Resilience of Distribution Systems: Concepts and Enhancement Approaches

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***Abstract*— Due to the increasing intensity and frequency of catastrophic power outages caused by severe weather conditions, there is a critical need for new concepts and technologies to enhance the distribution systems in their "resilience" with respect to these extreme events. Resilience, the ability to withstand and recover from extreme events, such as hurricanes, is an important attribute for the future power grid. The deployment of microgrids provides a promising solution for service restoration after a major outage. The increasing installation of distributed generators (DGs) is an important step toward a resilient distribution system. Nevertheless, several technical issues need to be addressed, including the limit on generation resources when microgrids are used for service restoration. In this paper, the concept and metrics for resilience of distribution systems will be presented. Approaches to improving resilience in distribution systems will be discussed. The proposed concept and metrics are integrated in a restoration algorithm and simulated with test cases from a 1069-node distribution system developed by PNNL. Simulation results of microgrids and DGs for service restoration after major outage scenarios will be reported.**

***Index Terms*— resilient distribution system, resilience, microgrid, extreme weather events, feeder service restoration**

I. INTRODUCTION

Presidential Policy Directive 21 [1] describes resilience as "the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions," such as hurricanes, snow storms, or earthquakes. Resilience is an important attribute for the future power grid [2]. Department of Energy (DOE), Office of Electricity Delivery and Energy, has a program on the R&D concerning resilience of distribution systems. Five areas are highlighted for residence studies. The focus of this paper is on the metrics for resilience and the enhancement of response and recovery using microgrids for service restoration after a major power outage.

Traditionally, research and development has been focused on distribution system reliability, which mainly deals with typical outages that do not cause severe damages. The SAIDI and SAIFI reliability indices measure the statistical frequency and durations of power outages. The "averaging" nature of these indices allows the large number of minor events to dominate the indices and, as a result, the severe events may be "masked" in the widely adopted reliability indices. [4]

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The impact of natural disasters on distribution systems can be severe. Multiple faults, including loss of power resources and damage on distribution networks, are not uncommon in major outage scenarios. It is generally difficult to restore services from an extreme weather event in contrast with the recovery from a typical power outage caused by a tree contact or car accident.

Microgrids can be used as a resiliency source to supply critical loads when power from the utility system is not available. K. Schneider et al., in [5] discussed the feasibility of using microgrids for service restoration after a major outage. The increasing deployment of distributed generators (DGs) is an important step toward a resilient distribution system. Due to the relatively small capacity of DGs within a microgrid, the capability of a microgrid to withstand disturbances may be weak. Large deviations in voltage or frequency can be caused by load pick-ups or transformer energization. Such deviations can cause undesirable events, e.g., relay tripping, and impede the process of system restoration. Thus, the dynamic performance of a microgrid needs to be considered in the development of system restoration plan.

The remainder of this paper is organized as follows, Section II presents the concept and metrics of resilience. Approaches to a resilient distribution system are discussed in Section III. The application of microgrids for service restoration in distribution systems are illustrated in Section IV. Finally, suggestions for the future work on power grid resilience are provided in Section V.

II. UNDERSTANDING RESILIENCE

A. Power System Resilience

Relative to transmission systems, distribution systems are usually more vulnerable to weather related events; most of the power outages in the U.S. occurred at the distribution system level [6]. Several factors can trigger a major power outage, e.g., extreme weather, cyber attack, and equipment failure. Although these events can become rare events-high impact contingencies, the DOE resilient grid R&D plan focuses on R&D for climate preparedness and climate impact resilience for electric distribution grid [3].

B. Concepts: Reliability Vs. Resilience

Reliability is an important attribute to describe system performance. Reliability is the ability to meet a high level of demand of the electricity consumers consistently. In contrast, resilience is about the performance with respect to specific extreme events. Reliability is normally measured by the frequency and duration of power outages. However, resilience evaluation relies on tracking the change of system performance before, during, and after the occurrence of the extreme events.

A reliable power system based on reliability indices might not be resilient [4]. Considering a highly automated system, a typical single fault can be removed or isolated quickly, indicating a high level of reliability. However, the same system may fail in an extreme weather event, indicating a low level of resilience. Note that, standard reliability indices for distribution systems (e.g. SAIDI and SAIFI) measure the statistical frequency and durations of power outages.

C. *Resilience Metrics*

To improve resilience in a distribution system with respective to extreme events, it is essential to properly quantify the system resilience. Then the resilience metrics will be used to guide the enhancement effort and evaluate the effectiveness. Resilience can be described by evolution of system performance after an event occurs. System performance can be quantified by considering the ability to serve the critical load. Here, critical load is designated to those necessary to maintain fundamental societal functions, e.g., hospitals, emergency operations center.

