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Using Microgrids for Critical Load Restoration in Distribution Systems

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Abstract: This paper proposes a restoration strategy using microgrids to restore power to critical loads to enhance distribution system resilience after an extreme event. The restoration problem is posed as an optimization problem to maximize the number of critical loads restored after the extreme event has resulted into multiple faults. After the fault, the restoration strategy alters the topological structure of the distribution network by removing the faulted lines and applies minimum spanning tree algorithm to find a possible topology that will be used for the restoration. The service time to the restored critical loads is incorporated as one of the constraints to ensure continuous supply for the duration of the outage. The problem is modeled as a mixed-integer linear program (MILP) and solved using the CPLEX solver on the MATLAB platform. The effectiveness of the proposed restoration strategy is validated using the modified IEEE 33-bus test system under multiple fault scenarios that represent damage resulted from the extreme event.

Keywords: Resilience, Distribution Systems, Critical load restoration, Microgrids, Mixed integer linear programming (MILP).

1. INTRODUCTION

Climate change is expected to increase the occurrence and severity of extreme weather conditions (e.g. earthquakes, floods and hurricanes) which will damage our electrical systems resulting into more large-scale power outages, affecting hundreds of millions of people including the country's critical services such as the security, health and economy (Kenward & Raja, 2014). For instance, weather-driven power outages costed the U.S economy approximately \$20-\$55 billion annually, causing around 147 million customers to lose power supply for at least one hour (Abi-Samra, 2013) (Kenward & Raja, 2014). In addition, 90% of customers during extreme weather events get affected due to damages at the distribution system level (Poudel & Dubey, 2019). The above-mentioned statistics highlights a crucial need to improve distribution system resilience against extreme weather conditions.

There is still no agreement regarding the definition of the concept of power system resilience. According to an earlier definition by the U.S Presidential Policy Directive 21 (PPD-21), power system resilience is defined as "*the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions*" (Office, 2013). Zooming into resilience at distribution level, a resilient distribution system should have the ability to restore power to the critical loads for the duration of outage resulted from extreme conditions (Poudel & Dubey, 2019). During extreme weather conditions when the main grid power is not available, microgrids (MGs) could be used to improve distribution system resilience (Bajwa, et al., 2019). In addition to using MGs (Ott, et al., 2019), (Wang & al., 2018) (Chen, et al., 2016), some recent studies utilize distributed energy resources (DERs) and distributed generation (DGs) to restore critical loads that belong to the distribution feeders (Poudel & Dubey, 2019) ,(Bie, et al., 2017). Researchers come up with different strategies to achieve distribution system resilience (Ott, et al., 2019), (Wang & al., 2018), (Poudel & Dubey, 2019).

(Ott, et al., 2019) proposed a two-stage load restoration strategy that utilizes interconnected multi-microgrids operating in islanded mode to restore a maximum number of disconnected loads to improve distribution resilience. They use outage management system to coordinate the interconnected multi-microgrids. (Wang & al., 2018) focuses on using existing microgrids to restore critical loads after an extreme event considering limited capacity of DGs within the microgrids. (Poudel & Dubey, 2019) proposed a framework to restore power to critical loads in the event of a major disaster by optimally using DERs, the framework also considers the critical load restoration time as well the post-restoration reliabity. Unlike the above studies, (Reddy, et al., 2018) considers the time required to find the optimal restoration plan i.e., the time it takes for repair crews to dispatch and isolate the faulted lines. This paper proposes a restoration strategy formulated as a mixed-integer linear programming (MILP) optimization problem that aims at using existing stand-alone microgrids to maximise the number of critical loads restored for a possible restoration time until the main grid recovers. The restoration time refers to the duration that a critical load can be served by a microgrid without any interruptions. After the extreme event and faults have been located, the proposed strategy isolates the faulted lines and applies the minimum spanning tree (MST) search approach considering the impedance of the lines to reconfigure the network with assistance of tie-lines to find a possible network topology with minimum impedance path. The advantage of this approach is that restoration paths that will be obtained by the MILP from the reconfigured topology will be of minimal losses. The MST also guarantees that the possible network topology obtained after the fault is a radial topology. The restoration strategy then translates the problem into a MILP problem by defining the distribution system's control variables and constraints in order to maximise the number of critical loads restored. The method focuses on using the estimated available generation of a microgrid to serve critical loads in the distribution feeders. The MILP solution provides a unique restoration path and restoration time for each restored critical load.

