Outage Management in Active Distribution Network with Distributed Energy Resources

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***Abstract*—The occurrence of extreme events may cause outages in the network, affecting loads that are crucial for the functioning of human life. Existing distributed energy resources can be utilized to provide reliable supply to critical loads by forming self-sustained islands within the network. Island partitioning as a restoration strategy is proposed in this paper. A graph theory-based island partitioning scheme and optimal load shedding are modeled for this purpose. Following the repair of failed components, the nodes in the islands need to reconnect to the main operating network. An optimal multi-step reconnection schedule is developed for the distribution network to revert to its normal operating state and topology. The proposed framework is evaluated on a modified IEEE 37 node distribution test feeder for two outage scenarios. Results indicate that the island partitioning is an effective restoration scheme, and the multi-step reconnection schedule is dependent on the outage scenario.**

***Index Terms*—Distribution network, service restoration, distributed generation, resilience.**

I. INTRODUCTION

THe ever-increasing human dependency on electricity for sustenance and development has necessitated the need for a resilient power system. Distinguishing features of a resilient power system include its ability to withstand and respond to major disruptions and to rapidly reinstate power supply with minimum interruption [1]. Over the years, several strategies have been explored to enhance the resiliency of the existing power grid. With the installation of distributed energy resources (DER) gaining prominence, uninterrupted power can be supplied to loads even in the presence of a network-wide outage by utilizing the local generation. Besides this, the advent of power electronic inverters and automated switches employed in the distribution network has facilitated the restoration of supply using local energy sources to critical loads like hospitals, data centers, and military bases [2]. Reconfiguration of the distribution network topology has often been discussed as an effective technique to manage outages caused by catastrophic events [3], [4]. However, during unfavorable circumstances, acquiring and remotely controlling the status of the switches in the distribution system may be challenging for the distribution system operator (DSO), particularly if the communication network has been compromised [5]. Additionally, tie switches may not be present in the isolated section downstream to the outage, making it impossible to utilize reconfiguration technology for outage management. Hence, in such scenarios, a feasible strategy is to rely on distributed generation (DG) units for providing sustained power to critical load centers.

A cluster of loads accompanied by the DG can be made to function as a separate entity that is self-sufficient when severe disruptions occur in the network. This scheme is referred to as island partitioning [6] and it helps to reduce outage time of the loads connected. Forming such islands around micro sources is desirable for achieving load generation balance and facilitating distributed control. In [7], [8], optimal island partitioning suitable for planning emergency load management has been discussed. In these works, the island partitions are obtained from sophisticated optimization algorithms considering parameters obtained from optimal power flow (OPF). However, there is uncertainty associated with distribution system operating conditions under such extreme circumstances, and hence performing network partitioning subject to OPF is not practical. Also, such studies are well suited for planning restoration strategy provided the outages in the network are known or are predicted. Given that the information on the DG installments and topology of the distribution network is available before the occurrence of an outage, a graph theory-based approach can be adopted to determine island partitions, which enables a fast and efficient response with a minimum outage duration. One such approach is developed in this paper, where a modified Kernighan-Lin graph partitioning algorithm is used primarily with a secondary optimal load shedding technique to achieve load generation balance and feasible operations within islands.

The service restoration by DG enables the DSO and maintenance personnel to assess the damage and launch prioritized repair on failed components without affecting important loads in the network [9]. After repair, the distribution system has to be brought back to its normal operating topology and state. Thus, the islands formed temporarily to mitigate the outage have to be reconnected to the main grid component. There is a need for an optimal strategy to transfer these self-sustained and confined subsystems to the main distribution network after repair and maintenance. Although several methodologies have been used in the literature to partition the distribution network into islands during outages due to extreme events, little discussion has been found in these works on how to reconnect the islanded sections to the main operating network following

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outage rectification. In [10], [11], a multi-step approach was used to meet the demand during an outage, by relying on DERs during the service restoration phase preceding repair. A similar approach is adopted in the current work, where the island transfer and re-energization of loads by the main grid are performed in steps in an optimal fashion while satisfying the network operation constraints.

The main contribution of this paper is to develop a graph theoretic island partitioning scheme, which is suitable for timely restoration of important loads during emergency conditions. Besides this, an optimal schedule for the stepwise reconnection of the loads following the network repair is also developed.

The organization of the paper is as follows. In section II, the approach used for island partitioning and load shedding is discussed. Section III discusses the scheme for optimal multi-step reconnection of the network after repair. The results are presented in section IV. Finally, conclusions and future work are discussed in section V.

