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Chapter 7

Microgrids as a resilience resource in the electric distribution grid

Gowtham Kandaperumal[a], **Subir Majumder**[b], **and Anurag K. Srivastava**[b]
[a]ComEd, Chicago, IL, United States
[b]Lane Department of Computer Science and Electrical Engineering, West Virginia University, Morgantown, WV, United States

1. Introduction

Recent statistics (Smith & Katz, 2013) show that the frequency of extreme weather events (also classified as low probability high impact, or LPHI, events), such as storms, floods, and wildfires, and associated substantiality of the power grid damage have soared up in the last decade. Recently occurred seven major storms have resulted into damages of over $1 billion each. While our power grid is designed to operate reliably, and industry-standard reliability indices such as SAIDI, SAIFI, CAIDI, and MAIFI (Khodayar et al., 2012) across multiple utilities around the globe strive to main associated countrywide-standard, these indices are primarily intended to capture low impact and high-frequency-type events. Continuing to be able to operate during events involving multiple contingencies is still a challenge. Furthermore, historical data shows that some of the areas are more prone to one kind of weather event than the other, and mitigation solutions to protect the grid for each kind of weather events can be different, and country-specific (Hussain et al., 2019). Therefore, there is no one-size-fits-all kind of solution available. Needless to say, the increasing severity of threats both from natural and weather events motivated researchers to develop a common measure to determine the impact of an event, but the globally accepted definition is still missing. However, as we will discuss later, criticality and uninteruptability of loads from the social point of view get higher precedence. It is intended that during these extreme events, the power utilities must able to be at least serve them.

Distribution networks are primarily the grid’s load center. Increasing deployment of smart grid infrastructure and local distributed generation has made the grid less reliant on the bulk transmission grid. Local resource availability and nonavailability of the transmission network in certain areas have motivated the community to develop islanded grid to serve a certain rural community, which is also known widely as rural μ-grids. Many communities around the world are openly accepting such an approach. In the event of disastrous events, if the distribution network is resource-rich, people have realized the μ-grids provide the ability to separate from the bulk transmission system ensuring survivability (Panteli et al., 2016); and consequently, μ-grids have been growing voice to be able to be utilized as resiliency mitigation solution (Maloney, 2020). The smaller geographical foot prints of μ-grids allow for continuity of service, while LPHI events affect a larger area. It is trivial that some of the loads can be shed to ensure continued supply for the critical infra-structure even in the resource-poor situation. Consequently, μ-grids represent a well-defined electrical system with local generation resources and associated loads that can, when necessary, operate independently in islanded mode. They may or may not be part of a larger grid, creating the main classification of grid-connected and remote μ-grids.

The condition of resourcefulness within a μ-grid may not always be satisfied, and some of the μ-grids can be resourceful compared to the others. Consequently, multiple μ-grids can be connected via transmission/distribution networks exchanging resources among each other (Chanda & Srivastava, 2016; Xu & Srivastava, 2016), improving robustness. Here, even if numerous power lines or μ-grids themselves get outaged, the rest of the μ-grids will still be able to perform, at least with load shedding, enabling robustness of the grid. μ-grids can isolate themselves if the transmission system is suffering from a cascaded outage (Guo et al., 2017). They can pick-uploads from the unhealthy non-μ-grid area (if μ-grid infrastructure exists) dynamically. All these benefits can be achieved remotely while the event is in progress.

Additionally, power lines are often de-energized prior to the event occurrence to avoid the origination of the secondary source of events originating from the power lines (Abatzoglou et al., 2020).μ-grids can keep the lights on in those areas that could not be served due to proactive de-energization and limited availability of tie lines. μ-grids are essentially useful during postevent restoration of the power system, even if the transmission lines becomes unavailable, ensuring faster recovery (C. Chen et al., 2016). However, as already discussed, all of these can be achieved if the μ-grids are resource-rich, capable of being operated as an island backed by advanced telemetry, modern information processing, and equipped with suitable control devices. Consequently, while the emergence of DER technologies, availability of flexible resources, improved manufacturing are certainly an enabler, the ability to connect and disconnect into the grid comes at a tremendous price. Therefore, the utility of using μ-grids as a resiliency resource is a crucial question, and in this chapter, we have tried to focus on the following questions:

- What are the key features of μ-grids that make it a resiliency resource?
- How is μ-grid resiliency evaluated?
- During the different stages of event progression, how will μ-grid operation change to enable resiliency?
- What are the challenges of utilizing μ-grids as a resiliency resource?

2. Key resources offered by microgrid within distribution system

μ-grids possess a unique set of features that allow for their operation to supplement the system's resiliency. Consider the portion of the distribution system that does not have μ-grid capability and suffers the same outage as the bulk distribution system during an LPHI event. The typical mitigation of LPHI outages is similar to existing distribution system mitigation strategies prescribed by utilities to alleviate grid blackout and improve system stability. Any centralized control that can be executed by the distribution network operator needs to be immediate and constrained to the location of sectionalizers and power sources to avoid cascading outages into the system. Typical operations to reduce discontinuity of service take the form of the following steps:

i. Reconfiguration using switches in the network to serve loads through an alternative source of power. Network reconfiguration changes the topology of the network to connect the disconnected portion of the distribution system to either a healthy circuit with enough capacity.

ii. Use of backup generation to provide service to loads that are disconnected from utility service. These backup generators are usually diesel units that are maintained for intermittent service during emergency conditions.

iii. Crew and resource dispatch to repair infrastructural damage and restore healthy operation of the distribution network. This step is usually very subjective on the nature of the distribution system and associated affected components.

iv. Adaptive islanding allows the distribution network to act as a μ-grid with a small electrical boundary and utilize distributed energy resources to power the μ-grid.

v. Shedding of nonpriority loads alleviates the generation load mismatch and can restore critical loads.

With μ-grid capability implemented, that is, the ability of the distribution network segment to operated isolated from the primary grid using local resources, certain features of the μ-grid can be leveraged to impart resilience. Microgrid architectures are varied, and there does not exist a single approach to utilize all μ-grids as a resilience resource. Instead, the following features can be assessed with location-specific threats applicable to the system and promise to improve resilience.

