MG1 to MG3 (shown in Fig. 4) with the minimum possible area (minimum area with three-phase load and at least one synchronous DG). In this situation, a part will be a floating part (yellow part in Fig. 4) in the network. Assuming that any of the MGs can supply the floating part, the whole or a part of this area can be connected to each MG. So, an index should be proposed to determine how loads of floating parts disperse between MGs.

Based on the above information, the objective function for determining the optimum number of MGs should have three parts; the first part represents the amount of supplied load, the second part represents the number of MGs, and the third part represents the dispersion of the loads between MGs. So, the objective function will be presented (7). The larger the index, the more resilient the network will be.

$$obj = P_{res} \times n_m \times \prod_{n'=1}^{n_m} \xi_{n'} \tag{7}$$

In this equation, the first and second terms are supplied load and number of MGs, respectively. In the third term ξ_n is the amount of supplied load in MG n. An essential point about the third term is that when a few variables with a constant summation are multiplied together, the result will be maximum when all the variables are equal. So, the third term has a maximum value when the load separates between MGs equally. However, it is almost impossible to separate the loads between MGs equally. So, it could be said that the closer loads of MGs, the higher the third term will be. Finally, to normalize this index, it can be rewritten as below:

$$obj = \frac{P_{res}}{P_{total}} \times \frac{n_m}{MG_{max}} \times \frac{\prod_{n'=1}^{n_m} \xi_{n'}}{\left(P_{res}/n_m\right)^{n_m}} \tag{8}$$

3.2.3. Algorithm for MG formation

At this stage, the algorithm for MG formation and decision making for number of MGs and supplied load is presented. In this algorithm, maximum number of formable MGs is determined by the algorithm presented in (3.2.1). Then run the optimization problem for MG formation (9) to (24) for all possible number of MGs (1 to MG_{max}). Then the resiliency index (8) will be calculated for all conditions and the configuration with maximum resiliency index will choose as the optimum solution.

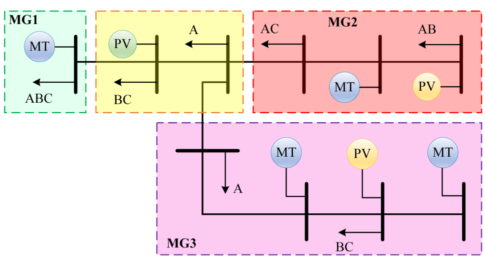

Fig. 4. Sample unbalance network

$$max\left(\sum_{n=1}^{n_m}\sum_{i=1}^{i_m}\sum_{t=1}^{t_{max}}\sum_{\delta} y_i^n \times \omega_i \times P_{i,t}^{D,\delta}\right) \tag{9}$$

$$1-\varepsilon \le \left|V_{i,t}^{\delta}\right| \le 1+\varepsilon \quad ,\forall i \in I, \delta \in P_0, \forall t \in T \tag{10}$$

$$\left(P_{ij,t}^{\delta}\right)^2 + \left(Q_{ij,t}^{\delta}\right)^2 \le \sigma_{ij}^n \left(S_{ij}^{max}\right)^2, \forall (i,j) \in L, \forall n \in N, \forall t \in T \tag{11}$$

$$\sum_{i=1}^{i_m} \sigma_{ik}^n P_{ik,t}^{\delta} + P_{i,t}^{G,\delta} - y_i^n P_{i,t}^{D,\delta} + s_i^{R,n} P_{i,t}^{R,\delta} - \sum_{j=1}^{i_m} \sigma_{kj}^n P_{kj,t}^{\delta} = 0, \forall k \in I, \forall n \in N, \forall t \in T, \forall \delta \in P_0 \tag{12}$$

$$\sum_{i=1}^{i_m} \sigma_{ik}^n Q_{ik,t}^{\delta} + Q_{i,t}^{G,\delta} - y_i^n Q_{i,t}^{D,\delta} + s_i^{R,n} Q_{i,t}^{R,\delta} - \sum_{j=1}^{i_m} \sigma_{kj}^n Q_{kj,t}^{\delta} = 0, \forall k \in I, \forall n \in N, \forall t \in T, \forall \delta \in P_0 \tag{13}$$