The rest of this paper is organized as follows: Section 2 discusses the problem formulation for the proposed restoration strategy; section 3 presents the results of the case study that validate the proposed restoration strategy. Conclusions are presented in section 4.

2. PROBLEM FORMULATION

The critical load restoration strategy is formulated using the following assumptions:

- Distribution systems have a meshed structure but are often operated radially. Hence, the assumption is that the distribution topology is radial after the extreme event.
- After the extreme event, the main grid power is not available, and MGs are operating in islanded mode for all the simulation cases.
- The microgrids would first serve their own critical loads and use the reserve power to serve the other critical loads on the distribution feeder it is connected to.
- The predicted power output of the microgrids is the combination of the distributed generation outputs within the MGs and its assumed to be constant as well as its reserve energy for the duration of a simulation case.
- Distribution lines have open/close switches.
- The loads are of fixed values of their maximum demand.
- To avoid frequent switching operation, the restoration strategy is determined only once, immediately after the extreme event and remains unchanged until the main grid power comes back.

2.1 Graphical representation

A graph-theoretic method is used to represent the distribution network and reconfiguring the network after fault isolation. The reconfigured network includes tie-lines. The network is modelled as a weighted undirected graph $G = (V, E, W)$, where V is the set of all vertices representing load nodes and microgrids, E is the set of all edges representing the distribution lines including the tie-lines and W is weighting of the edges in G using their line impedances. After the extreme event and fault locations have been determined and removed from the network, the proposed method uses minimum spanning tree (MST) discussed in (Li, et al., 2014). The approach searches for a path with minimum impedance from the microgrid node to all the nodes to form a tree post-fault radial topology with minimum power losses in the network so that more power can be available to be used to restore a maximum number of critical loads. However, power losses are not optimized in this paper. The obtained topology is then used by the MILP model to find a resilient restoration plan based on the number of critical loads restored.

2.2 Mathematical formulation

After the post-fault topology has been decided, the problem is formulated as a MILP optimization problem with an objective to maximise the number of critical loads restored weighted by their priority for a maximum possible restoration time, subject to power flow, service time, operation and connectivity constraints.

A. *Objective function*:

The following objective function has been used:

$$F = max \sum_{i=1}^{N} (w_i \cdot \gamma_i \cdot t_k),\ \ k \in M \tag{1}$$

where
F: Objective function.
i: Index for nodes.
N: Set of all nodes in the distribution network.
k: Index for microgrids.
w_i: Priority weighting factor of critical loads.
γ_i: Critical load status variable at node i.
t_k: Restoration time for microgrid k.
Subject to the constraints discussed in sections B, C, D and E below:

B. *Power flow Constraints*:

This paper uses a linearized approximation of a DistFlow model to formulate the power flow and voltage constraint of a radial distribution network at each bus (Yeh, et al., 2012) . DistFlow equations are optimal ac power flow equations for radial distribution networks (Baran & Wu, 1989). The linearized DistFlow equations used for the power flow are given as follows:

$$P_i^k = n_i^k p_i + \sum_{j \in Y} P_j^k\ , \forall k \in M, i \in N \tag{2}$$

$$Q_i^k = n_i^k q_i + \sum_{j \in Y} Q_j^k\ , \forall k \in M, i \in N \tag{3}$$

$$V_j^k = V_i^k - \frac{r_{ij} P_j^k + x_{ij} Q_j^k}{V_0}, \forall k \in M, i \in N, j \in Y \tag{4}$$