2.1 Resource flexibility

The inherent design and planning paradigm of μ-grids provide the operational flexibility, increased availability, and the distributed architecture required for the quick restoration and continuation of service to critical loads. The inherent vulnerability of bulk distribution systems also stems from the long distance between the generation source and the loads, contributing to increased susceptibility. The advantage of the operational flexibility is the high power availability of μ-grids during LPHI events where the event's impact is distributed unevenly. Therefore, the boundary of the μ-grid, limited by the switching configurations and location of DERs, can adjust to maintain service. The additional benefit of the smaller footprint of μ-grids also reduces the energy losses commonly observed in bulk distribution systems due to the radial nature and high R/X ratio. The size of the μ-grid envelope is defined by the area covered between the source and generation, ranging from a single building (generator-load pair) μ-grid to a full substation μ-grid with multiple DERs and loads with full integration contribute to the survivability.

μ-grids allow for bidirectional flexibility: upstream flexibility on the resource side and downstream flexibility on the load side. Fig. 7.1 shows the configuration of the μ-grids in relation to the flexible assets. Engineers can leverage the resource flexibility to ensure that the μ-grid can accommodate for resilient operation during LPHI events.

2.2 Energy storage

Energy storage allows the μ-grid to store energy from nondispatchable variable generation in the μ-grids and utilize it as a dispatchable source when

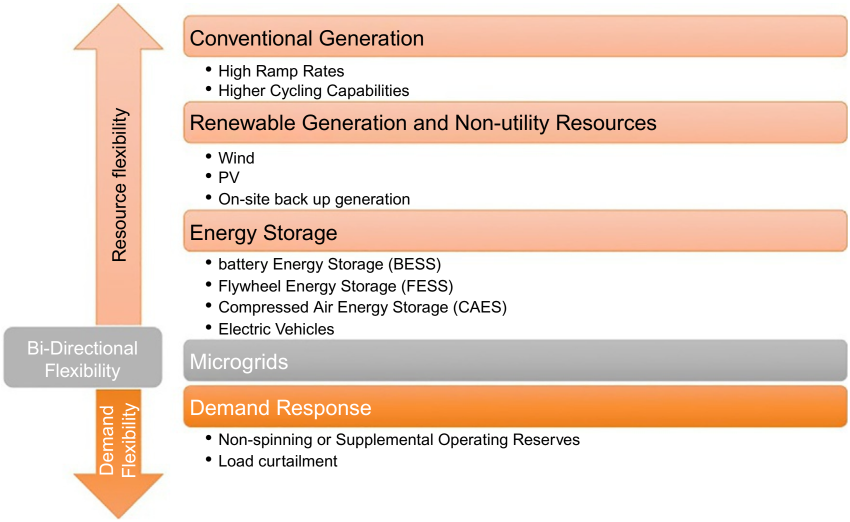

Fig. 7.1 Resource flexibility enabled by μ-grids. *(No Permission Required.)*

necessary. Commonly available in the form of battery energy storage systems, electric vehicles, pumped hydro plants, and more recently electric vehicles, energy storage have become an essential design consideration in μ-grids. Energy storage devices provide a fast response to absorbing the abrupt loss of generation due to LPHI events to reduce generation stress. Also, energy storage systems can provide improved μ-grid stability through voltage and frequency regulation. Typical BESS, implemented in most commercial instances using lithium-ion technology, the major issues in adopting storage into μ-grids seems to be the cost of the batteries, storage capacity, and operating times. Careful planning assessment needs to be considered to utilize energy storage as a resilience improving investment. The planning study should also include determining where in the μ-grid the energy storage unit be placed in the optimal location needs to be resolved as proposed in Kim and Dvorkin (2019).

2.3 Distribution automation

The unpredictability and variability introduced by DERs in μ-grids was once seen to add unwanted complexity to the μ-grid operation. Distribution automation (DA) is a potential solution to mitigate this problem. In addition to introducing control and monitoring to μ-grid assets, DA allows for enabling resilience by leveraging sensor networks, communication networks, controls, and data analytics.

DA as reported in available literature shows the following capabilities:

i. Improved outage management
- Remote fault location and diagnostics
- Automated feeder switching
- Outage status monitoring and notification
- Optimized restoration dispatch

ii. Voltage and reactive power management
- Integrated voltage and volt-ampere reactive (VAR) controls (IVVC)
- Automated voltage regulation
- Conservation voltage reduction (CVR)
- Real-time load balancing
- Automated power factor corrections

iii. Frequency and real power management

iv. Equipment health monitoring

v. Coordination of μ-grid assets

Each of these are potential application of the DA and can be utilized to enable resilience of the μ-grid.

3. Assessment of distribution system resilience with microgrid

μ-grids as a resilience resource can be realized in three stages, each corresponding to the progression of the event in the temporal horizon. In this section, we describe the resilience analysis process of μ-grids before, during, and after the LPHI event. The characteristics of the μ-grids that enable resiliency are:

- **Preparedness:** The property of the system's readiness for the incoming disruptive event. This multidomain property allows for the various mechanisms in the μ-grid to be ready to respond when the event progression starts.
- **Robustness:** The property of systems to resist change in topology when subject to stress
- **Absorption:** The property of the system to resist discontinuity of service when subject to an LPHI event
- **Response:** The property of the system to evaluate and select the appropriate control action to reduce the impact of the LPHI event and improve performance after the LPHI event has passed.
- **Recovery:** The property of the system to regain blue sky performance with minimum time.

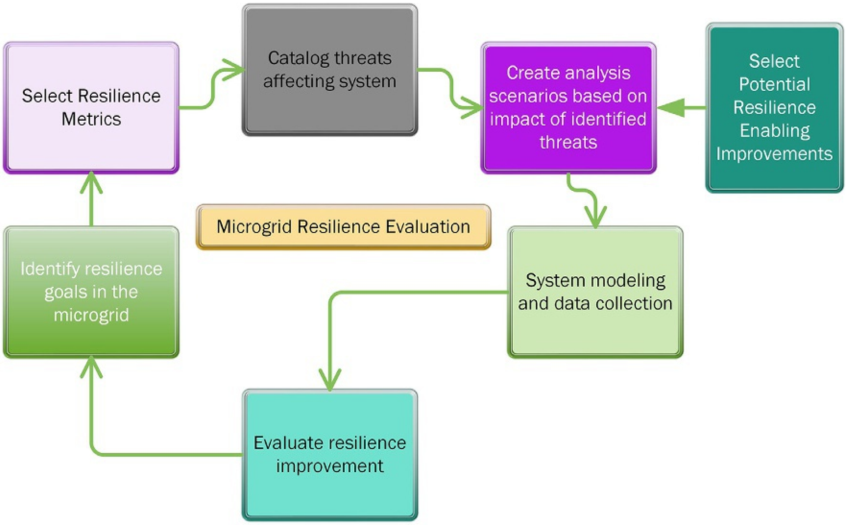

Fig. 7.2 μ-grid resilience evaluation. *(No Permission Required.)*

Careful planning study to assess μ-grid needs to be conducted to justify the initial capital investments in commissioning μ-grid capabilities in a distribution grid. Microgrids to alleviate reliability concerns are designed and implements to reduce the impact of upstream outages in the distribution network and reduce the loss due to the energy not served to the loads. Subsequently, the assessment of μ-grid resilience provides a business case to utilize μ-grids as a resilience resource. This can be quantified through the resilience assessment process shown below in Fig. 7.2. A special case of the resilience evaluation framework is the AWR resilience metrics-Anticipate metric for preevent resilience based on preparedness and ability to anticipate damage to the system; Withstand metric for during event resilience based on robustness and optimal utilization of resources to mitigate LPHI impact and Recover metric for the postevent resilience to address the rapidity and magnitude of the critical load restoration effort as presented in Fig. 7.3.