II. GRAPH-THEORETIC SELF SUSTAINED ISLANDING

As discussed earlier, the goal of forming islands around a local generating unit is to supply power to important loads in the network when the main grid is affected by a disastrous event. When extreme events occur, it is desirable to dynamically provide supply to critical load centers rapidly with minimum interruption. To this end, an islanding scheme based on available information such as, the topology of the distribution network, the location of DG and critical load points, can be used to partition the affected area in the network into multiple islands. Once the cluster of loads surrounding the DG operating independently from the grid is determined, self-sufficiency in the formed island is ensured by shedding loads of low priority. The outage management model developed in this work is described in Fig. 1.

The objective is to form islands that are comprised of loads and DG in the area affected by outage due to extreme events, to provide reliable supply with minimum disturbance. From the reliability perspective, the number of components between the source and the destination in a network must be minimal. This requires that a tight cluster of loads around each DG must be formed such that the distance of the loads from the DG is minimized. Also, it is imperative to form islands with minimum switching, since further disturbances in the network may aggravate the already stressed distribution network. These requirements are considered by the objective of the islanding scheme developed in this work.

The graph partitioning is a class of problems that form groups or clusters of vertices from a given graph G= (V, E), where V is the set of vertices and E is the set of edges. The distribution network model can be converted into its equivalent graph to determine communities within the network. Graph partitioning is an NP-hard problem and can be solved by heuristic algorithms [12]. One of the most powerful and efficient heuristic algorithms used for this problem is the Kernighan-Lin (KL) algorithm. Although the KL algorithm was initially proposed for bi-partitioning of a graph, it can be modified to perform multi-way partitioning [12]. The KL algorithm is based on iterative swapping of vertices to get a partition of vertices, such that the cut set between the partitions is reduced and the distance between the nodes in each partition is minimal. The cut set between partitions is associated with the line switching required to form islands, and minimizing the cut set ensures minimal switching. Also, the tight spatial clustering of nodes reduces the distance between the DG and the loads, resulting in both the reliable and efficient transfer of power. Hence, the KL algorithm is adopted for partitioning the affected area into multiple islands based on the number of DG. Algorithm 1 describes the problem-specific KL-based algorithm used in the study.

Algorithm 1 A multi-way KL algorithm to partition distribution network around DERs

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Generate a graph for the isolated section of the distribution network affected by outages
Determine the number of nodes ($N$) and the number of DER ($K$) devices in the graph of the isolated section
Designate each DER to $K$ different partitions
Divide the graph into $P$ and $\overline{P}$ partitions with $N/K$ and $N - N/K$ nodes, respectively
while $K \neq 1$ do
    for Each partition $P$ do
        for Every node $n$ in the partition $P$ do
            Calculate $E_n$=$\sum_v c_{nv}$ $\forall v \notin P$ and
              $I_n$=$\sum_v c_{nv}$ $\forall v \in P$; where $c$ = 1 if an edge exists between nodes $n$ and $v$
            Compute $D_n$=$E_n$ - $I_n$
        end for
    end for
    for Every pair in $P$ and $\overline{P}$ do
        if Pair $(n1, n2)$ where $n_1 \in P$ and $n_2 \in \overline{P}$ are not nodes with DER then
            Determine the gain or reduction in cut set if the pair $(n1, n2)$ is swapped, which is:
              $D_{n_1} + D_{n_2} - 2c_{n_1,n_2}$
            for All nodes $a \in P - \{n_1\}$, $b \in \overline{P} - \{n_2\}$ do
                Update $D$ considering the swap using:
                  $D'_a$=$D_a + 2c_{a,n_1} - 2c_{a,n_2}$ &
                  $D'_b$=$D_b$+$2c_{b,n_2}$−$2c_{b,n_1}$; where $c$=1 if nodes are connected
            end for
        end if
    end for
    Determine the number of swaps which maximizes the gain in cut set reduction and perform the swapping
    Lock the nodes in partition $P$ from any further swaps
    Update $N$=$N - N/K$ and $K$=$K - 1$
end while
Obtain the $K$ partitions for the isolated section downstream to network failure
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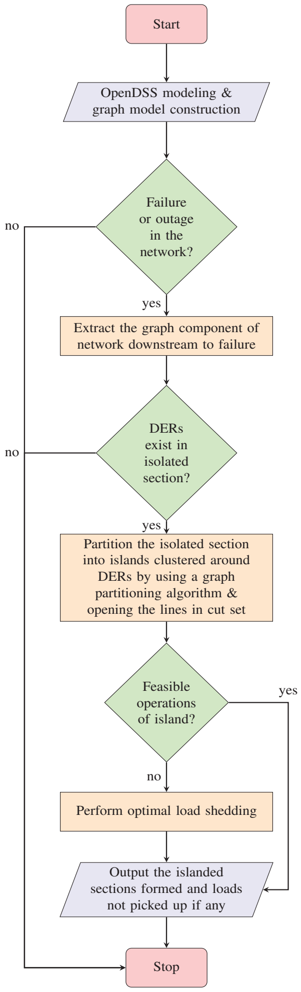