where:
P_i^k: Active power injected at node i by microgrid k.
Q_i^k: Reactive power injected at node i by microgrid k.
V_i^k: Voltage at node i when supplied by microgrid k.
V_0: Reference voltage
n_i^k: Node-microgrid assignment variable.
p_i: Active power demand at node i.
q_i: Reactive power demand at node i.
j: Index for children nodes.
N: Number of nodes
Y: Set of children nodes, subset of N

r_{ij}: Resistance between node i and j.
x_{ij}: Reactance between node i and j.

Since the post-restoration network is a tree topology with a microgrid at root node, each node has one-inflow power as shown in Figure 1.

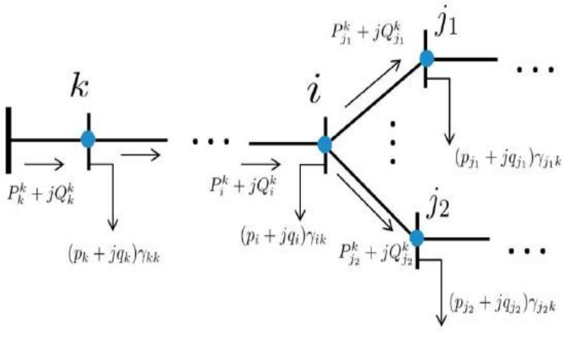

Figure 1: DistFlow model for a radial distribution network regarding microgrid $\boldsymbol{k}$.

For the voltage constraints in equation (4), the voltage at the microgrid node is set to the reference value, denoted by V_0^k. The linear approximation used in equations (2)-(4) is based on the justification by (Baran & Wu, 1989) that the non-linear terms represent the losses which in practice should be much smaller than the power terms and can be ignored. To show that the power flow results obtained using the linearized DistFlow model are valid, (Chen, et al., 2018) compared power flow results obtained from using the linearized DistFlow with OpenDSS results and show that there was a strong correlation with a maximum voltage error of 0.005 p.u. OpenDSS is an open-source distribution system simulator software developed by the Electric Power Research Institute (EPRI) that uses Newton-Raphson method to solve the power flow problem.

C. *Operation constraints*:

If node i belongs to microgrid k, the voltage (V_i^k) at that particular node should be within the range specified in equation (5) during the restoration process. The constraint in equation (5) also ensures that the nodal voltage will be zero for de-energized nodes. The total sum of the loads served by microgrid k should not exceed its maximum active and reactive power capacity at the time of the restoration. These constraints are expressed as in equations (6) and (7) respectively.

$$0.95 \times n_i^k \le |V_i^k| \le n_i^k \times 1.05, \forall k \in M, i \in N \tag{5}$$
$$0 \le \sum_{i=1}^{N} n_i^k p_i \le P_k^{max}, \forall k \in M, i \in N \tag{6}$$
$$0 \le \sum_{i=1}^{N} n_i^k q_i \le Q_k^{max}, \forall k \in M, i \in N \tag{7}$$

where
P_k^{max}: Active power capacity of microgrid k in kW.
Q_k^{max}: Reactive power capacity of microgrid k in kVar.

D. *Service time constraints*

This constraint is to ensure maximum possible duration (t_k) for which the microgrid can serve critical loads uninterruptedly with given amount of energy reserve. t_k depends on the reserve energy (E_k) of microgrid k at the time of the outage. It is assumed that the load profile is constant, and that the total sum of loads picked up by microgrid k is $\sum_{i=1}^{N} n_i^k p_i$. To obtain t_k for which MG k can serve $\sum_{i=1}^{N} n_i^k p_i$, the duration in which the picked loads remain served is constrained by the available energy reserve as seen in equation 8.