3.1 Preevent resiliency

The resiliency of the μ-grid before the event is affected explicitly by the ability of the system to anticipate and be prepared for the incoming threat event. At this stage, the μ-grid is expected to work under normal conditions or in "blue sky" conditions. The term blue sky is used to separate between the definitions of reliability and resilience as there can be high resilience and

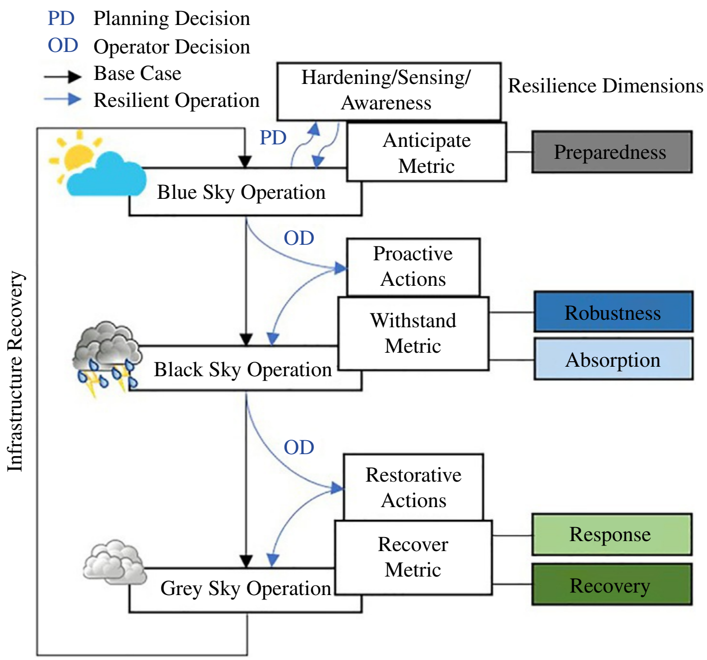

Fig. 7.3 Multitemporal resilience framework. *(No Permission Required.)*

low reliability in blue sky operation and high reliability and low resilience in normal operating conditions. Most of the preparedness strategies to improve μ-grid resilience in the blue sky mode are performed in the form of infrastructure hardening—the process of adding robustness, security, and stability of electrical assets to prevent failures due to the physical effects of the LPHI events. These include "undergrounding" of electrical poles, the elevation of flood-risk assets like generators and switch-gear, vegetation management, and overdesigned construction practices. In addition to hardening, planning efforts such as adding redundancy in the form of adding additional distribution feeders and associated switches, improving resourcefulness through the addition of DERs, better situational awareness through sensors and controls allow for increased resilience in the μ-grid.

Note: The ability of the system to anticipate, be prepared for, and mitigate the impact of the event is quantified by the anticipate metrics.

In order to assess resilience before the event, the system needs to be reviewed and assessed for metrics that will quantify system preparedness and the ability to anticipate, be prepared for, and mitigate the impact of the event. Preevent resiliency analysis helps develop business cases for

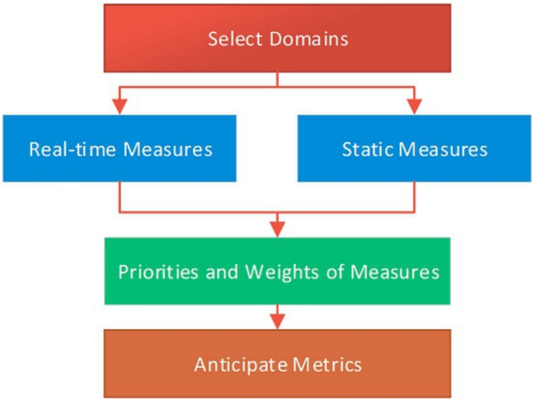

Fig. 7.4 Development of the anticipate resilience metric. *(No Permission Required.)*

resiliency improvement planning studies. The interdisciplinary nature of resilience requires the assessment to include domains that directly affect the μ-grid resilience. These domains include but are not limited to transportation system, fuel supply chain, cyber-communication systems, repair crews, and water distribution systems. These domains have many internal variables that can alter the resiliency of the system but can make the analysis data-intensive and complicated. The use of a composite preevent resiliency metric $\mathfrak{R}_{pre}$ that is objective-based and considers all domains involved is required. This preevent resilience metric should be developed as shown below (refer Fig. 7.4).

Factors from individual domains are selected based on careful consideration from all stakeholders. This process of careful elicitation can be exhaustive and time-consuming due to the system and threat-specific nature of the system in question.

3.2 In event resiliency

A few moments before the event progression starts, the system is operating in blue sky mode and is serving all its critical loads and is meeting some performance standards particular to that μ-grid. The ability of the system, from this point onward, to withstand the impact of the event, thereby ensuring continuous service to critical loads is quantified by the withstand metrics. The first step in the withstand metric evaluation is the selection of relevant resilience indicators that can increase or decrease resilience. The second step is to apply a threat impact analysis to observe the change in resilience indicators before and after the threat. This provides the user with a set of alternatives that can be passed through a multicriteria decision-making tool that can provide a comparative analysis of how the indicators vary between the alternatives. For a typical μ-grid, the resilience indicators pertaining to the withstand metric are:

- **Critical Load Count (CLC):** The number of critical loads still in operation while the event happens
- **Critical Load Rating (CLR):** The size of critical loads still in operation while the event happens
- **Total Available Generation (*G*):** Total generation available for dispatch to critical loads
- **Critical Load Demand (*D*):** Demand of the system
- **Topological Score ($\Re_T$):** A composite score indicating the various graph theoretical measures

A number of graph-theoretic techniques are available for engineers to choose when assessing μ-grid resilience. Let us consider a simple factor analysis using graph-based characteristics of the μ-grid to assess resilience.

