DISTRIBUTION GRID RESTORATION BY FORMING RESILIENCY-ORIENTED LESS-VULNERABLE MICROGRIDS

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ABSTRACT

In this paper a new method is introduced to increase the resiliency of a distribution grid by forming robust microgrids after extreme contingencies following disasters. The method tries to serve as much load as possible by forming microgrids with alleviated vulnerability based on the Manchester model and optimal AC power flow. The main feature of the proposed method is that the formed microgrids are less vulnerable to cascading failures. Whenever some lines are heavily loaded in an autonomous microgrid, they are likely to be tripped, which in turn could lead to the increase of power flow in the other lines and further overloads could occur until the system would collapse or lose a significant amount of load. The proposed method seeks for lines with the loadings more than a specified threshold and checks for the consequences of tripping such lines before formation of microgrids. Therefore, the risk of cascading failures is minimized in the formed microgrids. The resiliency is improved by alleviating the overloads that might happen upon disconnection of a line due to the faults. Reconfiguration is well exploited to create optimum topologies with the minimal risk of cascading failures. Reconfiguration methods in a microgrid require simultaneous application of continuous and discrete variables which makes solving the problem difficult. Genetic Algorithm is used to find the optimum microgrid's configuration with less vulnerable lines. The effectiveness of the proposed method is investigated by using a 4-feeder 1069-node unbalanced test system.

INTRODUCTION

Although reliability, affordability, flexibility, and efficiency of power delivery for end users in electric distribution systems is well investigated, the severe climate events is not considered in depth. Resiliency is considered as the ability to maintain service to critical load following an extreme event with low-probability and high-impact in a distribution system. Resiliency is improved by utilizing microgrids, applying distribution automation and vulnerability analysis as discussed in [1]. In this paper resiliency of distribution system in confronting extreme events is investigated from vulnerability point of view. The concept of vulnerability in a distribution system infrastructure could be seen as a global system property focuses on three elements [2]:

- The severity of loss and damages caused by the impact of extreme event considered as a technical dimension
- The severity of the system elements exposure to the extreme event, i.e., the probability that an element is exposed to the risk of suffering loss and damages
- Degree of resilience, i.e., the ability of the distribution system to forecast, deal with, endeavor and recover from the impact of an extreme event from technical/social point of view.

The vulnerability of distribution systems can be reduced by maintaining the access of power sources to critical loads in extreme events. Microgrids with fixed-generation and intermittent supply by renewable energy resources can be implemented to pick up critical loads. Reconfiguration of the distribution feeders in extreme events could be well exploited to allow the load to be served by a number of electrical islands in order to limit the extent disturbance propagation.

In this paper a new method is introduced to increase the resiliency of a distribution grid by forming robust microgrids after extreme contingencies following disasters. The method tries to serve as much load as possible by forming microgrids with alleviated vulnerability based on the Manchester model and optimal AC power flow. The main feature of the proposed method is that after forming microgrids upon disconnection from the upstream grid, different microgrids are formed with the less vulnerability by mitigating the cascading failure possibility. The heavily loaded lines in an autonomous microgrid are likely to be tripped, which could in turn lead to the power flow increase of other lines, this could increase the risk of cascading failures and vulnerability of the system. The proposed method analyses the system for lines with the loadings more than a specified threshold and checks the consequences of the outages of such lines before formation of microgrids. In other words, the microgrids are formed by considering the vulnerability and risk of cascading failures. Hence, the formed microgrids are immune to breakdown caused by severe overloads of the lines that may happen due to the outage of heavily-loaded lines. In other words, the formed microgrids are less vulnerable by alleviating the overloads that might happen upon disconnection of a line due to faults. Reconfiguration is used to create optimum topologies that could mitigate the risk of cascading failures. The usage of the reconfiguration methods in a microgrid requires simultaneous application of continuous and discrete variables which makes solving the problem difficult. The taxonomy R3-12.47-2 which is a 4-feeder 1069-node test system with DGs is used as the sample system to demonstrate the feasibility of the proposed method.

