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Toward a Resilient Distribution System

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***Abstract*—Resiliency with respect to extreme events, such as a major hurricane, is considered one of the key features of smart distribution systems by the U.S. Department of Energy (DOE). In this paper, approaches to resilient distribution systems are reviewed and analyzed. Three important measures to enhance resiliency, i.e., utilization of microgrids, distribution automation (DA), and vulnerability analysis, are discussed. A 4-feeder 1069-node test system with microgrids is simulated to demonstrate the feasibility of these measures.**

***Index Terms*—Distribution system, resiliency, extreme event, service restoration, distribution automation, microgrid.**

I. INTRODUCTION

Due to climate change and global warming, extreme weather events, such as hurricanes, ice storms, floods, droughts, and so on, have become more intense in recent decades and their strength and degree are growing [1], [2]. As a result, electrical power systems may suffer more severe “attacks” from extreme weather events, which will bring damages to the electrical infrastructure, leading to major power outages. For example, during Hurricane Sandy, the Long Island Power Authority (LIPA) experienced damages to 50 substations, 2,100 transformers, and 4,500 utility poles [3]. According to [4], 20 states together with the District of Columbia experienced power outages. In New Jersey, 65 percent of customers are interrupted at peak load. It took 6 days to restore 84 percent of the interrupted customers [3].

The transmission and distribution networks should be reliable and resilient with respect to such extreme events. This paper is focused on the distribution systems. Resiliency is considered to be “the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions [5].” For a distribution system, resiliency means the ability to avoid severe damages to the distribution infrastructure caused by extreme events and to restore as much load as possible in a short time after major outages.

In general, distribution system resiliency can be improved by hardening, redundancy, automation, distributed energy resources (DERs), and smart grid applications, such as fault detection, isolation, and service restoration. In recent years, many projects supported by the U.S. Department of Energy (DOE) are conducted to enhance reliability and demand response of distribution systems. According to the DoE Progress Report of the Smart Grid Investment Grant (SGIG) Program [6], 46 SGIG projects are focused on the deployment of distribution outage management with automatic switching devices to reduce the restoration time and cost of outages.

In this paper, attention has been paid to the catastrophic outages following extreme events and the measures to enhance resiliency of distribution systems. The main contributions of this paper include

1) The characteristics of catastrophic outages caused by extreme events are identified and compared with those of typical outages.

2) Approaches that can be applied by utilities to achieve resilient distribution systems are reviewed and analyzed.

3) Three effective measures to enhance distribution system resiliency, i.e., utilization of microgrids, implementation of distribution automation (DA), and vulnerability analysis, are investigated and demonstrated by simulation with a 4-feeder 1069-node test system.

The remaining of this paper is as follows. Section II describes the catastrophic outages due to extreme events. In Section III, approaches to resilient distribution systems are analyzed. In Section IV, three effective ways to enhance distribution system resiliency are investigated. The conclusion and future work are presented in Section V.

II. CATASTROPHIC OUTAGES DUE TO EXTREME EVENTS

Catastrophic outages due to extreme events are different from typical outages caused by tree contacts, vehicle accidents, or other common reasons.

In a typical outage, there is usually only one faulted element, say line faults. The customers at the downstream of the faulted element will be out of service. Since the transmission and distribution (T&D) networks remain largely intact during typical outages, service can be efficiently restored to the interrupted customers by implementing distribution system restoration (DSR) strategies [7].

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However, extreme events, such as a major hurricane, can damage many utility poles and destroy other electrical infrastructures within a short period of time and lead to numerous faults. The number of interrupted customers is much greater than that in a typical outage. Generators may be affected, resulting in a lack of power sources for service restoration. The T&D networks may be disconnected, so it is difficult for power sources to access interrupted loads.

The differences between typical and catastrophic outages are summarized in Table I.

TABLE I. COMPARISON OF TYPICAL AND CATASTROPHIC OUTAGES

Typical outages	Catastrophic outages
1. Single fault; 2. A small number of customers affected; 3. Power sources are available; 4. T&D networks remain intact; 5. Easy to repair and restore.	1. Multiple faults; 2. A large number of customers are out of service; 3. Lack of power sources; 4. T&D networks damaged; 5. Difficult to repair and restore.