$$\beta_i^n V_i = \beta_j^n V_j - \sigma_{ij}^n \left(Z_{ij}^* S_{ij} + Z_{ij} S_{ij}^*\right), \forall (i,j) \in I, \forall n \in N \tag{14}$$

$$\sum_{\delta}\left(\left(P_{i,t}^{G,\delta}\right)^2 + \left(Q_{i,t}^{G,\delta}\right)^2\right) \le s_i^{G,n} S_i^{max}, \forall i \in I_g, \forall t \in T, \forall n \in N \tag{15}$$

$$\frac{\left|S_{i,t}^{G,a} + \alpha S_{i,t}^{G,b} + \alpha^2 S_{i,t}^{G,c}\right|}{\left|S_{i,t}^{G,a} + S_{i,t}^{G,b} + S_{i,t}^{G,c}\right|} \le T_{ub}, \forall i \in I_g, \forall t \in T \tag{16}$$

$$\sum_{n=1}^{n_m} \beta_i^n = 1, \qquad \forall i \in I \tag{17}$$

$$\beta_i^n \le \beta_u^n, \qquad \forall i \in I, \forall n \in N, u \in U_i \tag{18}$$

$$y_i^n \le \beta_i^n, \qquad \forall i \in I, \forall n \in N \tag{19}$$

$$\sigma_{ij}^n \le \beta_i^n \times \beta_j^n, \qquad \forall (i,j) \in L, \forall n \in N \tag{20}$$

$$\sum_{n=1}^{n_m} \sum_{(i,j)\in L} \sigma_{ij}^n = N_l - n_m + 1 \tag{21}$$

$$s_i^{G,n} = \beta_i^n \times sdg_i, \qquad \forall i \in I, \forall n \in N \tag{22}$$

$$s_i^{R,n} = \beta_i^n \times sr_i, \qquad \forall i \in I, \forall n \in N \tag{23}$$

$$\sum_{n=1}^{n_m} s_i^{G,n} \ge 1, \qquad \forall n \in N \tag{24}$$

Table I. Resources considered in 37-node test system

Bus #	Type	Phase (A, B, C)	Power (kVA)
703	DG	ABC	570
711	PV	C	10
712	PV	B	5
718	DG	ABC	600
722	DG	ABC	540
724	WT	B	15
725	PV	B	25
731	WT	B	20
736	WT	B	5
737	DG	ABC	250
741	DG	ABC	200
742	WT	B	50
775	DG	ABC	360

The objective is maximizing the restoration of critical loads subject to constraints (10) to (24). Constraint (10) applies the maximum voltage deviations; (11) sets the loadability of the lines; (12) and (13) set the balance of the input and output active and reactive powers of each bus, respectively; (14) is the formulation of voltage calculation; (15) sets the maximum output power of each DG; (16) sets the maximum tolerable unbalance condition for the synchronous generators; (17) indicates that a bus could only be in one microgrid; (18) asserts that a bus could only be in a MG only if its parent node is also present in that MG that parent nodes can be obtained using BFS search algorithm [15]; (19) indicate that each load could supply in a MG that its relevant bus belongs to; (20) explains that a line is within a MG, if both its end buses are within that MG, otherwise, that line does not belong to any MG; (21) shows the number of closed lines to form nm number of MGs; (22), (23) shows that a generator/renewable source belong to a MG if the buses that have these resources belong to that MG; (24) shows that there should be at least one generator in each MG.

4. Numerical Results

In order to show the effectiveness of the proposed method, it is simulated on two unbalance distribution networks; IEEE 37- node and 123-node test systems. In the simulations, unbalanced load flow performed with GrilLAB-D [16], and the optimization problem is performed with GAMS and BARON (basic open-source mixed-integer nonlinear programming) solver. It is supposed that the diesel generators are the only dispatchable generating sources. So, they are considered as PV buses.

