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Chapter

RESILIENCY ASSESSMENT OF ELECTRIC POWER DISTRIBUTION SYSTEMS

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ABSTRACT

This chapter discusses the resiliency aspect of electric power distribution systems considering the role of distributed generation. A recovery (restoration) tool is developed that can emulate the recovery path of the distribution system after a contingency situation, then engineering resiliency assessment framework is applied to (semi)-quantitatively measure the dimensions of resiliency. The proposed procedure is implemented on a test system to demonstrate the key factors affecting the resiliency of a distribution system, including distributed generation.

Keywords: Distributed generation, Distribution systems, Resiliency, Rapidity, Redundancy, Resourcefulness, Robustness

INTRODUCTION

Natural disasters and intentional interdiction pose significant threats to human societies. Due to the negative impacts of these events on public well-being, economic prosperity, and national security, governments are obliged to make communities more disaster resilient [1,2].

The overall resiliency of a community is highly dependent on the resiliency of its critical infrastructures including public health, electric power, water supply, telecommunication and transportation networks that fall under the umbrella term of lifeline networks [3]. At first glance, resiliency may be deemed as an intuitive concept. However, quantitative assessment of resiliency is crucial for identifying vulnerabilities of critical infrastructures and disaster preparedness planning.

Quantifying resiliency is a challenging task. Several studies have proposed quantitative and semi-quantitative measures to assess the resiliency of different infrastructures. Regardless of the type of the infrastructure under assessment, these methods can be roughly divided into two major categories: economic resiliency assessment methods [4,5] and engineering resiliency assessment methods [1,6,7]. Engineering resiliency assessment methods are mainly based on the general framework provided by [8]. According to [8]:

> "*Resiliency is defined as a function indicating the capability to sustain a level of functionality or performance for structures, lifeline networks, or communities, over a period defined as the control time that is usually decided by owners, or society (usually is the life cycle, life span of the system.*"

This method uses MCEER (Multidisciplinary Center of Earthquake Engineering to Extreme Event) terminology which distinguish four dimensions for resiliency (see Figure 1). These dimensions are [8,9]:

- *Rapidity* is the capability to meet priorities and achieve goals in a timely manner to reduce interruption period in service provision and avoid future disruption.
- *Robustness* is defined as the system ability to withstand a given level of shock/stress without service interruption.
- *Redundancy* is defined as the availability of alternative resources in case of failure in some elements in a system.
- *Resourcefulness* is simply defined as ability of alternative resources to take care of responsibility of failed main components. In other words, is the system able to regain the pre-event functionality of the system using alternative ways?

In this work, the engineering resiliency assessment framework is utilized to analyze the resiliency of an electric power distribution system against the outages in post-event of a disaster. For this purpose, a recovery (restoration) tool for the distribution system is developed to emulate the system's recovery path. Then some contingency scenarios are generated and it is tried to restore the system to its partial or full functionality. Finally, the engineering resiliency assessment framework is applied to determine the four dimensions of the system's resiliency. Note that this work only focuses on short-term "electrical" recovery of a distribution network, and does not consider the recovery from structural and physical damages in the aftermath of a disaster.

RESILIENCY DIMENSIONS IN DISTRIBUTION SYSTEMS

Because of a natural disaster or interdiction, some parts of the electric power distribution systems may experience some degree of damage. Depending on the intensity and location of the incident, the electric power distribution system may sustain service outages in various areas. A resilient distribution system must be capable of fully or partially restoring service to outage areas in the aftermath of a disaster.

General Characteristics of a Distribution System

Traditionally, electric power distribution systems, are radial networks supplied through a substation transformer connected to the transmission system. Although operating radially, distribution networks are equipped with a set of normally open (NO) and normally closed (NC) switches. Under normal operating conditions, NO switches are open and NC ones are closed.

However, under emergency operating conditions, distribution network operator (DSO) can perform a series of switching maneuvers to restore the service to outage areas. During these switching operations, DSO may close NO switches, and open NC ones to reroute electricity and supply the distribution system with the help of neighboring feeders. Switches may be manual or automated. In traditional distribution systems, DSO must dispatch crew to perform switching maneuvers manually. However, in modern systems, automated remotely controlled switches can perform the maneuvers without human intervention.

With distributed energy resources (DERs) integrating into low- and medium- voltage systems, substation transformer and neighboring feeders are no longer the only source of electricity in modern distribution networks [10]. Hence, neighboring feeders along with DERs can also supply the loads in case of emergency.