PROBLEM FORMULATION

It is preferred to alleviate the overloading of the lines in the formed microgrids after extreme events. As fixed and intermittent supplies are considered in the formed microgrids, it is required to consider different time periods and update the supply level accordingly. Next, a random outage is simulated to investigate its consequence on the power flow of the remaining system. The new operating point is determined by solving the optimal power flow (OPF). If the OPF is converged, the algorithm checks another line in the same way as mentioned. If OPF does not converge, then it is required to reconfigure the formed microgrid by opening/closing the available tie switches. Otherwise load shedding is required until the OPF is converged. The lines with relatively high loadings (more than a specified threshold (70% here) are considered as having the potential for the next outage. It is worth mentioning that the routes in a microgrid are usually limited, so the outages of a few lines could lead to complete system collapse. For each line with the loading more than the specified level, a random number is extracted. If the loading of a line is a value between 70% and 90% and the random number is less than 0.3, it is selected for the next outage. Also, any line with loading over 90% and associated random number less than 0.4 is selected for outage, as the lines with loading over 90% have a higher probability to be disconnected. The microgrid may be split into several autonomous islands after the candidate lines are tripped. The power balance of the formed islands should be resumed as far as possible.

SAMPLE NETWORK

Taxonomy feeder R3-12.47-2 is developed by the Pacific Northwest National Laboratory (PNNL) and represents a moderately populated urban area. This is composed of single family homes, light commercial loads, and a small amount of light industrial loads. Approximately 33% of the circuit-feet are overhead and 67% underground. It would be expected that this feeder is connected to adjacent feeders through normally open switches. For this reason it would be common to limit the feeder loading to 60% to ensure the ability to transfer load from other feeders, and vice versa. The majority of the load is located relatively near the substation. Climate region 3 is the non-coastal South West of the United States and is characterized by a hot and arid climate. Within climate region 3 there are 3 12.47 kV feeder types. It is 4322 kVA [3].

Table 1: Taxonomy feeder R3-12.47-2 Data

Nodes	263
Voltage (kV)	12.47
Load (kW)	4300
Voltage Regulators	1
Reclosers	3
Residential Transformers	0
Commercial Transformers	57
Industrial Transformers	5
Agricultural Transformers	0

Simulations are performed on the Taxonomy "R3–12.47–2" sample distribution network, which is a prototypical unbalanced distribution feeder model for moderate urban areas. It is developed by the Pacific Northwest National Laboratory (PNNL) [3] with nominal voltage equal to 12.47 kV and load, including losses equal to 4.652 MVA. A test system with 4 feeders and 1069 nodes including microgrids is developed in [6] by combining four "R3–12.47–2" feeders, adding seven tie switches and four microgrids. It has 156 normally closed sectionalizing switches.

In this paper, the 4-feeder and 1069-node test system is used by replacing the microgrids by Distributed Generators (DGs) with intermittent generation, as shown in Figure 1. The transformer capacity at each feeder is 7.5 MVA. The active and reactive power limits of the DGs are shown in Table 2.

Table 2: Maximum Capacity of DGs

DG #	P (MW)	Q (MVar)	S (MVA)
DG1	5.15	2.25	5.62
DG2	1.65	0.95	1.90
DG3	2.50	1.75	3.05
DG4	1.00	0.55	1.14

Table 3 shows the remarkable power flows in the sample system which is shown in Figure 1 (pre-fault condition, all tie/DG switches open and all sectionalizing switches closed). They are calculated by GridLAB-D, which is a new power distribution system simulation and analysis tool with an advanced algorithm at its core designed for determining the simultaneous state of millions of independent devices [4]. Table 3 shows the loads of the three-phase transformers in each feeder of Figure 1. The advantages of GridLAB-D over traditional finite difference-based simulators are: handling unusual situations much more accurately, handling widely disparate time scales, ranging from sub-seconds to many years; its easy integration with new modules and third-party systems, lack of requiring the use of reduced-order models for the aggregate behavior of consumer or electrical systems, which averts the danger of erroneous or misapplied assumptions.