Fig. 1: A flowchart for formation of self-sustained islands during outages in the distribution network

Once the vertex partitioning results are available, the cut set that entails the edges or lines separating the different partitions are opened using sectionalizing switches, to form islands within the affected area downstream to the network failure. Additionally, it is necessary to minimize generation load imbalance and ensure that the sectionalized portion of the network is operating within acceptable limits. As a result, low priority loads are shed while simultaneously minimizing the Energy Not Served (ENS) in each islanded section. The load shedding and operation feasibility assurance in an islanded section is formulated as an optimization problem, which is described as:

$$Minimize \quad ENS = \sum_{t} \sum_{i \in U_L} w_i P_{i,t}^d \tag{1}$$

Subject to:

$$\sum_{i \in G} P_i - \sum_{j \in C_L} P_j \geq 0 \tag{2}$$

$$V_{min} \leq V_i \leq V_{max} \quad \forall i \in N_{island} \tag{3}$$

$$S_l \leq S_l^{max} \quad \forall l \in B_{island} \tag{4}$$

The objective ENS is calculated in (1) using the active power demand P^d and weight w of each node i in the unconnected set of loads U_L over the total restoration period. In (2), the sufficiency of power generated by DG to meet the total demand is considered as a constraint, where G is the set of generating units within the island and C_L is the set of connected loads. The voltage at all nodes in the island represented by N_{island} is constrained to be within acceptable limits in (3). In (4), the capacity of the lines is ensured to be within the maximum capacity limits, where B_{island} is the set of all branches in the island. Using this framework, the low priority loads are shed optimally to ensure that the islands formed during emergency conditions satisfy the requirements of a stable and reliable operating power network. Consequently, islands are formed in the distribution network as a restoration strategy during extreme events, to provide a reliable power supply to various important loads thereby minimizing outage duration.

III. OPTIMAL MULTI-STEP RECONNECTION

The restoration strategy developed in this work aims to support critical loads in the distribution network, when it is unable to use reconfiguration to mitigate the outage caused by catastrophic events. Under such circumstances, the islands continue to exist until the failed components are repaired. The rate of repair of component failure is subject to different parameters such as the extent of damage, availability of resources, etc., which is not considered in this paper. Once the repair is completed, the distribution network needs to return to its normal operating condition and topology. Thus, the islands in the network need to be reconnected to the main network. This is performed after closely monitoring the voltage, frequency, and phase rotation in the main distribution network [13]. If the operating condition of the main system is within acceptable limits, the transfer of islands to the main grid can be performed.

Often the island transfer is executed after achieving synchronization between the main distribution network and the DG islands. However, if the DG island system does not have synchronization sensors, as is usually the case, the common practice is to momentarily interrupt the loads within the islands and use the ‘open-transition transfer’ of the DG islands to the main network [13]. In this section, an optimal framework for load energization after one such island transfer is discussed.

The re-energization of the loads is to be performed in steps owing to stability issues. This is basically a scheduling problem where the loads are to be picked up in a minimum number of steps without affecting the stable operation of the distribution network. The bin packing algorithm is commonly used in operations research for similar kinds of scheduling [14] and is suitable for the re-energization problem.