3.2.1 Graph theoretic approach to ensure microgrid robustness

For the extraction of topological resilience indicators, the μ-grid is represented as a graph G of N nodes and E edges with the adjacency matrix A. The node elements in the system are transformers, switches, bus elements, usually in the form of switch-gear and circuit selectors. The edge elements are wires connecting the nodes together. Several methods are proposed in current literature to use graph theory techniques to analyze the robustness of the power grid (Motter & Lai, 2002; Solé et al., 2008). In the proposed topological analysis, the network is studied as an undirected and unweighted graph. The weight or the importance of the node are considered in the subsequent evaluations as loads are classified as high priority, medium priority, and low priority loads. The topological resilience indicators selected for this analysis are chosen to indicate how well connected the system is and how much perturbations can the system withstand. These indicators are chosen to represent the size, distribution, node, and link connectivity statistics of the graph.

Graph Diameter (*D*). The maximum eccentricity or the greatest distance from any two vertices indicates the size of the graph.

$$D = \frac{2|E|}{|N|(|N| - 1)} \tag{7.1}$$

Degree distribution ($<k>$). The degree of a node is the number of nodes connected to it. The connectedness of the graph is indicated by the degree distribution, which is the probability distribution of the degree over the entire network. The average degree distribution indicates the number of feeders arising out of a particular node. A high value of the average degree distribution indicates that there are nodes with high connectivity to other network nodes.

$$\langle k\rangle = \frac{2|E|}{|N|} \tag{7.2}$$

Average betweenness centrality (C_b). Betweenness centrality of a node x is defined as the number of shortest paths between all pairs of nodes in the connected graph passing through the given node x. It is a measure of node importance and indicates how many shortest paths are dependent on the nodes present. The average betweenness centrality provides a clue to how susceptible the graph is to perturbations or failures that can possibly sever connections between nodes as it is not favorable to have a node with high betweenness centrality fail in the system.

$$C_b(i) = \sum_{i \neq j \neq k} \frac{\sigma_{jk}(i)}{\sigma_{jk}} \tag{7.3}$$

Percolation threshold (f_c). Percolation theory can be employed to study the robustness of the network. Chanda and Srivastava describe the infinite-dimensional percolation analysis of a graph which is subject to random removal of nodes which is denotes by f (Chanda and Srivastava, 2016). This random removal is representative of an unfavorable event. For such study, it is observed that there exists a critical fraction of nodes removed f_c for which the graph degrades into individual isolated clusters. This critical fraction of nodes is called the percolation threshold shown below as an approximation using statistical mechanics approach (Radicchi, 2015).

$$f_c = 1 - \frac{1}{\kappa_0 - 1} \tag{7.4}$$

where $\kappa_0 = \langle\kappa^2\rangle / \langle\kappa\rangle$ and $<\kappa^2>$ is the square of the standard deviation of the degree distribution of the network. The critical fraction of nodes in this graph theoretical analysis should not be confused with critical loads, which are high priority loads that require nondiscontinuity of service during unfavorable events. However, these critical nodes are highly influential in the robustness of the system.

Algebraic connectivity (λ_{alg}). Also called the Fiedler value, it is the second smallest eigenvalue of the Laplacian matrix of the graph. The Laplacian matrix is the sum of the degree matrix D and the negative of the adjacency matrix A. The elements of the Laplacian are given by degree of the node i at diagonal (i,i) positions and by -1 at nondiagonal positions.

Once the topological resilience indicators are extracted, a vector of the indicators is obtained for each scenario that is analyzed. This is represented as

$$\vec{\mathfrak{R}}_{\tau} = [f_c, D, \wedge_2, C_B, \langle\kappa\rangle] \tag{7.5}$$

This vector represents the topological component of the resilience analysis. For each of the system configuration, threat scenarios or study cases, a new vector is created.

3.3 Postevent recovery resilience

The third stage of the event occurrence, when the threat has subsided and the system is trying to recover from the damaged state to the state of normal operation. In this stage, the response and recovery of the system is to be quantified. The recovery metrics depends on the rapidity of restoration, redundancy of resources, and resourcefulness of assets. The postthreat recovery of the system starts with the evaluation of system damage. The survey produces a damage report enumerating the number of damaged assets, including poles, lines, transformers, and switches, and the corresponding location.

With the postevent damage assessment, the recovery of the μ-grid would be a twofold process. The loss of generation would be rectified by the dispatch of the DERs or through blackstart restoration. Then the most resilient μ-grid restoration options need to be evaluated to be selected. As a use-case, let us consider the addition of automated switches that can be used for reconfiguration. With different configurations available, a similar method to the withstand metrics can be employed where the various rapidity and resourcefulness applications can be selected and compared. A typical recovery resilience calculation would be performed as follows. A factor extraction on several resilience indicators needs to be collected, such as the recover cost (RC)—the cost of equipment, labor, and material for the repair of the "downed" assets. The factor CLR is the weighted number of critical loads restored. The repair time RT is based on the type of equipment to be repaired. Since the methodology uses AHP for the computation, the relative time for the time and cost is sufficient to make a decision on the resiliency score. The repair time is the sum of the repair time for the equipment, time for the crew to get from the crew station to the equipment $T_{accessibility}$ and T_{OH}, the overhead for the crew to assemble the repair/recover work. The repair time is assumed to be 1 hour for a feeder, 4 hours for a pad-mounted switch, and 5 hours for a transformer.

$$\vec{\mathfrak{R}}_\tau = [RC, RT, CLR, SO, T_{SO}, \mathfrak{R}_\tau] \tag{7.6}$$

The number of switching operation required to restore the load (SO) and the time for the switching operations indicated the rapidity of the restoration process. These are computed for available restoration paths for each scenario. The use of real-world repair costs and times is not imperative because the AHP is a comparative process and does not require the factors to be accurate. This provides the Distribution Network Operator (DNO) with operational decision-making assistance on the most resilient restoration scheme.