4.1. IEEE 37-node Distribution Network

IEEE 37-bus distribution network that is considered in this simulation is presented in Fig. 5. Details about this system can be found in [17], and DGs' information is presented in Table I. Load ad DGs variation during a day is presented in Fig. 6. This network does not have any tie switches, so MGs should be formed by isolating a part of the system. The importance of different loads was randomly introduced in the range (1-10).

It is assumed that the fault occurrence on line 799-701 between 10 and 12 AM will isolate all parts of this network from the upstream network. With the maximum formable algorithm, it is obtained that up to 4 MGs can be formed. The minimum buses to form MGs, floating part (FP), and master DG (MDG) in each MG are presented in Table II.

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As mentioned, up to 4 MGs can be formed in the isolated area ($MG_{max} = 4$). So, all possible cases are forming 1 to 4 MGs that is presented in this section and the results are presented in Table III.

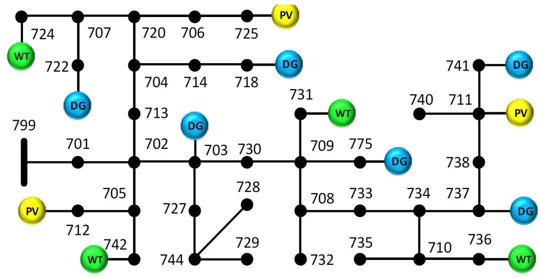

Fig. 5. IEEE 37-node test system

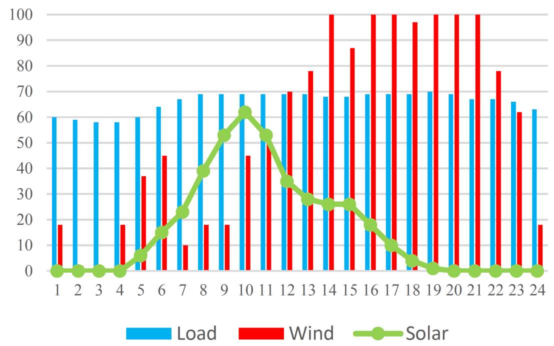

Fig. 6. Variation of load and renewable sources during a day

Table II. Minimum bused to form MGs in 37-node distribution network

MG	Nodes	MDG
1	704-714-718-720-706-725-707-722-724	718
2	703-727-744-728-729	703
3	708-709-731-732-775-733	775
4	734-710-735-736-737-738-711-740-741	737
FP	701-702-713-705-712-742-730	-

Table III. Results for MG formation in 37-node test system

n_m	$P_{res}^{p.u.}$	Reliability	Resiliency	Time (s)
1	0.8624	0.2500	0.2156	5.06
2	0.7936	0.4111	0.3262	9.50
3	0.7879	0.2909	0.2292	24.56
4	0.6007	0.6278	0.3771	58.23

4.1.1. Forming one MG in the isolated area

In this case, the entire isolated network will be divided into a single MG. It is expected that in this situation the highest amount of load supplies. The results of solving the optimization problem for MG formation show that 1462.11 kW of the loads will be supplied. The total amount of loads in the isolated part is 1695.33 kW, so the supplied load index (the first part of (8)) is equal to 0.8624, and the reliability index (the second and third part of (8)) is equal to 0.25. So, the resiliency index (8) is equal to 0.2156.

4.1.2. Forming two MGs in the isolated area

In this case, the isolated part will be divided into two MGs. The optimization problem results for MG formation show that 1345.5 kW of the loads will be supplied. The optimum configuration for MGs is presented in Fig. 7(a). In this situation, supplied load in MG1 and MG2 equals 956.34 kW and 389.16 kW, respectively. As a result, the supplied load index is equal to 0.7936, the reliability index is equal to 0.4111, and as a result, the resiliency index is equal to 0.3262.