III. APPROACHES TO RESILIENT DISTRIBUTION SYSTEMS

Approaches to resilient distribution systems mainly fall into three categories, i.e., construction programs, maintenance measures, and smart grid techniques [8].

Concerning construction programs, a straightforward way is to reinforce utility poles and overhead distribution lines. It improves the ability of distribution systems to ride through high-intensity winds, heavy ice storms and other extreme weather events. Replacing overhead lines with underground cables is also an effective approach. Since undergrounding the entire distribution network is costly, a better choice is to identify and underground the key components that are important for system resiliency. For new distribution systems, the construction standards should be improved by considering the impact of extreme events.

System maintenance helps to identify the devices that are close to the end of life or have a good chance to fail. Then the utilities can replace these devices. Maintaining the clearance between distribution lines and trees reduces the possibility of tree contacts with distribution lines during a storm. Identifying and hardening vulnerable components is also important for power sources to access critical loads during extreme events.

Smart grid techniques play an essential role in resilient distribution systems. Smart grid infrastructures include advanced metering infrastructure (AMI), remote-controlled switches/transformers/voltage regulators, telecommunications, data management, and distribution/outage management system (DMS/OMS). These facilities enable real-time monitoring and remote control and enhance visibility and controllability of distribution systems. Smart grid applications, such as fault location, isolation, and service restoration (FLISR), enable online analysis and intelligent decision making for distribution systems. FLISR is able to locate and isolate the faulted zone and implement service restoration schemes as a decision support tool for distribution system operators [9]. Making use of DERs to serve critical loads during extreme events is also considered as a smart grid technique that contributes to resiliency. Microgrids provide a practical way to integrate DERs. A microgrid can be operated in grid-connected or island modes. It can disconnect itself from the grid during extreme events to serve critical loads [10]. It can also support service restoration of critical loads on distribution feeders [11].

There are other techniques that contribute to resilient distribution systems. For example, accurate extreme weather forecasting helps utilities to be better prepared before extreme weather events arrive. It is also possible to anticipate outages following extreme events. Then utilities can have labor and supplies ready for repair and restoration actions.

The approaches to resilient distribution systems are summarized in Table II.

TABLE II. APPROACHES TO RESILIENT DISTRIBUTION SYSTEMS

Category	Approaches
Construction programs	1. Reinforcing utility poles and overhead distribution lines 2. Replacing overhead lines with underground ones 3. Improving construction standards
Maintenance measures	1. Life time/Failure prediction 2. Vegetation management 3. Vulnerability analysis
Smart grid techniques	1. Advanced metering infrastructure (AMI) 2. Advanced control and communication 3. Distribution/Outage management system (DMS/OMS) 4. Fault location, isolation, and service restoration (FLISR) 5. DERs and microgrids
Other approaches	1. Extreme weather forecasting and outage prediction 2. Labor management 3. Anticipate supplies needed

IV. ENHANCEMENT FOR RESILIENCY

A. *Utilization of Microgrids*

According to the 2012 DoE Microgrid Workshop Summary Report [12], "a microgrid is a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island-mode." A microgrid helps serve critical loads during major outages in two ways.

- A microgrid can be disconnected from the grid and use DERs to serve critical loads within it. In this case, the microgrid works in an island mode and takes the responsibility to maintain system stability and voltage profile. Examples of microgrids serving local loads during extreme events can be found in [10].
- A microgrid can help restore service to critical loads on distribution feeders where power supplies are not available or sufficient [11]. The microgrid is reconnected to the distribution feeder after the faulted zones are isolated. It outputs electric power to serve critical loads on the feeder as emergency sources. An example is shown below to demonstrate the

effectiveness of microgrids in enhancing distribution system restoration capability.

Consider a test system with 1069 nodes and 4 distribution feeders, as shown in Figure 1. It is based on the taxonomy “R3-12-74-2” developed by the Pacific Northwest National Laboratory (PNNL), which is a representation of a moderately populated urban area [13]. Four microgrids are connected to the four feeders, respectively. The maximum capacity of the microgrids that can be used to restore interrupted loads are given in Table III.