4. Strategies for enabling distribution system resiliency with microgrids

While an LPHI event is on the horizon, the primary objective of the operator is to let the system "bend" proactively (also known as preventive techniques) (Panteli et al., 2017) and adapt to the looming threat to avoid the future cascading failure of the power system (Guo et al., 2017). The μ-grid, in this regard, emancipates a part of the grid to be operable in isolation. The AWR framework discussion clearly divides the entire event temporal horizon vis-à-vis resiliency improvement strategy road-map into three stages. The first stage is called on immediately following the situational awareness signal received from the resilience monitoring system. If the power system resiliency deteriorates, the power system operator will switch from economic operation mode to resiliency mode, where minimization of the load curtailment, maximization of energy served, or minimization of energy not served becomes the main objectives (Bhusal et al., 2020). The loads can also be shredded based on their criticality, resource availability, and ability to form a μ-grid. Operational crews and moving diesel generators (Wood, 2020a, 2020b) are also deployed simultaneously for safety-related de-energization and systemwide reconfiguration, which can also include manually formed μ-grids. It is also notable that the entire distribution network may get isolated from the transmission grid following the dissipation of the disastrous event. Repair crews can be prepositioned (C. Chen et al., 2017) to ensure faster restoration. Nevertheless, this stage is required to be carried out sufficiently in advance for ensuring the in-event safety of the operational crews. The second stage commences with the event striking the critical power infrastructure. The crews' limited availability enforces that the majority of the requisite deployed operation will be carried out remotely.

Once the disaster has precipitated, the repair crews can be deployed to estimate the damage and prioritize the recovery and re-energization process, considering predeployed moving diesel generators and prepositioned crews. Here, restoration of the network necessitates the availability of, as discussed, sufficient black start capability (Schneider et al., 2017) for being able to be operated as μ-grid, or availability of the transmission network. Therefore, depending on the distribution network's operability as a μ-grid, there are two main facets for system operation in this stage (Amin Gholami, Aminifar, & Shahidehpour, 2016). If the network is incapable of operating as a μ-grid, with transmission network outage, a top-down approach needs to be deployed. Here, the network can be restored only after reconfiguration of the transmission network. Restoration of loads would also be carried out after due reconfiguration of the distribution network, only after the primary substation is re-energized. If the network can operate as a μ-grid, restoration of loads within the distribution network can be carried out independent of restoration of the transmission network. The speed of restoration would, of course, be limited by local resource availability. Typical objective function considered by the system operator in this stage will be the minimization of total restoration time and maximum critical infrastructure restoration (Bhusal et al., 2020).

While the discussed three steps are relatively independent in nature, the action plans rely on the measures taken in one of the earlier stages and are shown in Fig. 7.5. In the rest part of this section, we will discuss the challenges of the described three stages and the utility of μ-grid in their mitigation.

4.1 Proactive management and control

As discussed earlier, preevent control and resource allocation begin with a forecasted situational awareness signal. Although the consensus lies in the difficulty of precise evaluation of the origin of the critical weather events and the probability of event severity (Y. Wang et al., 2016), the recent

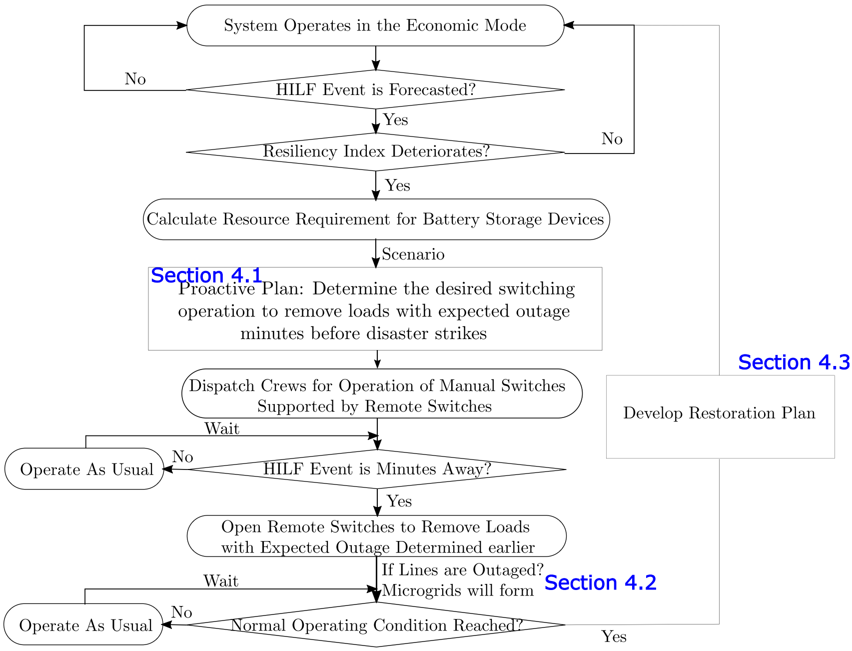

Fig. 7.5 Sequential resiliency management and control. *(No Permission Required.)*

advancement in the accuracy of the weather models has significantly improved the short-term prediction accuracy. In this regard, the use of predicted wild-fires propagation path into an early warning signal for the transmission system outage is already discussed in the literature (Dian et al., 2019), and power utility companies in the United States are actively seeking to develop such early warning signal for the distribution network and use it to improve networkwide resiliency (Boston Consulting Group, 2020). Literature, such as Guikema et al. (2014), Liu et al. (2005), and Nateghi et al. (2014), utilizes statistical models to estimate power outages, which can be utilized to allocate resources, including the deployment of µ-grid to reduce outage duration, based on historical in-event monitoring data (Ji et al., 2016). Even if a disaster strikes energized poles and wires, especially in the case of hurricanes, snowstorms, typhoons, windstorms, floods, and lightning storms, the component failure rate varies with the intensity of hazardous forces. A generic fragility curve can be utilized in this regard for depicting the failure probability of the equipment (Panteli et al., 2016). The intensity of the weather events can also significantly vary spatiotemporally (Y. Wang et al., 2016). Contrarily, the wildfire events directly affect the flow through the transmission lines (Choobineh et al., 2015), and the lines are required to be dynamically rated (Trakas & Hatziargyriou, 2018), forcing the distribution to operate as μ-grid. Multiple μ-grids can be connected to each other, forming a multi-μ-grid (Chanda & Srivastava, 2016; Schneider et al., 2017). Nevertheless, for the event modeling purpose, the propagation of both of these kinds of weather events can be treated as the Markov decision process (Bertsimas et al., 2017; C. Wang et al., 2017).