4.1.3. Forming three MGs in the isolated area

In this case, the isolated part of the network will be divided into three MGs. Results of the optimization problem show that 1335.84 kW of loads will be supplied. The optimum MGs configuration is presented in Fig. 7(b). In this situation, supplied load in MG1 to MG3 is equal to 956.34 kW, 175.95 kW, and 203.55 kW, respectively. So, the supplied load index is equal to 0.7879, the reliability index is equal to 0.2909, and as a result, the resiliency index is equal to 0.2292. The essential point, in this case, is that the number of MGs has increased compared to the previous case (forming one MG), but the reliability index has decreased. On this subject, it can be stated that the reliability index consists of two parts; the number of MGs and scattering over loads. In this case, the number of MGs increased, but there is a large discord between supplied loads in different MGs (956.34, 175.95, 203.55 kW).

4.1.4. Forming four MGs in the isolated area

In this case, the isolated part of the network is divided into four MGs. Results of the optimization problem show that 1018.44 kW of the loads will be supplied. The optimum configuration for MGs is presented in Fig. 7(c). In this situation, supplied loads in MG1 to MG4 are equal to 494.04 kW, 173.88 kW, 175.95 kW, and 174.57 kW, respectively. So, the supplied load index is equal to 0.6007, the reliability index is equal to 0.6278, and the resiliency index is equal to 0.3771.

As shown in Table III, forming 1 MG in the isolated area will result in the highest amount of supplied load and the least reliability. Moreover, forming 4 MGs will result in the least supplied load and the most reliability. Eventually, forming 4 MGs has the most resiliency index and is the optimum configuration for MG formation.

4.2. IEEE 123-bus distribution system

The modified IEEE 123-bus distribution network is used for simulations in this part. Details about this test system can be found in [17]. There are six tie-switches: 60-160, 97-197, 13-152 and 18-135 that are normally closed and 54-94, and 151-300 that are normally open. This system is a three-phase unbalanced one with single-phase loads and DGs. 123-node distribution network and considered sources are presented in Fig. 8. Simulations are done in three scenarios; in the first scenario, a single fault; in the second scenario, multiple minor faults and multiple major faults are determined in the third scenario.

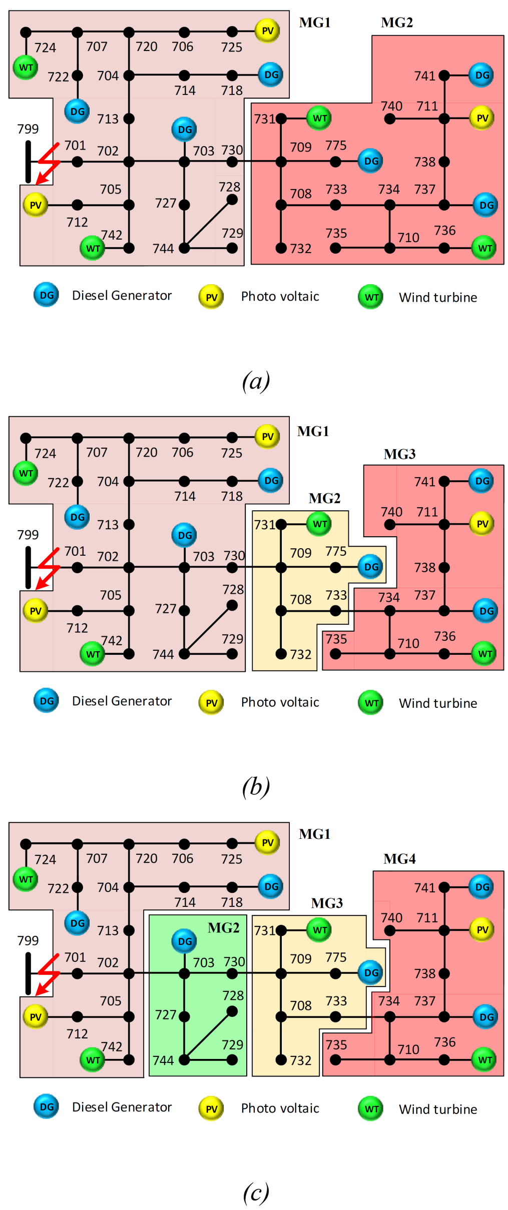

Fig. 7. Forming different number of MGs in isolated part; (a) Forming two MGs, (b) Forming three MGs, (c) Forming four MGs