Table 3: Power Flows in Different Zones

Switch #	Zone #	Power_in (VA)
R3-12-47-2_switch_12	Z24	+4.42e+6+1.408e+6j
R3-12-47-2_switch_14	Z22	+4.42e+6+1.407e+6j
R3-12-47-2_switch_16	Z4	+4.42e+6+1.407e+6j
R3-12-47-2_switch_29	Z30	+4.42e+6+1.407e+6j
R3-12-47-2_switch_21	Z8	+4.42e+6+1.407e+6j
R3-12-47-2_switch_35	Z18	+4.15e+6+1.326e+6j
R3-12-47-2_switch_19	Z5	+4.15e+6+1.321e+6j
R3-12-47-2_switch_32	Z23	+4.15e+6+1.320e+6j
R3-12-47-2_switch_18	Z6	+4.15e+6+1.319e+6j
R3-12-47-2_switch_24	Z7	+4.14e+6+1.307e+6j
R3-12-47-2_switch_34	Z19	+3.63e+6+1.139e+6j
R3-12-47-2_switch_9	Z2	+3.63e+6+1.138e+6j
R3-12-47-2_switch_15	Z14	+3.57e+6+1.116e+6j
R3-12-47-2_switch_2	Z16	+3.55e+6+1.097e+6j
R3-12-47-2_switch_4	Z9	+3.55e+6+1.096e+6j
R3-12-47-2_switch_5	Z10	+3.38e+6+1.034e+6j
R3-12-47-2_switch_26	Z11	+85955.5+26009.6j
R3-12-47-2_switch_7	Z26	+628543+187133j