$$\left(\sum_{i=1}^{N} n_i^k p_i\right) \times t_k \le E_k, \forall k \in M, i \in N \tag{8}$$

t_k can be calculated as:

$$t_k = \frac{E_k}{\sum_{i=1}^{N} n_i^k p_i} \tag{9}$$

Considering the total energy reserve available in the network and the total critical load demand that need to be restored, the maximum possible duration (T_{net}) that the microgrids can serve the critical loads can be calculated as:

$$T_{net} = \frac{\sum_{i=1}^{k} E_k}{\sum_{i=1}^{N} p_i} \tag{10}$$

This means that the critical loads should be allocated amongst the microgrids in such a way that, each critical load is served for the maximum possible duration (i.e. $t_k \approx T_{net}$).

E. *Connectivity constraints*:

The distribution network in this paper is considered to be radial and so, a radial topology should be maintained during the restoration process, i.e. a load can only be served by one microgrid through a unique path and restoration paths to other loads do not overlap:

$$\sum_{k=1}^{M} n_i^k \le 1, \qquad \forall i \in N \tag{11}$$

3. CASE STUDY AND SIMULATION RESULTS

The MILP problem in this paper is solved using CPLEX 12.9. MATLAB R2018a is used to formulate the MILP which is then linked with the CPLEX solver to solve the optimization problem. The simulations were carried out on PC with Intel Core i3-6006U, 2.0 GHz processor and 4 GB RAM. The average simulation time is 8.16 seconds. The proposed restoration approach is verified using the modified IEEE 33-node test feeder system shown in Figure 2. The test feeder is modified to include two MGs connected at nodes 6 and 33. The loads at nodes 9, 17, 21, 28 and 33 are assumed to be the critical loads. The test system has 5 tie lines with normally opened sectionalising switches that will assist in the reconfiguration of the network after the fault. The detailed information of the MGs and the critical loads are listed in Tables 1 and 2, respectively. The locations of the MGs and the parameters of critical loads, the weighting factor are randomly selected at the beginning of the simulation and are maintained unchanged throughout the simulation for validating the proposed restoration method. The maximum power rating of the MGs is the maximum available power that each MG can supply to serve the critical loads on the distribution feeder.

Table 1: Critical load parameters

Node	**P (kW)**	**Q (kVar)**	**Weighting factor**
9	60	20	1.0
17	60	20	0.95
21	90	40	0.98
28	60	20	0.8
33	60	40	1

A weighting factor is assigned to each critical load to ensure that loads with higher priority are restored first in the event that there is shortage of supply.

Table 2: Microgrids parameters

MG	Node	P^{max} (kW)	Q^{max} (kVar)	Energy reserve (kWh)
1	6	180	70	850
2	33	300	240	1250

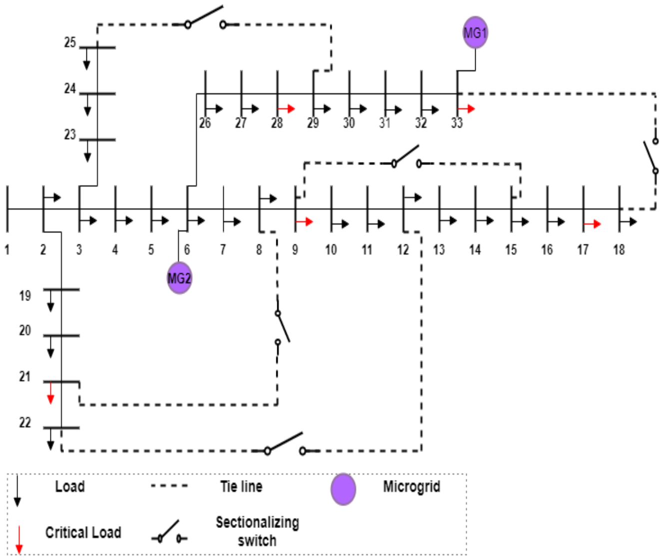

Figure 2: Modified IEEE 33-node test system

Five independent scenarios are simulated to demonstrate the effectiveness of the proposed critical load restoration method. The proposed restoration strategy is shown in Figure 3.