4.2.1. Single fault

A single fault is assumed on line 60-160 (F1 in Fig. 8). The fault is cleared by opening the tie-switch 60-160. The methodology proposed in [2] is only based on forming MGs. In [2], for this particular scenario, seven MGs are formed after clearing the fault. Moreover, it is required to shed 20 kW load. However, in the proposed method, by using tie switches, isolated parts can be connected to the upstream network and there is no requirement of load shedding. As presented in Table IV, there are five different configurations connect the isolated part to the upstream network. So, the optimum configuration should be chosen based on the objective function (1). The objective functions for different configurations are presented in Fig. 9. As it is evident in this figure, the second configuration is the optimum one.

4.2.2. Multiple minor faults

Two faults on line 18-135 and 60-160 (F1 and F2 in Fig. 8) are assumed the same as in [2]. The faults are cleared by opening the tie-switches 18-135 and 60-160. In [2], restoration is performed by forming nine MGs; meanwhile, 40 kW load is also shed due to the supply deficiency. In the proposed algorithm, by changing the configuration of the network, it is possible to connect all parts of the network to the upstream network. So, it is possible to restore all amount of loads without load shedding. In this situation, only one configuration can connect all the isolated areas to the upstream network. In this configuration, the tie-switches 54-94 and 151-300 should be closed.

4.2.3. Multiple major faults

This scenario assumes that three faults occur on lines 97-197, 18-135, and 60-160 (F1, F2, and F3 in Fig. 8). A large part would be isolated. In this situation, a configuration connects a part of the isolated area to the upstream network. As a result, a part of the system will remain isolated. According to the maximum formable MG algorithm that is presented in (3.2.1), 3 MGs can be formed in the isolated area. In this situation, supplied load, reliability, and resiliency index should be calculated for forming 1MG to 3MGs.

By forming one MG in the isolated area, 835 kW of the loads will be supplied. Due to the 1075 kW load in the isolated area entirely, the supplied load index is equal to 0.7767. The reliability index is equal to 0.3334, and finally, the resiliency index is equal to 0.2589. By forming two MGs in the isolated area, 815 kW of loads will be supplied and as a result, supplied load index is equal to 0.7581. In this situation, 280 kW of the loads will be restored in one MG, and 535 kW will be restored in the other one. So, the reliability index is equal to 0.6014, and the resiliency index is equal to 0.4559. By forming three MGs in the isolated area, 755 kW of the loads will be supplied, so the supplied load index equals 0.7023. In this situation 80 kW of the loads will be supplied in one MG, 335 kW of the loads will be supplied in another MG, and 340 kW of the loads will be supplied in the last MG. So, the reliability index is equal to 0.5717 and as a result, the resiliency index is equal to 0.4015. Finally, the whole calculated indexes are presented in Fig. 10. As it is clear from this figure, by forming one MG, the maximum amount of loads will be supplied and forming two MGs will result in the maximum amount for reliability index. Totally, forming two MGs is the optimum configuration in this situation that is presented in Fig. 11(b).

5. Conclusion

A Resilient distribution grid has the ability to withstand and recover from low-probability high-impact events. Resiliency against these events is conceptualized in three distinct stages: prior, during and after the event. Rapid recovery is a feature of after an event stage. In this paper, restoration strategies to restore maximum loads as quickly as possible are investigated. The proposed approach attempts to restore the critical loads by using tie-switches to reconfigure the network. In case of isolated areas without the possibility of using upstream utility grid, sectionalizing the grid into several microgrids (MGs) is proposed to improve the system resiliency. The number of isolated MGs is an issue that is required to be properly determined. So, a new approach is proposed to compromise between amount and reliability of supplied load to find the optimum number of MGs in order to optimally allocate the resources to critical loads. The proposed method is simulated on the unbalanced IEEE-123 and 37-bus distribution grid with random locations for DERs. The results show more critical supplied load using reconfiguration and optimal configuration for MGs based on the proposed objective function.