In the absence of long-term realistic prediction models, robust optimization as a part of proactive management (Gao et al., 2017) is widely used in the literature. As discussed, since the action plans rely on the measures taken in one of the earlier stages, simultaneous consideration of preevent resource allocation (symbolizing "wait and see") with real time in-event dispatch (symbolizing "here and now") can also be considered as a part of robust optimization (A. Gholami, Shekari, et al., 2016; A. Gholami et al., 2019). This enables the predictive-corrective action plan in the decision-making. As discussed in the AWR framework, the availability of the number of lines in a network significantly affects resiliency, and therefore, the removal of all the to-be-affected lines may not be realistic. Consequently, one may also ensure a certain minimum number of vulnerable lines within a distribution grid remain connected in anticipation of an event while ensuring minimal state transition, line outages, and load curtailment (Amirioun et al., 2018).

The discussed proactive crew mobilization (Maryland Energy Administration, 2020) is also driven by safety-related de-energization, expected damage (in terms of the value of the lost load, VOLL), load criticality (loads, such as hospital, water treatment facilities have higher priorities), manual μ-grid formation, the crew dispatching cost, and crew availability. Often, some of the energized equipment is required to be de-energized a priori to avoid origination of secondary disaster (e.g., public safety power shut-off, or PSPS, events in the state of California, United States (Abatzoglou et al., 2020)), or hasten postdisaster recovery (e.g., preevent generator shut down before tsunami and snow avalanche in Alaska, United States). In this case, the reconfiguration is needed to be carried out with sufficient delay to ensure customers are served for the longest possible duration. These operational crews can also facilitate the creation of μ-grid as a defensive islanding strategy, where, even if a part of the grid were required to be isolated, the customers would remain energized during the disaster. This strategy can also help us alleviate cascading outages. The presence of both remote and manually operable switches can be considered in this effort, where operational crews are dispatched insufficient advance so that their safety can be ensured (Arab et al., 2015). Furthermore, the dispatch of the crews and moving diesel generators (Martini, 2014) need to be coordinated. In case the repair crews are dispatched a priori, they must be safely located sufficiently away from the hazard zones (Arab et al., 2015). Although these moving diesel generators can have black start capability, limited fuel availability (Gao et al., 2017), and limited charging capability of batteries (Pandey et al., 2020) are also major concerns for the isolated μ-grid survivability. Additionally, the limited availability of other resources also enforces the available local resources with the μ-grids to be scheduled appropriately to reduce the downtime for the critical loads (Rahman, 2008). Furthermore, if isolated μ-grid operation is looming, the operator might schedule their resources conservatively via resiliency cuts (Khodayar et al., 2012) (by limiting utilization of certain resources above the threshold, precharging batteries (Pandey et al., 2020), etc.).

In the following part of this subsection, we will describe the proactive decision-making strategy through an example. From Fig. 7.5, we observe that the system would continue to operate in the economic model until an LPHI event is forecasted. If the withstand resiliency metric for the concerned system deteriorates, the system will jump to resiliency mode, where the operator aims to supply as much critical load as possible within the system. In this mode, the operator will initially estimate the nodes within the distribution system with the expected outage. If any generator is located within this region, in order to achieve postdisaster expedited recovery, those generators will also be taken out from the grid. Given the finiteness of the available switches, it is expected that some of the additional set of nodes will also be outaged. As a part of operating both manually and remote operable switches, to ensure crew safety, requisite manual switching operations are required to be carried out significantly earlier in the temporal horizon. However, it is also not recommended to disconnect the loads with the expected outage (LwEO) several hours before. This motivates us to solve this problem in two stages. The first stage deals with the operation of manually operable switches, which are assisted by the remotely operable switches, which are to be deployed significantly ahead of the event. Second stage deals with the isolation of LwEO through remote switches, which can be modified as the forecast gets revised. Therefore, this approach utilizes a flavor of predictive- corrective approach. It may so happen that following the disconnection of LwEO, some of the unaffected parts of the network need to be operated as a μ-grid (if designed a priori). The LwEO remains connected to the main grid through remotely operable switches (if that

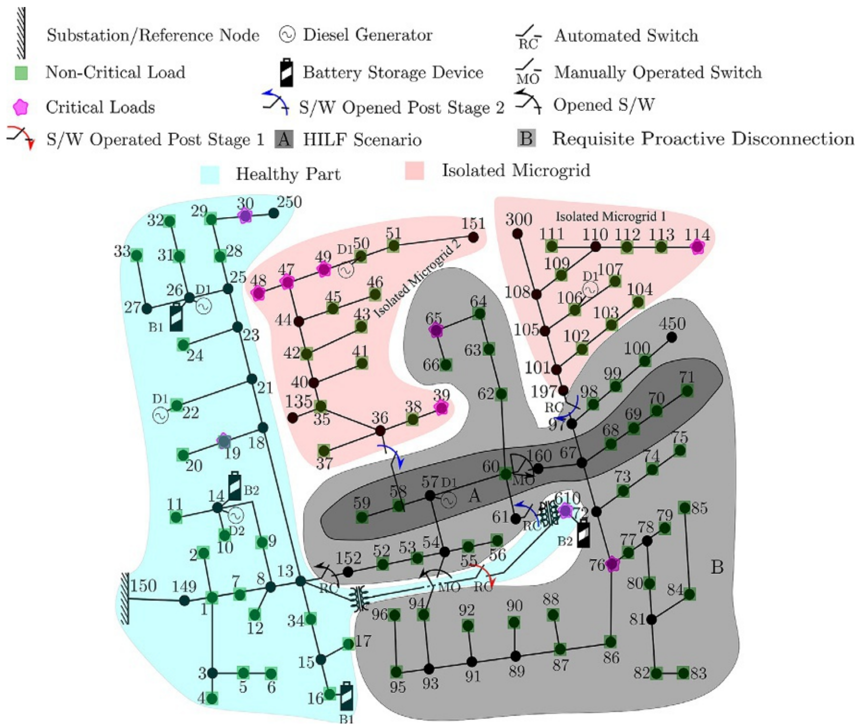

Fig. 7.6 Proactive control with μ-grid for modified IEEE 123-bus system. *(No Permission Required.)*

segment is not designed to operate as a μ-grid) while ensuring the flow through the associated switch is zero. This will ensure that in the event the LwEO is isolated, the operation of the healthy part of the system will not be disturbed.