TABLE III. MAXIMUM CAPABILITY OF MICROGRIDS

Microgrid	M1	M2	M3	M4
Active power (MW)	5.15	1.65	2.50	1.00
Reactive power (MVar)	2.25	0.95	1.75	0.55

Table IV presents two restoration scenarios. Restoration schemes with and without microgrids are compared. From the results, it can be seen that using the generation capacity of microgrids improves restoration capability of the distribution system in two ways.

- Reducing the number of switching operations during the restoration process and consequently shortening the restoration time, which is the case of scenario 1.
- Restoring more loads when the distribution system does not have sufficient power capacity for all interrupted loads, which is the case of scenario 2.

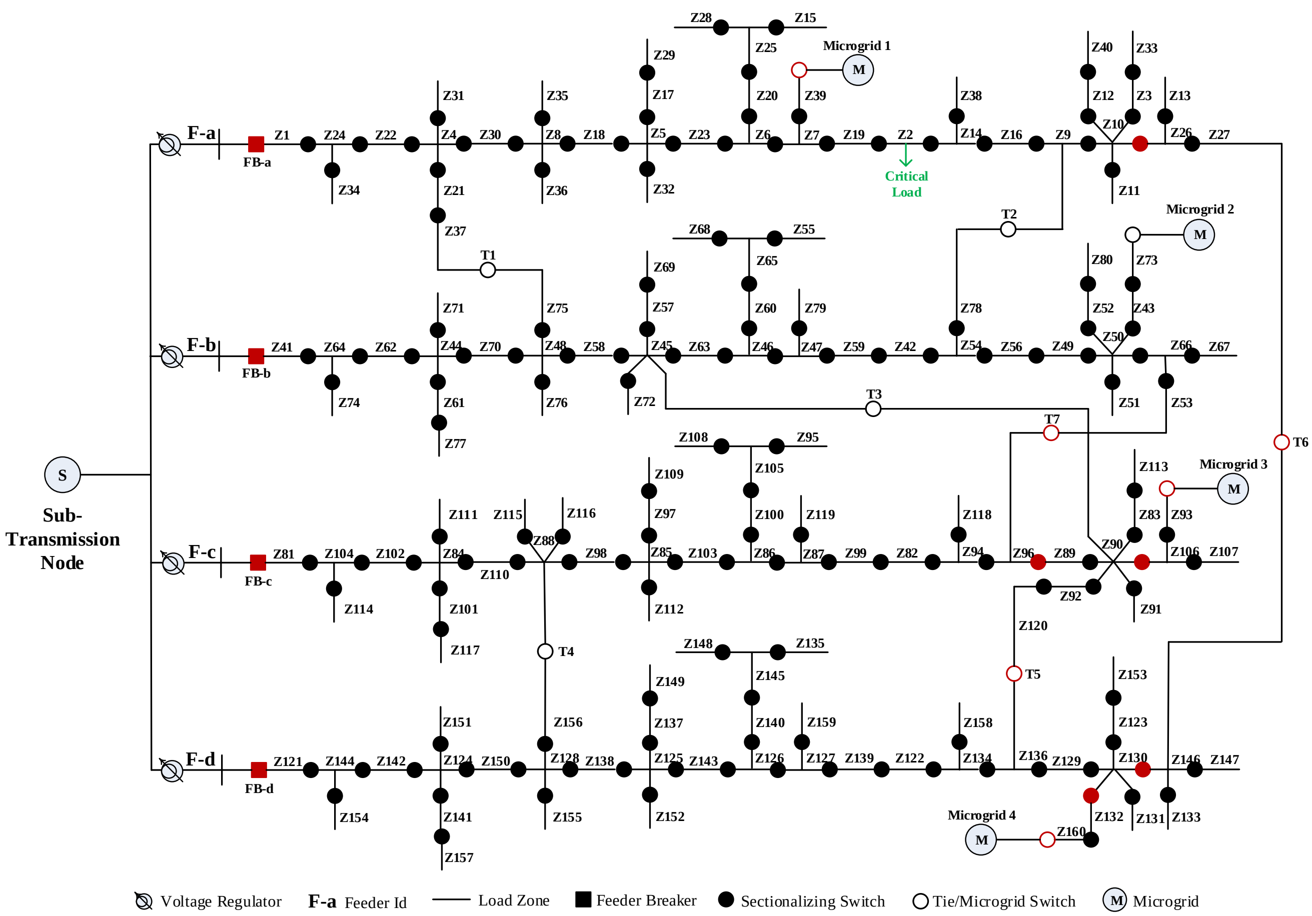

Figure 1. One-line diagram of the 4-feeder 1069-node test system.