3.1 Minor damages scenarios

A. Scenario 1: Scenario with and without service time constraint

In this scenario, the first simulation is done with no lines damaged, both MGs are available and only the main grid is not available. Table 3 and Table 4 show the results when the restoration time (t_k) of the picked CLs is not maximised and when it is maximised, respectively. Using equation (10) the maximum possible restoration time for this scenario is 6.36 hours. It can be noted from Table 3 that when t_k is not maximised, MG_6 ends up supplying CL at node 9 only with a load demand of 60 kW leaving all the other loads to be supplied by MG_33 (load demand of 270kW). As a result, the CL at node 9 is restored for a longer period of 14.2 hours and the other CLs for 4.6 hours. The above situation can be avoided as it is not fair by ensuring that each CL is at least restored for a duration close to the maximum possible duration (i.e. $t_k \approx T_{net}$). In Table 4 the service time constraint is included in order to remove the bias. It can be noted that MG_6 is no longer supplying CL 9 only but also CL 21 and the restoration time results show fair allocation of MG reserve energy to each critical load and each CL is restored for a duration close to the maximum possible restoration time. This scenario shows the effect of maximising restoration time to ensure that each CL is served for a possible duration. The following scenarios will all include service time constraint.

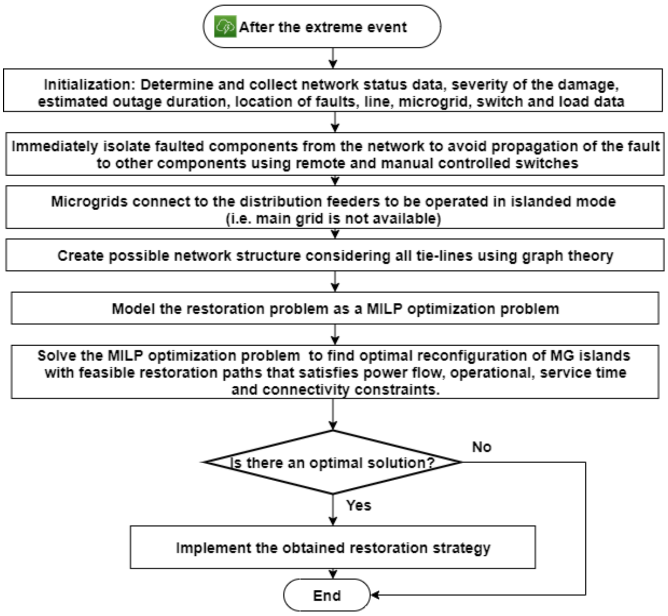

Figure 3: Proposed restoration strategy framework.

Table 3: Restoration strategy for scenario 1 without service time constraints

WITHOUT SERVICE TIME CONSTRAINT			
MG node ID	CLs	Restoration paths	Restoration time (t_k in hours)
MG_6	9	6-7-8-9	14.2
MG_33	17 21 28 33	33-18-17 33-32-31-30-29-25-24-23-3-2-19-21 33-32-31-30-29-28 33	4.6

Table 4: Restoration strategy for scenario 1 with the service time constraint

WITH SERVICE TIME CONSTRAINT			
MG node ID	CLs	Restoration paths	Restoration time (t_k in hours)
MG_6	9 21	6-7-8-9 6-5-4-3-2-19-20-21	5.67
MG_33	17 28 33	33-18-17 33-32-31-30-29-28 33	6.94

B. *Scenario 2: Multiple faults*

It is assumed that lines 2-19, 28-29 and the switch connecting the tie line from 8-21 are faulted during the restoration process. The faulted lines are randomly selected. The restoration strategy results for this scenario are shown in Table 5. Comparing the results from Table 5 with those from Table 4, it can be seen that the restoration path for CL 21 has changed from ***6-5-4-3-2-19-20-21*** to ***6-7-8-9-10-11-12-22-21*** due to the loss of line 2-19. The results of this scenario demonstrate that the proposed restoration strategy is able to effectively reconfigure the network based on fault locations and manages to restore 100% of the CLs. The restoration plan is shown in Figure 4. The red line between node 33-18 shows that the tie lie is in-service.