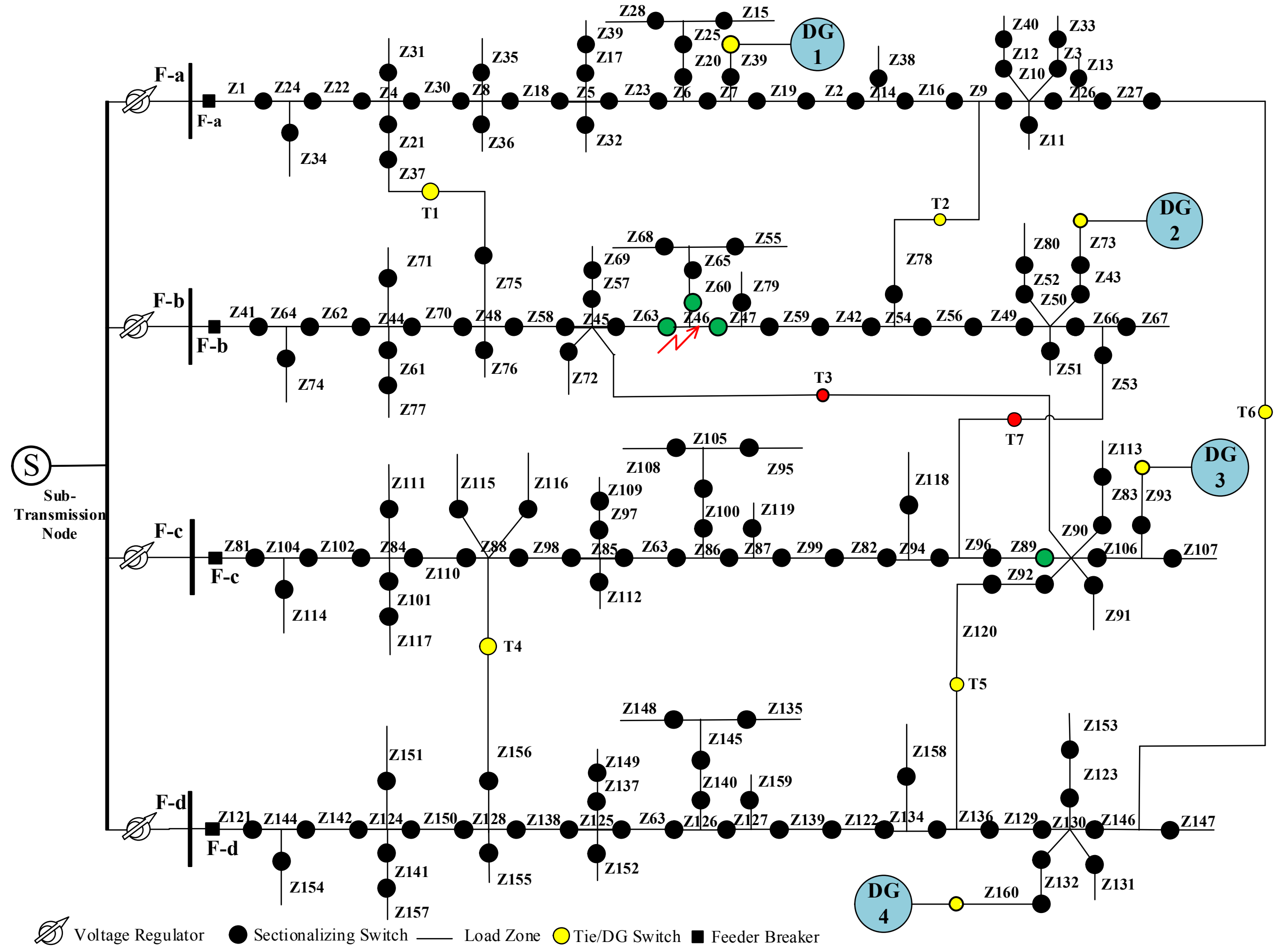

Figure 1: One-line diagram of the 4-feeder 1069-node test system for a mild fault on F-b

SIMULATION RESULTS

Figure 1 shows a fault on section Z146 which could be isolated by opening sectionalizing switches after tripping of feeder breaker and fault location finding. For a resilient restoration considering the problem formulation as mentioned, tie switches T3 and T7 are closed and the sectionalizing switch between Z89 and Z90 is opened. In this case the formation of microgrids is not required. It is worth noting that if the load of de-energized area on Feeder-b is transferred to Feeder-c, then the system would be overloaded. The overloading condition would be mitigated by a load transfer operation through transferring some load of Feeder-c to Feeder-b by opening Z89-Z90 and closing T3. This is a combination of zone restoration through load transfer [5]-[6].

As another case study, a severe fault is considered at Z144, which makes Feeder-d out of service, so 4.42MW+1.408Mvar supply is lost. The DGs could be well exploited to compensate for this deficiency, but the point is reconfiguration should be performed by minimizing the risk of overload of the path between the DGs and the loads. Although DG-4 is located on F-d, its capacity is not enough to serve the lost loads, while DG-1 has the largest capacity. Figure 2 shows the operations that have been done to restore the system in an efficient way. DG-1, DG-3 and DG-4 are switched on along with T3, T4, T5 and T6. Sectionalizing switches Z6-Z7, Z94-Z96, Z90-Z106, Z134-Z136, Z130-Z146 and Z130-Z132 are switched off for keeping the paths in its primary radial condition.

In this Scenario, the number of switching operations is high, because it is intended to keep the routes in radial condition. However, if the DGs could be interconnected, either with themselves as a larger microgrid, or interconnected together along with the upstream network, the switching operation would be minimized. The resiliency could be improved if the restoration process alleviates the loadings of the lines connecting the supplies to critical loads, in order to decrease the system vulnerability [2].