As shown in Fig. 7.6, the proposed strategy has been depicted using a modified IEEE 123-node system. Locations of manually and remotely operable switches are given. Grayed-out section with the symbol, A, identifies HILF estimated outage scenario. Due to the absence of switches, the entire light grayed region identified with symbol B will be outaged. Highlighted areas in pink color are connected through the LwEO region, and hence will be required to be operated as μ-grids when the event is in progress (if designed). Critical loads connected at node 610 will be connected into the main grid through the associated manually operated switch. To ensure that subsequent disconnection of LeWO, the healthy part will not be disturbed, one needs to ensure that flow through switches 36–58, 97–197,

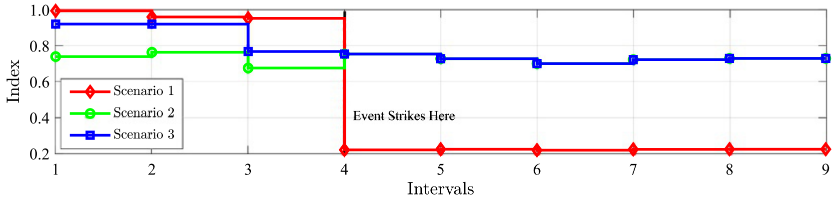

Fig. 7.7 Temporal variation of the withstand metric for modified IEEE 123-bus system. *(No Permission Required.)*

and 61–610 is zero following stage 1, will be opened minutes before disaster strikes. Furthermore, the LwEO will be continued to be supplied in case the HILF event never strikes. Furthermore, since the stage 2 plan is implemented only through remote switches, changes in weather prediction will not be harmful to the operational crews, and, is beneficial due to correction possibility. Therefore, it is clear that the discussed two-stage approach (scenario 3) is beneficial compared to the single-stage fire-and-forget (scenario 2), or no action (scenario 1) approach, and is shown Fig. 7.7.

4.2 Postevent recovery

Although a μ-grid is designed to disconnect from the grid autonomously, it is expected to operate in grid-connected mode during normal operating condition (Z. Wang & Wang, 2015). Once the contingency event strikes the distribution network, a part of the grid can become de-energized, as a part of an antiislanding protection scheme, or operate as a μ-grid. Availability of system status information, infrastructure resources (reclosers, energy storage system, DERs, mobile generators) facilitates the seamless formation, and successful operation of such μ-grid (C. Chen et al., 2017). In this regard, Gouveia et al. (2013) utilize emergency demand response from responsive loads (including EVs) for successful primary frequency control within a μ-grid establishing continuous load generation balance. The use of CHPs, and diesel generators for postevent operation is also a widely accepted choice (KEMA, 2014; Maloney, 2020). Depending upon the R/X ratio of the distribution network, $P-V$ and $Q-\delta$ droop characterized can be utilized (Abdelaziz et al., 2014) for power balance while ensuring protection devices does not get triggered.

Here, the grid can also be equipped with self-healing technologies, such that once a de-energization event has occurred, the μ-grid can intelligently pick-up loads within its vicinity (assuring survivability) (Adibi & Fink, 2006). The resiliency could be further improved by dynamic creation of μ-grids, forming networked μ-grid, multienergy μ-grids, or energy hub (Hussain et al., 2019). The dynamic μ-grid creation is especially favored as a reactive mechanism and is often facilitated by software algorithms for controlling the switches (Simonov, 2014). Artificial intelligence, multiagent (Dehghanpour et al., 2017), fuzzy logic (Hussain et al., 2017)-based techniques can be utilized to facilitate demand response, DER, and storage system dispatch as a part of advanced operation strategy within a μ-grid. In case multiple μ-grids are formed, multiple μ-grids may self-organize into a cluster (Ding et al., 2017; He & Giesselmann, 2015) for optimal power-sharing (Zadsar et al., 2017), if the capability exists. AC, DC, and hybrid-AC-DC μ-grids can be utilized for resiliency improvement (Pannala et al., 2020). Such a power sharing approach ensures the self-sufficiency and stability of the network as a whole.

The distribution network in its entirety can be decomposed into multiple μ-grids (C. Yuan, 2016). However, as discussed earlier, limited fuel availability limits the operating modes of these μ-grids and can be categorized into basic autonomous, fully autonomous, and networked μ-grid (Zia et al., 2018). While the disaster is in progress, the μ-grid might limit its resource provision to critical facilities. The use of the distributed multiagent system to achieve such a self-healing ability for a μ-grid has been discussed in Colson et al. (2011). Given that the μ-grids remain energized during the progressing event, it can serve black-start capability to re-energize disrupted main generators (Schneider et al., 2017). Therefore, depending upon its capability of the resource within a μ-grid, and deployed smart switches, and tie-switches, it can be categorized into three major categories (Schneider et al., 2017): (i) local resource, (ii) community resource, (iii) black-start resource. In case some of the switches are not automated, the system operators can also facilitate μ-grid formation remotely. Once the emergency transpires, it will switch back to the normal mode. Reliance on the communication network in such a venture can be facilitated by adopting a distributed approach (C. Chen et al., 2016). The utilization of centralized communication architecture may not be suitable in this regard due to network-level vulnerabilities.

4.3 Restoration process

In conjunction with the traditional distribution service restoration as a part of the outage management system (OMS) (Singh et al., 2017), here the post contingency recovery begins with damage assessment through ground check, aerial survey, and customer trouble calls, SCADA (protective relays, fault indicators, etc.), AMI, μ-PMU, social media, and advanced resiliency monitoring system (ARMS) as a part of the advanced distribution management system (ADMS). All of this information can be fused to provide grid status as a part of the decision support tool. Large scale deployment of monitoring devices in a smart grid facilitates such treatment (Mohamed et al., 2019). Following this, the operator calculates the optimal route for crew dispatch, crew schedule to mobilize crew from one site to another while minimizing the repair and restoration time for the critical loads. Crew and resource budget is also a major concern in this step and often responsible for delayed recovery (W. Yuan et al., 2016). Contrary to the preevent proactive crew dispatch (if carried out), the state of system outage is already deterministic. Furthermore, one also needs to ensure that antiislanding protection for each of the backup generators/DERs is present, such that the safety of the repair crew is never compromised.

In the absence of local DERs, to speed up the restoration process, moving diesel generators are often deployed (Lin et al., 2019). Additionally, deployment of generators needs to be well-coordinated with switching strategy (B. Chen et al., 2019) to enable the creation of multi-μ-grid, which was not possible due to the absence of sufficient grid intelligence and generators with black-start capability. Such multi-μ-grid framework can significantly deviate from the traditional sequential predetermined restoration priority list (Freeman et al., 2010) and move to parallel service restoration, hastening the entire process. Note that, in this case, crew routing vis-à-vis vehicle routing problem, diesel generator dispatch, and power system re-energization need to be carried out simultaneously, similar to a multienergy system, which has gained significant attention in recent years.