Because of the rapid growth of electricity demand, and emergence of free electricity trading environments, distribution systems are operating closer and closer to their capacity limits. Grid reinforcement, which involves upgrading distribution branches or substation transformer is a very effective but expensive solution to reliability issues in distribution systems. However, grid upgrades if done carefully and effectively, can significantly contribute to distribution systems resiliency. Extensive planning studies [11] might be needed to efficiently identify optimal candidate branches for grid upgrades.

Considering these characteristics, the terminology of engineering resiliency is applied to quantify resiliency of distribution systems. In the next section, semi-quantitative measures are assigned to the four dimensions of resiliency, i.e. rapidity, robustness, redundancy and resourcefulness.

Functionality of a Distribution System

Before defining dimensions of resiliency, we need to come up with a definition for functionality of a distribution system. Essentially, a distribution system is fully functional when it can supply all the customers (i.e., loads). Therefore, functionality decreases if DSO should shed parts of system's loads. Although this definition is simplistic, it is adequate for our purpose that is short-term resiliency assessment.

Rapidity

Rapidity r_1 or the recovery rate of a distribution system depends on several factors including but not limited to:

- Response time of distribution system operator (DSO) which in depends on the knowledge and skills of human operators in traditional systems or, computational capability of automated energy management systems (EMS) in modern systems.
- Availability of crew, and crew dispatch and travel time if switches are manual, or the response time of automated switches.
- Ramp rates of DERs.

Depending on the characteristics of distribution system, and size of outages, recovery time T^r may vary from several minutes to several hours.

Rapidity can be quantified as the amount of load restored over the recovery period. In other words:

$$r_1 = \frac{\text{Total recovered load}}{T^r} \qquad (1)$$

The rapidity index r_1 shows how the distribution network is capable of fast and efficient recovery from a contingency.

Robustness

Robustness (r_2) is the ability of the system to maintain its functionality at post-contingency period. Therefore:

$$r_2 = \frac{\text{Total supplied load right after the event}}{\text{Total load}} \times 100\% \qquad (2)$$

Obviously r_2 is a quantity varying from 0 to 100 %. The more r_2 is closer to 100 the more resilient system is.

Redundancy

NC and NO combination of switches, DERs, neighboring feeders and grid reinforcement contribute to the redundancy (r_3) of a distribution system. The effectiveness of redundancy is greatly affected by resourcefulness. It is challenging to define a quantitative measure for redundancy. In this work, we define several levels of redundancy for a distribution system and assign specific scores (s^{r_3}) to them. These levels include:

- Switches (alternative paths)
- Grid upgrades
- DERs with unity power factor
- DERs with flexible power factor

A resilient distribution system can have a single element of redundancy or a combination of elements. We simply assume that for combinations of redundancy elements, the overall redundancy will be the summation of each individual element's score. For example, if the distribution network has switches with $s_{sw}^{r_3}$ and DERs with $s_{der}^{r_3}$ then $r_3 = s_{sw}^{r_3} + s_{der}^{r_3}$.

The assigned scores are extremely case-dependent and highly associated with the system fragility and weak points.

Resourcefulness

Resourcefulness r_4 is very difficult to quantify. It mainly depends on the capabilities of DSO. For the rest of this work, it is assumed that the DSO is deemed to be skillful and knowledgeable enough to take appropriate actions under emergency conditions.

RESTORATION AND DISASTER RECOVERY OF A DISTRIBUTION SYSTEM

In the aftermath of a disaster, a rapid and efficient EMS can help DSO come up with a recovery plan to return the system to full (100%) or at least partial (<100%) functionality. Unlike regular EMS (REMS), emergency EMS (EEMS) cannot be very complicated and detailed. The main functionality of EEMS is to provide DSO with the simplest recovery plan in a shortest time possible.

From operation point of view, the difference between REMS and EEMS are:

- The objective of EEMS is solely minimizing lost loads, while REMS can be multi-objective, with cost minimization having the highest priority
- Depending on the severity of outage, EEMS may relax voltage constraints to some extent to find a feasible temporary operating plan, while REMS normally uses rigid voltage constraints
- EEMS can temporarily release the constraint of radial operation, while REMS always operates the distribution system in a radial fashion.
- EEMS considers load shedding (LS) as the last resort, to find a feasible operating plan, while in REMS that is not an option.

Next section presents a potential mathematical formulation of an EEMS.

Emergency Energy Management System

Nomenclature:

$J(.)$: Cost function that is the total active load shed

Ω^n : set of nodes, indexed by i

Ω^b: set of branches; there is a branch between nodes i and j, if $i,j \in \Omega^n$ and $ij \in \Omega^b$

Ω^{sw}: set of switches; there is a switch between nodes i and j, if $i,j \in \Omega^n$ and $ij \in \Omega^{sw}$

P/Q_i^g : Active/reactive power generation at node i.