A system performance curve in response to an extreme event is shown in Fig. 1. The level of system performance is a function of time, e.g. $F(t)$. The system performance function is the total power supplied to critical loads. Suppose an extreme event strikes the distribution system at t_e. Consider the state of event progress (t_e to t_{pe}). After extreme event occurred, the system is assumed to stay operational through initial disruptions for a short period of time; system performance remains at the normal level of F_0. After that, the impact of extreme event expands and service to many customers is interrupted. As a result, $F(t)$ decreases until it is stabilized at t_{pe}. Then, the system restoration process starts at t_r. As customer service is restored, the level of $F(t)$ increases and stays at a higher level at time instant t_{pir}. Later, when power is available again from the utility system, the system returns to normal (t_{ir} to t_{pir}). The recovery process ends at t_{pir} and the system performance returns to the normal level.

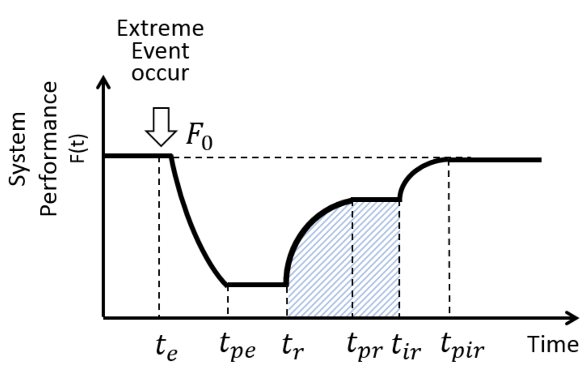

Fig. 1. Evolution of system performance curve following an extreme event [5]

Resilience can be defined and categorized into different families based on the quantifying factors[5][7][8][9]. One family is based on the area associated with the system performance curve. In [5], resilience is evaluated by the integral of the performance function over the specific time period, e.g.,

$$R = \int_{t_r}^{t_{ir}} F(t)\ dt$$

where, R is the resilience level during the period t_r , t_{ir} , associated with the shaded area in Fig. 1. It is the restorative state and post-restoration state, in which a restoration strategy is applied. The system's ability to recover is critical to the system performance. Hence, by this concept, resilience is measured by the performance during the time interval (t_r, t_{ir}).

There are other options for resilience indices, when considering system performance in the pre-event period [7] (e.g. t_e to t_r). Resilience can also be quantified based on other factors, such as probability and economic factors [8][9].

III. ENHANCEMENT OF RESILIENCE

This section will discuss the enhancement of resilience by improving the recovery ability, utilizing microgrid as a resource after a major outage.

A. *Feasibility Study for Microgrids as Restoration Resources*

"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." [10]. After an extreme event, electric power from the transmission and distribution system might not be available to deliver power to end-users. However, it is possible to utilize a microgrid to restore critical loads in the region by reconfiguring distribution system facilities available after the extreme event.

In [11], K. Schneider et al., illustrated that a microgrid can be used as a resilience source in three operating configurations: local resource, community resource, and black start resource. The concepts are examined in a study case including Washington State University Microgrid and part of primary distribution systems owned by the local utility. The test system is illustrated in Fig. 2.

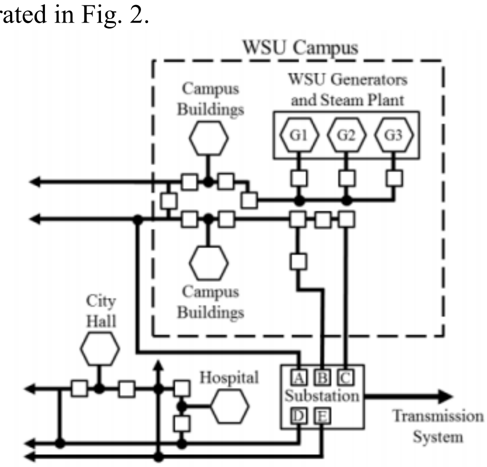

Fig. 2. Illustration of the WSU campus, South Pullman Substation, and selected Avista Utilities distribution feeders [11]

System restoration relies on facilities that are available, e.g., lines, breakers, and transformers that connect the distributed resources to end-use loads. When the infrastructure inside a microgrid is intact, it can serve its local load, operating as a "local resource," e.g., WSU campus load in Fig.2. In this configuration, microgrid only supplies the end-use loads inside the microgrid itself; there is no delivery across the distribution system outside the microgrid.

Microgrid also has the potential to supply critical loads outside the microgrid in the event of a severe weather event, when the utility power is not available. Using the extra capacity to supply critical load in the connected distribution systems, it helps to reduce the impact of a prolonged outage by supporting basic social services, e.g, the emergency operations center in the city hall in Fig. 2. Note that, an agreement to support this mode of operation is needed between the utility and the microgrid [11].