The bin packing problem is an NP hard combinatorial optimization problem, which can be solved using classical as well as heuristic methods [15]. Given a set of items $\mathbb{L} = \{i_1, i_2, i_3, ..., i_m\}$ with weights $w_{i_1}, w_{i_2}, w_{i_3}, ..., w_{i_m}$, the goal is to pack these m items into a minimal number of bins $B_1, B_2, ..., B_k$ of capacity $C_1, C_2, ..., C_k$. The minimum number of bins required is determined using an optimization technique. In the re-energization problem, the items to be packed or scheduled are the loads in the network and the load demand corresponds to the weight of the items. The loads being energized in steps is equivalent to packing the items into bins, and the capacity of the bins in this case is the maximum allowable load pick up in a step. This is formulated as a mixed-integer programming problem and its objectives and constraints are described below:

$$Minimize \quad \sum_{j=1}^{k} z_j \tag{5}$$

$$x_{ij} = \begin{cases} 1 & \text{if load or item } i \text{ is in bin } j \\ 0 & \text{otherwise} \end{cases} \tag{6}$$

$$z_j = \begin{cases} 1 & \text{if bin } j \text{ is used} \\ 0 & \text{otherwise} \end{cases} \tag{7}$$

subject to:

$$\sum_{j=1}^{k} x_{ij} = 1 \quad \forall i = 1, ..., n \tag{8}$$

$$\sum_{i=1}^{m} w_i x_{ij} \leq z_j C_j \quad \forall j = 1, ..., k \tag{9}$$

$$\sum_{h=1}^{j-1} x_{(i-1)h} = 1 \quad \forall i = 1, ...n \ ; \ \forall j = 1, ..., k \tag{10}$$

where x_{ij} is the decision variable that determines the bin or step in which load pickup is scheduled, and z_j determines the utilization of a bin. The objective is to minimize the number of bins used for total load pick up as represented by (5). In (8), the load is constrained to be completely picked up in a particular step and fractional pickup is not permitted. The total load picked up in a step is ensured to be within the maximum allowable load pick up considering stability in (9). In order to avoid large frequency deviations, the load pickup at each step is constrained to 5% of the total generation in the network [10]. Also, considering the radial nature of the distribution network, energizing a node is dependent on the preceding node, which is considered as a constraint in (10).

IV. RESULTS AND DISCUSSION

The proposed framework of outage management and multi-step reconnection after repair is tested on a modified IEEE 37 node distribution test system. The loads in the network are assigned weights to represent their importance. Four distributed solar generators are considered at nodes 706, 713, 727, and 738 with sizes of 400, 200, 400, and 500 kW, respectively. Each PV unit is integrated with a battery energy storage system (BESS). The rated capacity of each BESS is comparable to the rating of the associated PV, and the aggregated capacity of the four BESS is 1,000 kWh. A reserve of 40% of the BESS rated capacity is maintained at all times during normal operations for emergency conditions. The charging and discharging cycle of the BESS is designed to achieve the maximum utilization of PV generation during normal operations. During the outage, the BESS operates only in the discharge mode when the PV output is insufficient to meet the demands. It is assumed that the outage occurs at 11:00 am and the rectification of the failure is completed at 7:00 pm, after which the reconnection is to be performed. Two case studies are considered to evaluate the effectiveness of the proposed method.

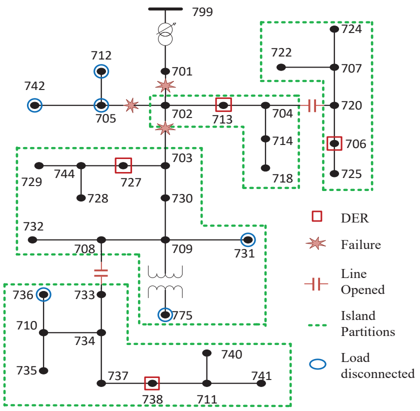
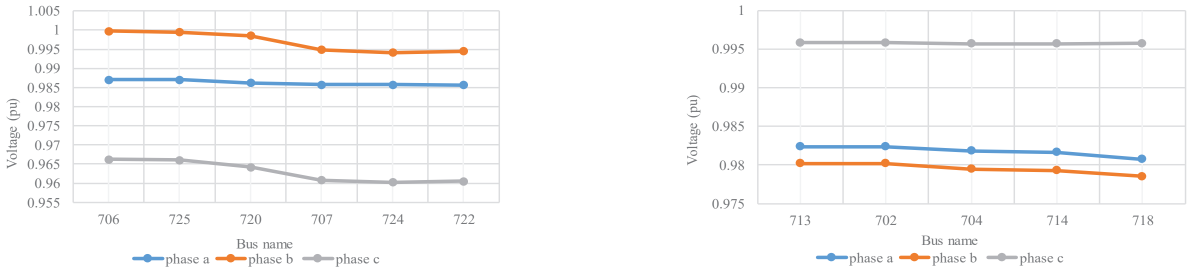


Fig. 2: The modified 37 node distribution test system with DERs, illustrating feasible island partitions formed for Case 1