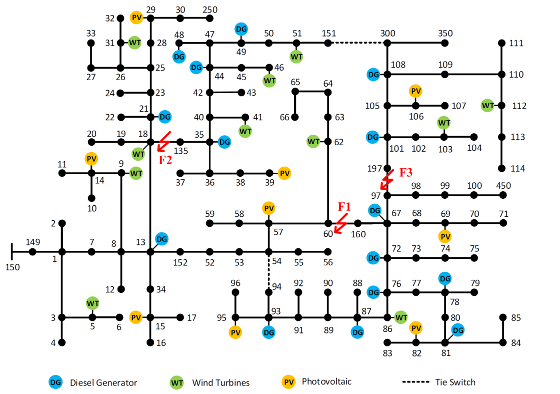

Fig.8. IEEE 123-bus distribution network

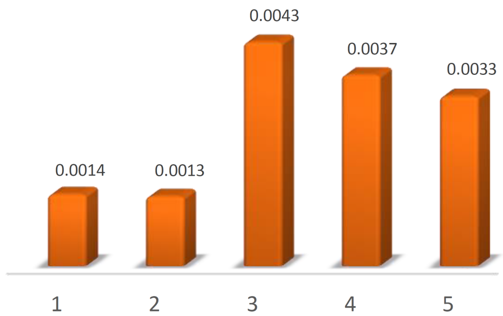

Fig. 9. Objective function for different configuration of first scenario of 123-node distribution network

Table IV. Different configurations for the first scenario in IEEE 123-node distribution network

Config.	Line with switch					switching	Loss (kW)
	54-94	151-300	13-152	18-135	97-197		
1	1	0	1	1	1	1	24.05
2	0	1	1	1	1	1	23.83
3	1	1	1	1	0	3	25.51
4	1	1	1	0	1	3	21.78
5	1	1	0	1	1	3	19.36

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Nomenclature

$\boldsymbol{i,j,k}$	Bus index
δ	Phase index
n	Microgrid index
t	Time index
u	Parent node index
I	Set of buses
L	Set of lines
N	Set of microgrids
I_g	Set of buses with generating sources
U_i	Set of parent nodes for bus i
P_0	Set of phases (A, B, C)
S_{ij}^{max}	Maximum power flow through line ij
MG_{max}	Maximum number of formable MGs
$S_i^{G,max}$	Maximum power of generator at bus i
N_m	Number of switches in the network
n_m	Number of MGs that intended to be formed
P_{loss}	Total power loss
P_{total}	Total active load of the network
T_{UB}	Maximum tolerable unbalance of synchronous generators
ω_i	Importance coefficient of the load at bus i
n_m	Number of microgrids
$P_i^{D,\delta}/Q_i^{D,\delta}$	Active/reactive load at bus I ans phase $\boldsymbol{\delta}$
sdg_i	Binary parameter indicating whether a generator is connected to bus I or not
sr_i	Binary parameter indicating whether a renewable source is connected to bus I or not
$v_{i,t}^{\delta}$	Bus voltage at bus i at time t in phase $\boldsymbol{\delta}$
$P_{ij,t}^{\delta}/Q_{ij,t}^{\delta}$	Active /reactive power flow of line ij at time t in phase $\boldsymbol{\delta}$
$P_{i,t}^{G,\delta}/Q_{i,t}^{G,\delta}$	Active/reactive power generation by generator at bus I at time t in phase $\boldsymbol{\delta}$
$P_{i,t}^{R,\delta}/Q_{i,t}^{R,\delta}$	Active/reactive power generation by renewable sources at bus I at time t in phase $\boldsymbol{\delta}$
$P_{non-res}$	Total power not restored at the isolated part
N_{sw}	Number of switching
ξ_n	Total active power restored at microgrid n
P_{res}	Total active power restored
σ_{ij}^n	Binary variable indicating line ij belong to microgrid n
y_i^n	Binary variable indicating whether load i is picked up by microgrid n
$s_i^{G,n}$	Binary variable indicating whether DG i is belong by microgrid n
$s_i^{R,n}$	Binary variable indicating whether renewable source i is belong by microgrid n
β_i^n	Binary variable indicating whether bus i belong to microgrid n