Table 5: Restoration strategy for scenario 2

LINES 2-19, 28-29 AND 8-21 ARE FAULTED			
MG node ID	CLs	Restoration paths	Restoration time (t_k in hours)
MG_6	9 21	6-7-8-9 6-7-8-9-10-11-12-22-21	5.67
MG_33	17 28 33	33-18-17 33-32-31-30-29-25-24-23-3-4-5-6-26-27-28 33	6.94

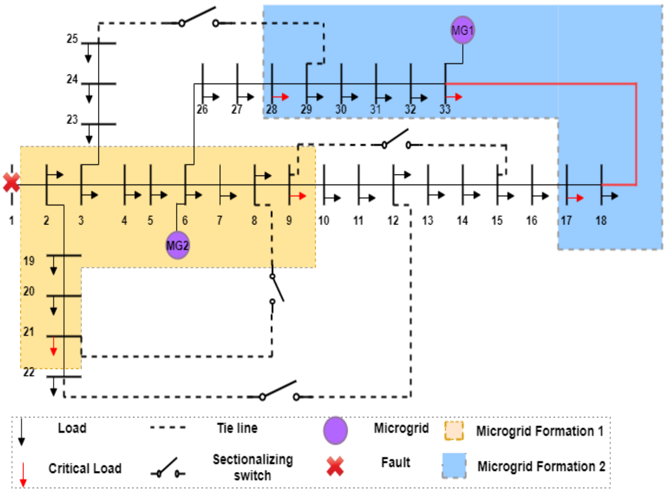

Figure 4: Restoration plan for scenario 2 in minor damages

3.2 Major damages scenarios

A. *Scenario 3: Multiple faults and 85% reserve energy for MG1*

Adding to the damaged lines in scenario 2, it is assumed that line 9-10 is also faulted and the transportation of fuel to MG_6 was affected during the extreme event as results the reserve energy for MG_6 reduced to 85% of its reserve energy (i.e. 722.5 kWh). The total amount of reserve energy in the network is now reduced from 2100 kWh to 1972.5 kWh. Using equation (10), the maximum possible duration for this scenario also decreased to 6 hours due to the reduction of energy reserve. The restoration strategy results for this scenario are shown in Table 6. Comparing the results in Table 6 and those is Table 5, note that due to the reduction of the energy reserve in MG_6, in Table 6 MG_6 is restoring a lesser load demand of 120kW and in Table 5 it was 150kW. The change in load allocation amongst the microgrids is so that the available generation resources are allocated in such a way that each CL is served for a maximum possible duration, which in this scenario is 6 hours. Note that in Table 6, the CLs served by MG_6 and MG_33 are restored for 6.02 and 5.95 hours respectively. This scenario demonstrates that, with reduced generation resources the restoration strategy is still able to maximise the restoration time of each CL.

Table 6: Restoration strategy for scenario 3

LINES 2-19, 28-29, 8-21 and 9-10 ARE FAULTED. MG_6 ENERGY RESERVE REDUCED TO 722.5 kWh			
MG node ID	CLs	Restoration paths	Restoration time (t_k in hours)
MG_6	9 28	6-7-8-9 6-26-27-28	6.02
MG_33	17 21 33	33-18-17 33-18-17-16-15-14-13-12-22-21 33	5.95