$P/Q/S_i^d$: Active/reactive/apparent load at node i.

$p_i^{f^d}$: Load power factor at node i.

P/Q_i^g: Active/reactive/apparent LS at node i.

$P/Q/S_{ij}$: Active/reactive/apparent ij Branch flow.

V_i: Voltage magnitude at node i.

δ_i: Voltage phase angle at node i, and $\delta_{ij} = \delta_i - \delta_j$.

G_{ij}: Element ij of Conductance matrix G_{bus} which is the real part of network's Y_{bus}matrix.

B_{ij} Element ij of Susceptance matrix B_{bus} which is the imaginary part of network's Y_{bus} matrix.

u_{ij}: Switch status; 0: open, 1: close.

γ_{ij}: Branch/Switch reinforcement factor.

The objective of EEMS is minimizing LS in the entire distribution system. Mathematically, we can show this as:

$$\min J = \sum_{i \in \Omega^n} P_i^{d,ls} \tag{3}$$

Objective function (3) is subject to operating constraints under emergency conditions. These constraints include:

Power balance:

EEMS must find a feasible solution to power flow in the distribution network, which is represented as:

$$P_i^g - \left(P_i^d - P_i^{d,ls}\right) = \sum_{ij \in \{\Omega^b \cup \Omega^{sw}\}} P_{ij} \tag{4}$$

$$Q_i^g - \left(Q_i^d - Q_i^{d,ls}\right) = \sum_{ij\in\{\Omega^b \cup \Omega^{sw}\}} Q_{ij} \tag{5}$$

where

$$P_{ij} = V_i V_j \left(G_{ij}\cos\delta_{ij} + B_{ij}\sin\delta_{ij}\right) - V_i^2 G_{ij} \tag{6}$$

$$Q_{ij} = V_i V_j \left(G_{ij}\sin\delta_{ij} - B_{ij}\sin\delta_{ij}\right) + V_i^2 B_{ij} \tag{7}$$

when $ij \in \Omega^b$, and

$$P_{ij} = u_{ij}\left[V_i V_j \left(G_{ij}\cos\delta_{ij} + B_{ij}\sin\delta_{ij}\right) - V_i^2 G_{ij}\right] \tag{8}$$

$$Q_{ij} = u_{ij}\left[V_i V_j \left(G_{ij}\cos\delta_{ij} - B_{ij}\sin\delta_{ij}\right) - V_i^2 G_{ij}\right] \tag{9}$$

when $ij \in \Omega^{sw}$

In (4) and (5) switches are treated as branches with unknown (variable) statuses. If a switch is closed, $u_{ij} = 1$ and active/reactive power flow through the switch will contribute to active/reactive power balance at sending and receiving nodes i and j. If a switch is open $u_{ij} = 0$ and there will be no active/reactive power flow through the switch. When forming system's Y_{bus} matrix to determine G_{ij} and B_{ij}, EEMS assumes that all switches are closed.

Also, note that (4) and (5) allow for LS to find a feasible solution to power balance if resources are not adequate to maintain all the demand. Also, normally LS is done such that load power factor is preserved. In other words:

$$\frac{P_i^{d,ls}}{S_i^{d,ls}} = pf_i^d \tag{10}$$

Voltage constraints:

Like normal operating conditions, under emergency conditions nodal voltages must remain within acceptable range. However, EEMS may apply looser constraints on voltages than REMS.

$$V_i^{min} \leq V_i \leq V_i^{max} \tag{11}$$

Generation active/reactive limits:

Substation transformer and DERs have specified upper and lower bounds on active and reactive power they supply.

$$P_i^{g,min} \leq P_i^g \leq P_i^{g,max} \tag{12}$$

$$Q_i^{g,min} \leq Q_i^g \leq Q_i^{g,max} \tag{13}$$

Load shedding limits:

Amount of load shed at each node i is bound by total load at that node.

$$0 \leq P_i^{d,ls} \leq P_i^d \tag{14}$$

$$0 \leq Q_i^{d,ls} \leq Q_i^d \tag{15}$$

Branch/Switch flow limits:

EEMS needs to keep each branch ij flow under its loading capability. A similar constraint applies to closed switches, since they have a limited capability of transferring power.

$$0 \leq \left|S_{ij}\right| \leq \gamma_{ij} S_{ij}^{max} \tag{16}$$

where

$$S_{ij} = \sqrt{P_{ij}^2 + Q_{ij}^2} \tag{17}$$

Note that in (16) γ_{ij} can be used for planning (preparedness) purposes only. By studying γ_{ij} DSO can identify where and by how much grid upgrades can contribute to system resiliency.