Microgrid can be used as a black-start resource. Unlike hydroelectric plants, some thermal units do not have the back-start capability. In order to bring these units back on-line, it is necessary to first energize transmission lines and then serve the auxiliary load at power plants to facilitate start-up. If a microgrid is near the location of a power plant without the black-start capability, it is possible that a microgrid provides cranking power for non-black-start units.

B. Microgrids as Restoration Resources and Potential Solutions

When utilizing a microgrid as a resilience resource, it is necessary to operate the microgrid in acceptable operating conditions. The voltage, current, and frequency should satisfy operating constraints. Due to the relatively low capacity of generating units within a microgrid, microgrids may have a weaker capability to withstand disturbances and absorb shocks. Excessive load pick-ups on a microgrids can cause an undesirable impact such as frequency drops and system instability. Whether a particular switching operation associated with load pick-ups can cause undesirable effects can be determined by simulation. In practice, a nomogram [11] associated with the microgrid can be used to determine what generation resources are necessary to start certain loads without overloading the generators, and violating frequency or voltage constraints. Such nomograms are constructed by off-line simulation.

Another issue is the in-rush currents while energizing transformers. Charging currents associated with re-energization of secondary service transformers and underground cables have the potential to cause voltage sags and/or swells. Under-voltage relay in distributed generations may be triggered if a continuous under-voltage condition exceeds the setting threshold. This is an important technical issue when a microgrid is used as black-start resources. Since a large amount of reactive power needs to be absorbed when higher voltage long line sections are to be energized during a black start. Furthermore, simulation based on appropriate models and operation conditions is needed to determine the impact of in-rush in restoration schemes.

IV. MICROGRID FOR RESTORATION

When a microgrid is used as a restoration resource, several technical issues should be considered: operational constraints on feeders, dynamic constraints of generation resources, limits on power resource, and stability of islanded microgrids, This section will discuss the use of a microgrid as a resiliency source. A restoration procedure is illustrated with a case study based on the PNNL 1069 node distribution system model [12].

A. Restoration Algorithm

Considering the scenario that, after an extreme event, the electric power from upstream, utility side is not available. Then, faulted zones are isolated and interrupted islands are formed. The only power resource in the region is within microgrids and microgrids are operated in an islanded mode. Microgrids would first supply power to its own critical load. If there is remaining available generation resource, critical load outside the microgrid can be restored through the utility distribution system.

The restoration procedure can be formulated as an optimization problem. The objective function is to achieve maximum service time weighted by load priority, when using the microgrid to supply load service [12], e.g.,

$$\max \sum_{i \in L} t_i \, c_i$$

where, t_i is service time after a major outage without the utility power. The symbol c_i is the weighting factor associated with load priority. L is the set of potential load zones to be restored. The choice of weighting factors is empirical. In general, weighting factor c_i is greater than or equal to zero. Negative weighting factors can be used for non-critical load zones that should be excluded from this stage of service restoration.

Y. Xu et al., [12] proposed an algorithm for restoration using microgrids to serve the critical load. The algorithm consists of finding restoration paths, determining generation dispatch, scheduling power output, and planning restoration actions. After solving the optimization problem, generation dispatch is designated by pairs from a microgrid to critical load zones to be restored. Then, the restoration paths can be determined accordingly.