B. *Scenario 4: Multiple faults and reduction in generation resource availability*

It is assumed that lines 6-26, 2-19 and 8-21 are faulted and the maximum output power for MG_33 dropped by 50% (from 300 kW to 150 kW) and the reserve energy became 60% of the original (i.e. it reduced to 750 kWh). The energy reserve for MG_6 is as in scenario 3 (i.e. 722.5 kWh). The total amount of generation resource in both microgrids decreased (i.e. the total maximum power decreased from 480 kW to 330 kW and the total reserve energy decreased from 2100 kWh to 1472.5 kWh). Note, the total CL demand remains unchanged (i.e. 330kW). The results of the restoration strategy are shown in Table 7. It can be observed that CL 28 remains unserved since there is no possible way of splitting the CLs amongst the MGs without exceeding the available maximum power output of each MG. Therefore, one of the CLs loads has to be sacrificed and not be served. In this case, higher priority loads take preference and as result CL 28 remains unserved since it has lower priority (i.e. 0.8) compared to other CLs. Since CL 28 cannot be served, the other CLs have to be allocated fairly amongst the MGs, hence CL 21 is served by MG_6 as opposed to MG_33 as seen in Table 6. This scenario demonstrates that in situations where the generation resources are limited, critical loads with higher priority are served first provided that there are available restoration paths to those critical loads as it can be seen in Table 7.

Table 7: Restoration strategy for scenario 4

LINE 6-26, 2-19, 8-21 ARE FAULTED. MG_33 POWER IS 150 kW WITH 1472.5 kWh TOTAL ENERGY RESERVE			
MG node ID	CLs	Restoration paths	Restoration time (t_k in hours)
MG_6	9 21	6-7-8-9 6-7-8-9-10-11-12-22-21	4.81
MG_33	17 33	33-18-17 33	6.25
	28	Not served	

C. *Scenario 5: Critical lines damaged*

In this scenario, it is assumed that lines 33-18 and 15-16 are damaged and the network is as the original. Note that in

Figures 2 and 4, lines 33-18 and 15-16 are the only possible paths to supply the CL at node 17 from both MGs. The restoration strategy results are shown in Table 8. As expected, during the restoration process the CL at node 17 remains unserved as there is no restoration path to it. The purpose of this scenario is to show that when all the possible restoration paths to a CL are damaged during the restoration process, the restoration strategy cannot serve those loads as they are isolated from the restoration network topology. This case represents the limitations of the proposed restoration strategy.

Table 8: Restoration strategy for scenario 5

LINES 33-18 AND 15-16 ARE FAULTED			
MG node ID	CLs	Restoration paths	Restoration time (t_k in hours)
MG_6	9 21	6-7-8-9 6-7-8-9-10-11-12-22-21	5.67
MG_33	28 33	33-32-31-30-29-28 33	10.41
	17	Not served	

4. CONCLUSIONS

A restoration strategy that uses existing stand-alone microgrids to restore critical loads on the distribution feeders for a maximum restoration time after an extreme event when the main grid power is not available is proposed. The proposed restoration strategy is validated through a case study containing 5 scenarios. It is demonstrated that in case of multiple faults on the distribution feeders due to an extreme event, the restoration strategy is able to effectively reconfigure the topology of the network and allocate the available generation resources of the microgrids to serve a maximum number of critical loads weighted by their priority for a maximum possible restoration time so as to improve distribution system resilience. The obtained results also demonstrated that the strategy of using MGs to enhance the resilience of the distribution system is limited by the availability of the generation resources in the MG.

Operational constraints and a radial topology are guaranteed to be satisfied. The proposed strategy can be applied to other radial distribution networks. In this paper the contribution of the restoration strategy towards resilience is not quantified using any resilience index, instead the number of restored critical loads and their service time are quantified empirically. Future work will include maximizing the restoration time based on the estimated outage duration and model uncertainties of intermittent energy resources. The proposed strategy will be applied to a real system to test its effectiveness in practical situations.

5. ACKNOWLEDGEMENTS

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