TABLE IV. RESTORATION SCHEMES WITHOUT AND WITH MICROGRIDS

Scenario	Fault location	Restoration schemes without microgrids	Restoration schemes with microgrids
1	Z6	Open: Z49-Z50, Z90-Z92 Close: T2, T5, T7	Close: Z39-Microgrid1
2	Z127	Open: Z46-Z47, Z96-Z89 Close: T3, T5, T7 *Partial Restoration*, 315.04 kVA load should be shed at feeder **F-b**	Open:Z50-Z43, Z90-Z92 Close: T3, T5, Z73-Microgrid2

B. *Automation Increases Resiliency*

Distribution automation (DA) enables efficient implementation of smart grid applications through remote monitoring and control [14].

Distribution system restoration (DSR) is a smart grid application that restores interrupted loads by a sequence of switching operations after an outage. To implement a DSR plan with manual switches, field crews are sent to open or close switches, which is time-consuming. A remote-controlled switch (RCS) can be operated by distribution operators in the distribution operation center. A restoration plan using RCSs can be implemented much faster than one using manual switches. Therefore, upgrading manual switches in existing distribution systems to RCSs can significantly reduce the restoration time.

The test system shown in Figure 1 is used to show the benefits that can be achieved by installing RCSs. Fifteen switches are upgraded to RCSs, including four feeder breakers, five normally closed sectionalizing switches, three normally open tie switches, and three microgrid switches. The RCSs are marked in red in Figure 1.

Suppose a fault occurred at zone Z110, the restoration schemes with and without RCSs are given in Table V.

TABLE V. THE RESTORATION SCHEMES WITHOUT AND WITH RCSS

Without RCSs	**With RCSs**
Step 1: open Z90-Z92, close T5 Step 2: open Z96-Z89, close T3 Step 3: open Z110-Z88, close T4	Step 1: close T6, open Z130-Z146 Step 2: open Z90-Z106, close Z93-M3 Step 3: open Z96-Z89, close T5 Step 4: open Z110-Z88, close T7

From Table V, it can be seen that the restoration scheme with RCSs first operates only RCSs to restore as much load as possible and then uses all available switches to pick up the remaining interrupted loads. Therefore, it contains more switching operations than the restoration scheme without RCSs. However, since RCSs are operated much faster than manual switches, the implementation time of the restoration scheme with RCSs is much shorter.

Assume that the mean time to operate a manual switch and a RCS are 30 minutes and 20 seconds, respectively. In the above example, the implementation time for the restoration plans without and with RCSs are 180 minutes and 32.33 minutes, respectively.

Further assume that the mean time to repair is 4 hours and the permanent failure rate of each zone is 0.02. The System Average Interruption Frequency Index (SAIFI) and System Average Interruption Duration Index (SAIDI) are calculated using the method proposed in [15] and shown in Table VI. It can be seen that, by installing RCSs, SAIFI and SAIDI are improved significantly.

TABLE VI. IMPROVEMENT IN SYSTEM RELIABILITY

	Without RCSs	With RCSs	Improvement
SAIFI	0.78	0.6169	20.92%
SAIDI (minutes)	60.96	24.68	59.62%

It should be noted that installing RCSs is costly. Therefore, in practical, the placement of RCSs should consider both functional requirements and cost benefits. A systematic method is proposed in [16] to determine the optimal number and locations of RCSs, which helps a distribution system reach its maximum restoration capability by installing a minimum number of RCSs.

C. *Vulnerability with Respect to Extreme Events*

Vulnerability is "the collection of properties of an infrastructure system that might weaken or limit its ability to maintain its intended function, or provide its intended services, when exposed to threats and hazard that originate both within and outside of the boundaries of the system [17]." For a distribution system, its main function is to provide service to customers, especially critical loads. During extreme events, the access of power sources to critical loads should be maintained. By providing redundancy of power sources and paths from sources to critical loads, the vulnerability of distribution systems can be reduced.