A. Case 1: Outage of Three Lines

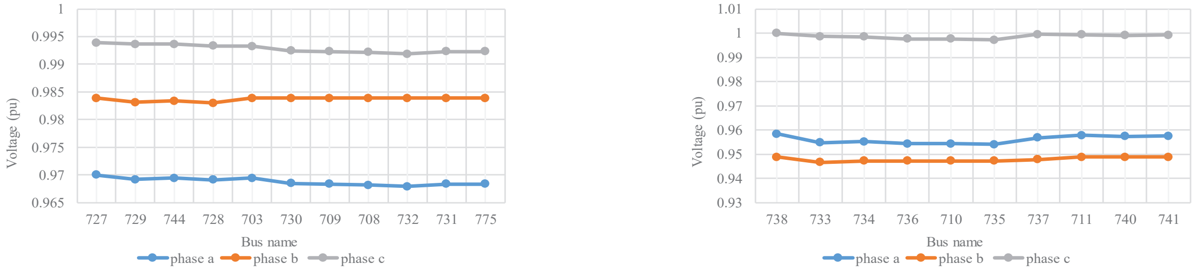
In this case, the outage is simulated at three lines between nodes 701-702, 702-703, and 702-705. Fig. 2 illustrates the island partitions created to mitigate the outage along with the loads shed. As seen in the figure, there are two isolated sections formed, i.e., one beyond line 702-713 and the other downstream to node 703. In both these isolated sections, there exist two DER units each to assuage the outage. The graph partitioning methodology is applied to obtain a tight cluster of loads around the DERs with minimum switching. The lines opened to separate the partitions are also marked in Fig. 2. The formed islands, load shed, and the ENS are summarized in Table I. It is observed that islands 1 and 2 formed in one isolated section do not require any load shedding, owing to their smaller size and sufficient DER capacity. However, islands 3 and 4 that are created in the other isolated section are larger in size; a few loads are shed in order to achieve generation sufficiency. The voltage profiles of the four islands after partitioning and optimal load sheddings are depicted in Fig. 3. It is observed that the voltages at various nodes in the islands are within acceptable limits.

Following the repair, the nodes are reconnected to the main distribution network using the multi-step reconnection approach. The optimal steps in which the nodes in the islands are reconnected are summarized in Table II. It is seen that the nodes in island 2 are initially picked up by the main network followed by islands 1, 3, and 4. This is owing to the radiality constraint imposed where the preceding node is to be energized before a node is connected to the network. Hence, the islands are connected in order of its proximity of the point of common coupling to the source bus. Also, not all the nodes



(a) Voltage profile of island 1

(b) Voltage profile of island 2



(c) Voltage profile of island 3

(d) Voltage profile of island 4

Fig. 3: The voltage profiles of the islands after partitioning for Case 1

in an island are completely picked up before another island transfer is initiated. In order to satisfy the capacity constraint while simultaneously minimizing the number of steps, a few nodes in the island are picked up at later stages. For example, node 718 in island 2 is picked up after island 1 transfer is initiated. The total load connected at each step is also provided in Table II.

TABLE II
OPTIMAL MULTI-STEP GRID ENERGIZATION OF LOADS FOR CASE 1

Step	1	2	3	4	5	6	7	8	9	10	11	12	13
Nodes picked	702 713 704 714	720 706 725 707	718 724	722	703 727 730 709	708 732 733	744 729 734	737	738	711 731	741 710 735	740 736	728 775
Load connected (kW)	112	116	116	147	116	116	115	127	115	78	116	115	114

B. Case 2: Outage of Four Lines

In this case, the outage is simulated at four lines between nodes 701-702, 702-703, 730-709, and 709-731 as shown in Fig. 4. The isolated section of the graph between nodes 701 and 703 is partitioned into two islands in association with the two DER units present in this section. The component of the graph beyond node 703 is by default split into two sections by the component failure. However, each of these downstream sections can function as a self-sustained island as they house DERs. The results of graph partitioning and optimal load shedding are summarized in Table III. In this case, islands 3 and 4 are formed due to outages, which is not the result of the graph partitioning scheme. As compared to Case 1, due to the nature of outage, the distribution of loads to DERs is quite large, which necessitates shedding of loads resulting in increased ENS. The voltage profiles of the islands are shown in Fig. 5. Since the island 1 formed in this case is same as that in Case 1, the corresponding profile is not included in Fig. 5. The result of the optimal multi-step reconnection is summarized in Table IV. It is observed that the reconnection of nodes to the main network is dependent on the location of the outage and the islands formed during restoration.