SIMULATION RESULTS

The proposed algorithm is implemented in GAMS [12] environment running on an Intel® Xeon™ CPU E5-1620 3.6 GHz PC with 8 GB RAM. The proposed framework is a MINLP model which can be easily solved by commercial solvers such as DIscrete and Continuous OPTimizer (DICOPT) [13].

This section presents a few case studies to assess the resiliency of a distribution network to outages followed by a disaster.

Emergency Energy Management System

Figure 2 shows the schematic diagram of IEEE 33- bus distribution feeder [14] which is used as the test system. The total complex demand is 3715+j2300 kVA, and total apparent demand is 4369 kVA. Under radial operating conditions we can identify 4 main paths in this distribution network:

- Path I encompassing nodes 1:18
- Path II encompassing nodes 19:22
- Path III encompassing nodes 23:25
- Path IV encompassing nodes 26:33

The capacity of each distribution branch is assumed be 120% of its power flow under normal operating conditions (i.e., nominal loads and basic radial topology). This suggests that the distribution network is operating very close to its limits. Also, we assume that the substation transformer is sized to be able to generate up to 4 times of the total nominal load.

The basic distribution network is modified to include:

- A set of 5 switches between node pairs 8-21, 9-15, 12-22, 18-33 and 25-29 [15].
- DERs at nodes 5, 7, 9, 11, 13, 17, 20, 22, 24, 26, 29 and 31.

Table 1 shows the connection points of DERs and their capacities. These DERs get disconnected in case of an outage and reconnect to the system if necessary.

Table 1. DER connection points and capacities

Location	5	7	9	11	13	17	20	22	24	29	31
$P^{g,max}$[kW]	67	224	63	54	69	63	98	98	65	139	166

In addition, the following redundancy scores are assigned to the redundancy elements:

- (0) Basic distribution network (i.e. minimum redundancy)
- (3) Switches (i.e. alternative paths)
- (1) Reinforced network (i.e., increased capacity)
- (1) DERs with unity power factor
- (2) DERs with flexible power factor

It is assumed that this distribution system is fully automated and has an average recovery time of $T^r = 15$ min or 0.25 h for all the events. Moreover, for measuring resiliency, only consider active loads are considered and reactive loads are not included in calculations of functionality or resiliency dimensions.

In the following case studies, the resiliency of the test distribution network is assessed in three specific events.

This section presents a few case studies to assess the resiliency of a distribution network to outages followed by a disaster.

Event 1: Branch 3-4 outage

Branch 3-4 is in the upstream distribution network and thus, its functionality greatly affects the overall functionality of distribution network. Therefore, branch 3-4 outage is deemed to be a severe contingency.

Minimum redundancy: Figure 3 shows active/reactive generation and LS for the basic distribution network which has minimum redundancy. All loads located downstream of branch 3-4 are completely shed. Substation transformer is the unique source of generation which is connected to node (bus) 1. In this case, $J = 2235$ kW, $r_1 = 0$ kWh, $r_2 = \frac{3715\text{-}2235}{3715} \times 100 = 39.8\%$, and $r_3 = 0$.

Switches: Figure 4 shows active/reactive generation and load shedding for the distribution network equipped with 5 switches. Switches 9-15 and 25-29, are closed and EEMS can pick up some loads on Paths I and IV. In this case, $J = 2133$ kW, $r_1 = \frac{1582\text{-}1480}{0.25} = 408$ kWh, $r_2 = 39.8\%$, and $r_3 = 0$

Switches+Reinforced network: Figure 5 shows active/reactive generation and load shedding for the distribution network equipped with 5 switches and doubled branch capacity. In this case, in addition to switches 9-15 and 25-29, switch 18-33 is also closed and EEMS can restore more loads on Paths I and IV. In this case, $J = 1617$ kW, $r_1 = 3060$ kWh, $r_2 = 39.8$ %, and $r_3 = 4$.

Switches+DERs with unity power factor: Figure 6 shows active/reactive generation and load shedding for the distribution network equipped with 5 switches and DERs as described in Table 1. These DERs follow IEEE 1547 standard that does not allow for reactive power exchanges at the connection point of DERs and distribution network. Switches 9-15, 18-33 and 25-19 are closed and DERs provide EEMS with more capacity for restoring loads on Paths I and IV. In this case, $J = 1470$ kW, $r_1 = 2472$ kWh, $r_2 = 39.8$ %, and $r_3 = 4$.