Define the weight of a path as the total amount of load on the path. For a source and a critical load, the shortest path is defined as any path whose weight is minimum amount all paths between them. The following steps are used to identify the shortest paths from all sources to a particular critical load.

Step 1) Model the distribution system as a weighted undirected graph. Zones are represented as vertices while switches are modeled as edges. Each vertex has a weight equal to the amount of load connected to it.

Step 2) Identify all power sources in the distribution system, including substations (the power comes from generators in the transmission system), DERs, and microgrids.

Step 3) Suppose that the critical load is connected to vertex *s*. Find the shortest paths from *s* to other vertices using the Dijkstra's algorithm [18], which is slightly modified for graphs with weighted vertices. The pseudo code for the modified algorithm is shown below. In the pseudo code, *G* is the graph representing the distribution system. *G.V* is the vertex set of *G*. *G.Adj*[*u*] is the adjacent list of vertex *u* in *G*. For each vertex *v*, *v.d* is called the estimated distance from *s* to *v* and *v.π* is the predecessor of *v*. *w* specifies the weight of vertices. *Q* is a min-priority queue of vertices, keyed by their *d* values.

MODIFIED_DIJKSTRA (G, w, s)

```
for each vertex v ∈ G.V
    v.d = ∞
    v.π = NULL
s.d = 0
Q = G.V
while Q ≠ ∅
    u = EXTRACT-MIN (Q)
    for each vertex v ∈ G.Adj[u]
        if v.d > u.d + w(v)
            v.d = u.d + w(v)
            v.π = u
```

Step 4) Evaluate the paths found in Step 3) by unbalanced three-phase power flow calculations. Remove the paths that will lead to overloading or low voltage.

As an example, suppose a critical load is connected at zone Z2 on feeder **F-a** in the distribution system shown in Figure 1. There are five power sources that may be able to provide electricity service to the critical load, i.e., the substation and the four microgrids. Apply the above steps to find the shortest paths from power sources to zone Z2. GridLAB-D [19] is used to perform power flow calculations. Two paths are found, i.e.,

- From the substation through feeder **F-a** to zone Z2;
- From *Microgrid 1* through feeder **F-a** to zone Z2.

During extreme events, at least one of the two paths must be maintained. Otherwise, the critical load at Z2 will be lost.

Note that it is not sufficient to consider connectivity only. Power flow evaluation (Step 4) is necessary, since the capacity of DERs and microgrid is usually limited and a long-distance path may lead to unacceptable low voltages. Consider the critical load at zone Z2 in Figure 1. Both Microgrids 1 and 2 are close to the critical load and have the potential to serve the critical load when the major source, i.e. the substation, is not available. Power flow calculations are performed for the two paths. The results are shown in Table VII. It can be seen that Microgrid 1 has a sufficient capacity to serve the load along the path while Microgrid 2 does not. Therefore, Microgrid 2 cannot be used to serve the critical load although there is a path in between.

TABLE VII. POWER FLOW CALCULATION RESULTS

Path	Active Load	Reactive Load	Load Voltage
Microgrid 1 – Z2	538.6 kW	161.9 kVar	0.9993 p.u.
Microgrid 2 – Z2	3.192 MW	961.8 kVar	0.9968 p.u.

V. CONCLUSION AND FUTURE WORK

In this paper, approaches to resilient distribution systems are reviewed and analyzed. A test system has been simulated to demonstrate the feasibility of three effective measures to enhance system resiliency, i.e., utilization of microgrids, implementation of distribution automation, and vulnerability analysis.

One major difficulty for utilities to adopt new technologies is the absence of realistic test beds. New technologies need to be evaluated in near-real world environment before they are applied to the real distribution systems.

Traditional distribution systems cannot become resilient in one step. The transition will take place in a gradual way. It may need years to achieve a certain level of resiliency. During this period, traditional and new technologies will coexist [20]. Coordination is necessary. Different levels of control systems, such as DMS and microgrid EMS, should work in harmony. Protection and restoration schemes must re-consider the radial structure of distribution systems as DERs and microgrids are integrated. New market mechanisms considering traditional and new participants are also required.

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