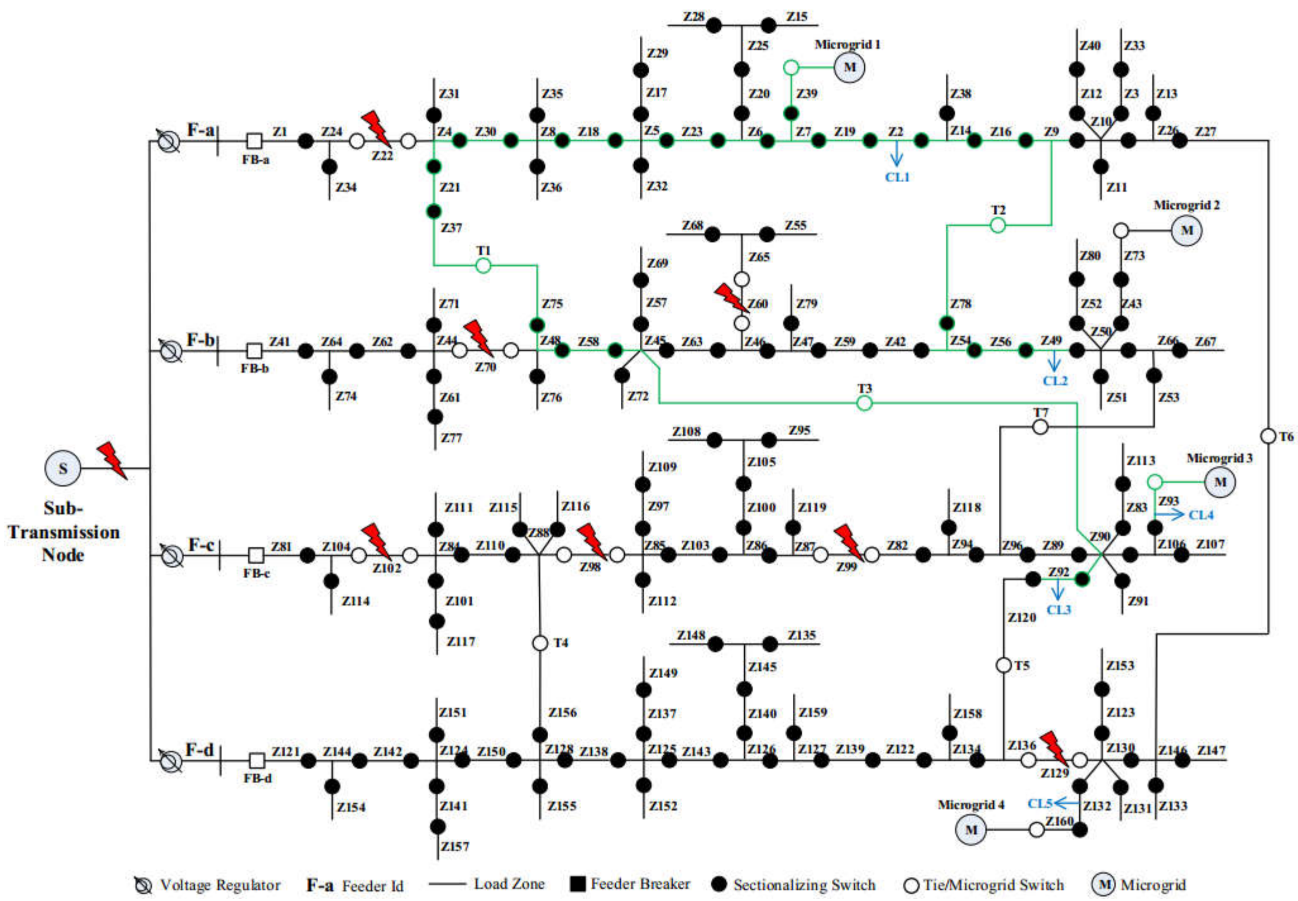

Fig. 3. PNNL 4-feeder 1069-bus test distribution system [11]

B. Study Case

The test system has 4 feeders with a total of 1069 nodes. Four microgrids are assumed to be available. Load zones (critical and non-critical) are connected to the distribution feeders. The 1069-node system is shown in Fig. 3. Generation and load data of microgrids are given in Tab. 1.

Table 1 Generation and load data of microgrids

	Microgrid index	1	2	3	4
Power Capacity	P (MW)	8.50	4.25	5.95	3.40
	Q (MVar)	5.27	2.63	3.69	2.11
Generation Resource (MWh)		65	30	45	25
Critical Load	Demand(MW)	4.38	2.10	2.95	1.86
	Power factor	0.9	0.9	0.9	0.9

The restoration procedure is obtained using the algorithm described in this section. The results show that four critical loads out of five can be restored. The generation dispatch and power output schedule are: zones Z2, Z49, and Z92 are served by microgrid 1 for a duration of 7.82 hours. Z93 can be restored by microgrid 3 for 10 hours. The restoration paths are displayed in green in Fig. 3.

The restorative actions are as follows: microgrid 1 restores critical load zones (e.g. Z2, Z49, and Z92) with five switching operations, microgrid 3 restores Z93 with one switching operation. Note that there will be voltage sags and frequency deviations after each switch operation. It is possible to achieve better dynamic performance by picking up load in smaller groups, which would reduce its effectiveness due to longer implementation time. Tradeoffs between effectiveness and dynamic performance needs to be made.

V. Conclusion

Resilience is a key attribute for the future power grid. Microgrid is a promising solution to enhance resilience of a distribution system. The installation of microgrids will increase a power system's capability to respond to and recover from extreme conditions. Although there are regulatory and technical issues that need to be resolved, the deployment of microgrid is increasing. Technical and non-technical issues need to be addressed to facilitate this trend.

A part of this project, an actual field test was conducted with the WSU campus microgrid. From an outage state for a portion of the campus load, the WSU generator is used to pick up critical loads on campus. Then the transformer between the WSU distribution system and utility distribution system is energized as a step to demonstrate the technical feasibility to use a microgrid to provide black start power to the utility side. In-rush currents and other critical measurements are recorded to allow the development of accurate models for further study.

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