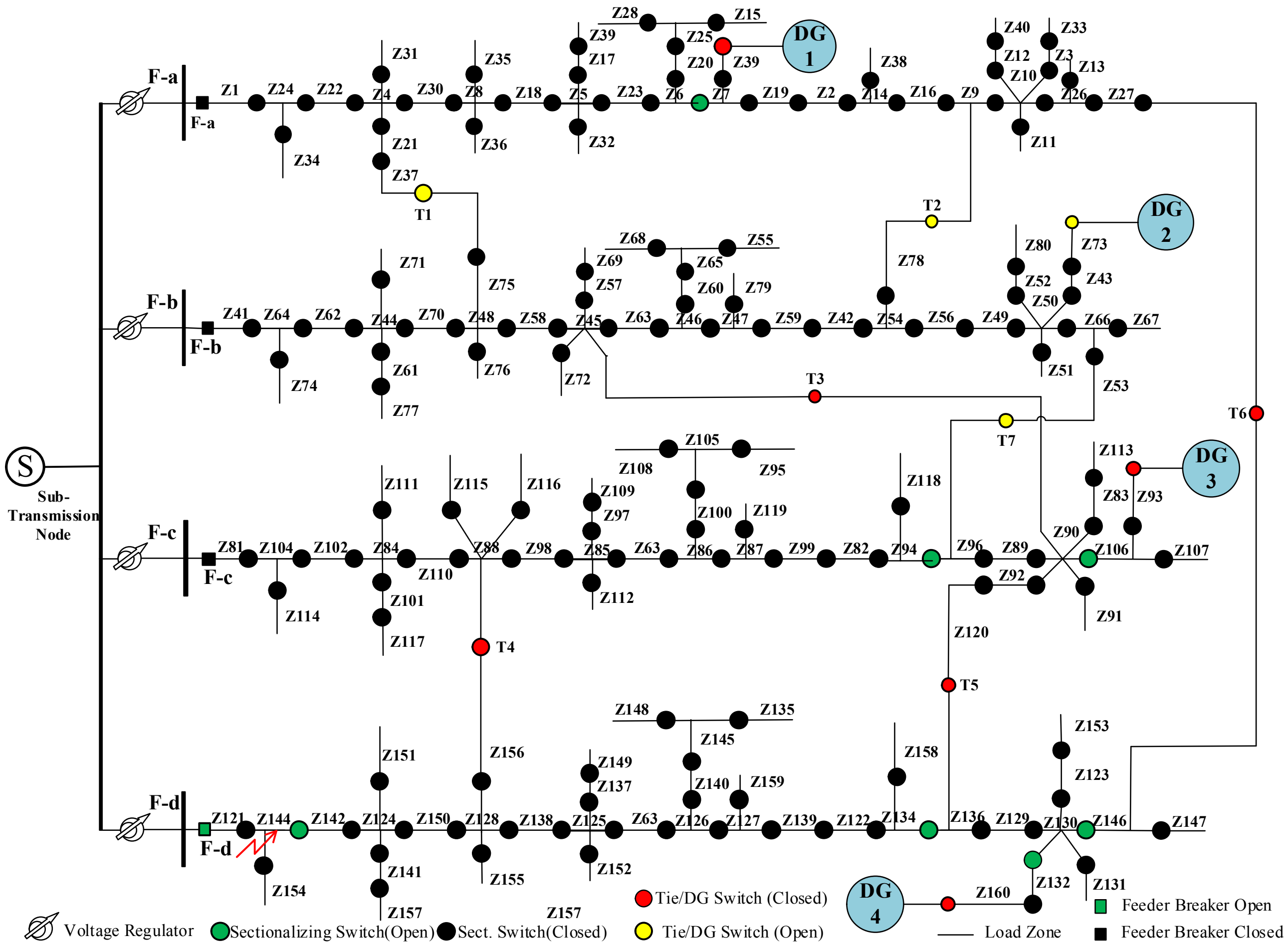

Figure 2: One-line diagram of the 4-feeder 1069-node test system for a severe fault on F-d

CONCLUSIONS

In this paper, the resiliency of a distribution grid is investigated in extreme contingencies by mitigating the risk of cascading failures though alleviating the loadings of the lines connecting the supplies to critical loads. The concept of the method is that the heavily loaded lines are more likely to be tripped, which in turn could lead to the increase of power flow on the other lines leading to system collapse. The proposed method checks for the lines with higher loadings (more than a specified threshold) and investigates the consequences of their outages before formation of a microgrid to minimize the vulnerability. A test system with 4-feeders, 1069 nodes and 4 DGs is used for simulations. The work is in progress to consider larger distribution networks with a high penetration level of unbalanced renewable energy resources.

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