Switches+DERs with flexible power factor: Figure 7 shows active/reactive generation and load shedding for the distribution network equipped with 5 switches and DERs as described in Table 1. These DERs can exchange reactive power with distribution network. It is assumed that each DER can generate/absorb up to 50% of its maximum active power generation capacity (shown in Table 1). Switches 8-12, 18-33 and 25-29 are closed to reroute power flow, and EEMS can now restore more load on Paths I and IV comparing to the previous case. In this case, LS further decreases and reaches to $J = 1076$ kW, $r_1 = 4636$ kWh, $r_2 = 39.8$ %, and $r_3 = 5$.

Maximum redundancy: Figure 8 shows active/reactive generation and LS for the distribution network which has maximum redundancy, which means: Switches+Reinforced network+DERs with flexible power factor. In this case, switches 8-12, 18-33 and 25-29 are closed, $J = 533$ kW, $r_1 = 6808$ kWh, $r_2 = 39.8$ %, and $r_3 = 6$.

Event 2: Branch 2-19 outage

Under normal operating conditions, branch 2-19 supplies load on Path II. Considering the size and number of loads on this path, branch 2-19 is not considered as critical.

Minimum redundancy: Figure 9 shows active/reactive generation and LS for the basic distribution network which has minimum redundancy. All loads located downstream of branch 2-19 are completely shed. In this case, $J = 360$ kW, $r_1 = 0$ kWh, $r_2 = \frac{3355}{3715} \times 100 = 90.3$ %, and $r_3 = 0$

Switches: Figure 10 shows active/reactive generation and load shedding for the distribution network equipped with 5 switches. Switches 8-12 and 9-15 are closed and EEMS can pick up all the loads on Paths II but should shed some loads on Path I to possibly release some capacity to reroute power flow. In this case, and $J = 163$ kW, $r_1 = 788$ kWh, $r_2 = 90.3$ %, and $r_3 = 3$.

Switches +Reinforced network: Figure 11 shows active/reactive generation and load shedding for the distribution network equipped with 5 switches and doubled distribution capacity. Switches 8-21 and 9-15 and 12-22 are closed and EEMS can fully restore all the loads. In this case, $J = 68$ kW, $r_1 = 1168$ kWh, $r_2 = 90.3$ %, and $r_3 = 4$.

Switches+DERs with unity power factor: Figure 12 shows active/reactive generation and load shedding for the distribution network equipped with 5 switches and DERs with unity power factor. Switches 9-15 and 12-22 are closed and EEMS can fully restore all the loads. In this case, $J = 0$ kW, $r_1 = 1440$ kWh, $r_2 = 90.3$ %, and $r_3 = 4$.

Switches +DER with flexible power factor: Figure 13 shows active/reactive generation and load shedding for the distribution network equipped with 5 switches and DERs with flexible power factor. Switches 8-21 and 9-15 are closed and EEMS can fully restore all the loads. In this case, $J = 0$ kW, $r_1 = 1440$ kWh, $r_2 = 90.3$ %, and $r_3 = 5$.

Maximum redundancy: Figure 14 shows active/reactive generation and load shedding for the distribution network with maximum redundancy. Switches 8-21 and 9-15 are closed and EEMS can fully restore all the loads. In this case, $J = 0$ kW, $r_1 = 1440$ kWh, $r_2 = 90.3$ %, and $r_3 = 6$.

Table 2. Resiliency measures in different events with different actions

Contingency	Index	Min. redundancy	Switches	Switches+ reinforced network	Switches+ DERs+ pf =1	Switches+ DERs+ flexible pf	Max. redundancy
Event 1	r_1	0	408	3060	2472	4636	6808
	r_2	39.8	39.8	39.8	39.8	39.8	39.8
	r_3	0	3	4	4	5	6
	J	2235	2133	1617	1470	1076	533
Event 2	r_1	0	788	1168	1440	1440	1440
	r_2	90.3	90.3	90.3	90.3	90.3	90.3
	r_3	0	3	4	4	5	6
	J	360	163	68	0	0	0

CONCLUSIONS

For improving the resiliency of power grid, a restoration strategy was proposed. It tries to use the available flexibility resources to minimize the load shedding in post-contingency events. The proposed methodology is implemented in GAMS software as a mixed integer non-linear model. To summarize the resiliency assessment of distribution networks, the following conclusions can be derived as:

- The flexibility resources can improve the resiliency of distribution networks. These resources include DER power factor control, switching maneuver and network reinforcement.
- The proposed formulation can be improved by adding OLTC and capacitor switching actions as decision variables in case of contingency.
- Considering the uncertainty of contingencies and availability of DER resources can achieve better precision and robustness for DSO [16].

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