TABLE I
GRAPH-THEORETIC ISLAND PARTITIONING FOR CASE 1

Island No.	DER/ root node	Nodes in island	Load node not picked	ENS (kWh)
1	706	725, 720, 707, 724, 722	-	-
2	713	704, 714, 718, 702	-	-
3	727	703, 730, 709, 728, 744, 729, 731, 732, 708, 775	775, 731	770.53
4	738	733, 734, 737, 736, 710, 735, 711, 740, 741	736	370.05

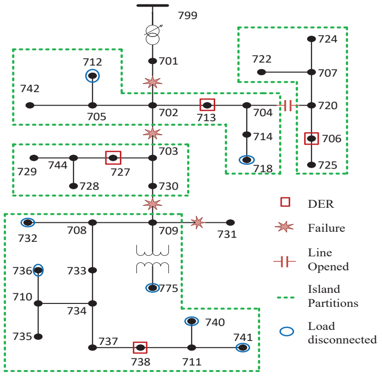
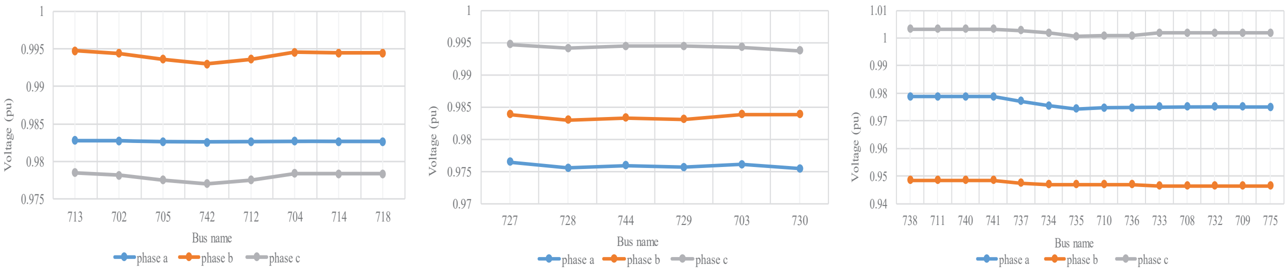


Fig. 4: The modified 37 node distribution test system with DERs, illustrating feasible island partitions formed for Case 2



(a) Voltage profile of island 2

(b) Voltage profile of island 3

(c) Voltage profile of island 4

Fig. 5: The voltage profiles of the islands after partitioning for Case 2

TABLE III
GRAPH-THEORETIC ISLAND PARTITIONING FOR CASE 2

Island No.	DER/ root node	Nodes in island	Load node not picked	ENS (kWh)
1	706	725, 720, 707, 724, 722	-	-
2	713	702, 705, 742, 712, 704, 714, 718	718, 712	1,612.69
3	727	703, 730, 728, 744, 729	-	-
4	738	711, 740, 741, 734, 735, 710, 736, 733, 708, 732, 709, 775	740, 741, 732, 736, 775	1,953.76

TABLE IV
OPTIMAL MULTI-STEP GRID ENERGIZATION OF LOADS FOR CASE 2

Step	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Nodes picked	702 713 704 714	703 730 709 708 732	720 707 724	727 733	705 744 712	718 729	706 725 742	728	734 775	737	710 738	711 740 741	735	731 736	722
Load connected (kW)	112	116	116	116	116	116	123	115	116	127	115	116	78	116	147

V. CONCLUSION

In this paper, a graph theory-based island partitioning scheme was proposed as a restoration strategy during an outage in the network. The self-sufficiency of the islands was further ensured by optimal load shedding. Subsequent to the repair of failed components, in order to regain the normal operating state and topology, an optimal schedule for reconnecting the islanded nodes was derived. The methodology was evaluated on a modified IEEE 37 node distribution test system for two different scenarios. The results indicated that the island formation in response to the outage was quite effective in providing reliable supply to critical loads while satisfying system constraints. In addition, the reconnection of nodes to the main network was found to be dependent on the nature of the outage and the formation of islands.

The DERs in this study were considered to operate independently to supply the demand of the associated islands. This could further be extended to incorporate networked islanding mode where multiple DERs co-ordinate to meet the demand of an island. Additionally, the restoration strategy can be further improved by considering the network reconfiguration capability which enables interconnection between different sections of the network. Besides this, the dynamic response of the network can be evaluated during both island formation and reconnection to ensure safe and stable operations with the proposed scheme.

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