It is also notable that alongside the destruction of electricity and communication infrastructure, other unity infrastructure can breakdown as well (Girgin & Krausmann, 2014). In this scenario, even if gas-fired generators remain unscathed, the generator will be outaged, crippling the capability of a μ-grid (Zerriffi et al., 2007). To circumvent this problem, literature considers information sharing among multiple infrastructure resources (Capozzo et al., 2017). Additionally, one also needs to account for the interdependence among these critical infrastructures. For example, suppose gas pump plants are not treated as a critical facility and restored earlier. In that case, the gas-fired generators cannot be brought online, degrading the power system resiliency significantly (Lin et al., 2019). The required integrated approach for designing a restoration plan for the grid should also adapt to the changing disaster landscape. In case of proactive decision-making, this integrated solution will be part of the "wait and see" problem.

5. Barriers and challenges

μ-grids, enabled by the advanced decision support system and availability of copious local resources, can supplement the primary grid unavailability in the wake of a disaster, leading us to enhanced emergency preparedness of the grid (Xu & Srivastava, 2016). Isolation from the primary grid can help protect the load center from the possible cascaded outage, even in the wake of a cyber-attack. Along with the utilization of physical properties of the power system, μ-grid control center (MGCC) facilitated by decision support tool from local measurements can also utilize advanced software algorithms to manage resources within its premises, dynamically pick up load through increasing its boundary (Hussain et al., 2019), and create a μ-grid cluster, collaborating in a power-sharing approach. The use of clean energy resources during normal operation also facilitate GHG emissions reduction. Always-on power can ensure (Maloney, 2020): (i) continued access to food and water, (ii) operability of clinics, pharmacies, hospitals, (iii) long-term availability of transportation fuel, (iv) continued availability of distribution retail supply-chain, (v) last-minute provision of necessary home-safety and repair tools. Furthermore, many companies, such as Schneider Electric, ABB, Siemens, General Electric, Alstom, Tesla, and Google as of date are developing and deploying their prototype. In the aftermath of the California wildfire and PSPS events, μ-grids have gained a lot of attention from the California Public Utilities Commission (Wood, 2020a, 2020b). However, reaping such huge benefits comes with an enormous price. This section will focus on various barriers, concerns on economic viability, policy requirements, and regulatory barriers, specific to μ-grids as a resiliency resource.

5.1 Barriers

Several implementation challenges require special consideration to achieve the desired level of resilience during major events. These barriers are majorly divided into five categories and are discussed below:

5.1.1 Renewable uncertainty

While higher penetration of renewable-interfaced DERs, coupled with improved predictability of renewable energy resources, enhances the distribution network's self-sufficiency, renewable uncertainty is still a concern during natural disasters. Since event origination and dissipation time cannot be predicted accurately, compensation for the renewable induced variability becomes hard to manage, and the conservative operating solution becomes very expensive. Additionally, during certain weather events, the renewable output becomes zero, leading to resource deficiency and in-event infrastructure damage, especially to renewable generators, blockage of renewable generators due to uprooted trees would lead us to rely on a new set of resources in the postevent aftermath. Furthermore, traditional scheduling frameworks (including stochastic model) consider longer scheduling horizon (Hussain et al., 2019). In-event higher level of uncertainty associated with renewable resources makes real-world deployment of these solutions difficult. Therefore, robust uncertainty handing and predictive-corrective control approach need to be incorporated in the modeling to let the system operate at the desired level of resiliency independent of its operating condition.

5.1.2 Control issues

While it is almost universally accepted that μ-grids can operate as an islanded grid, can connect and disconnect from the main grid, it is a challenge to determine when do we allow the μ-grid to unilaterally disconnect (as a part of "intentional islanding") and when do we allow it connect back to the main grid. If the action is reactive, a temporary outage or voltage dip might be observed within the μ-grid, which will clear itself following the ramping up of local generators. In the case of insufficient responsiveness, the μ-grid would have to utilize its local black start capability, and the internal monitoring system and protective relays, which can often be cost-prohibitive (Hussain et al., 2019). The presence of numerous local DERs makes internal coordination to become challenging, and a comprehensive understanding of the interconnectedness of all the components becomes essential. Furthermore, the majority of DERs are inverter-interfaced, and after disconnection from the primary grid, it reduces its inertia significantly. Consequently, in the event of insufficient flexible fast ramping resource, even if load-generation balance is ensured, the ROCOF of the system will be very high, and traditional protection system settings would also be required to be updated accordingly. This is also true when a μ-grid is dynamically expanding its territory. Furthermore, a fixed μ-grid boundary may not be suitable in a dynamic environment.

5.1.3 Communication infrastructure

Coordination among a multitude of local DERs, requisite local measurements as a part of decision support tool, crew-coordination, as a part of MGCC requires communication links with real-time control capability. Depending on the level of sophistication, one can select the best option among numerous possible options such as WiFi, Bluetooth, Zigbee, passive optical network, and mobile communication technologies (Zia et al., 2018). Various communication architectures, such as centralized, decentralized, hierarchical, and distributed methods, can be utilized. While centralized frameworks are advocated for their ability to better manage local resources (Khodaei, 2014) within a μ-grid, it is well known that lack of redundancy makes centralized framework especially susceptible to communication failure, which would be the case especially in the wake of natural disaster or cyber-threats. While decentralized structure can help us alleviate some of the challenges, reduced visibility reduces its cost-effectiveness (Hussain et al., 2019). Software-defined networking is also proposed in the literature for enhanced resiliency (Jin et al., 2017). Distributed coordination schemes are known to be resilient to communication link failure and have also been considered in the literature. Therefore, there is a growing need to develop robust and event-agnostic communication infrastructure for the successful deployment of μ-grids as a resiliency resource.

5.1.4 Computational need

The increasing complexity of the problem requiring efficient dispatch of multiple renewable interfaced DERs, transmission line switching, crew-dispatch coordination requires sophisticated software algorithms for management. The underlying algorithms need to be robust and need to account for the simplification utilized for disaster planning. The developed decision from the software algorithms needs to be further verified utilizing high-fidelity models before deployment to satisfy safety-related concerns. While distributed optimization techniques can be utilized in this regard (Y. Wang et al., 2016), associated techniques for power system resiliency are still in their infancy. The plans need to be constantly updated with changing operating scenarios. The model also needs to account for the possibility of data corruption due to the possibility of a communication outage.

5.1.5 The need to aggregate: Cost-benefit analysis

Over the years, the critical facilities have been using backup diesel generators (Maloney, 2020). However, one major drawback in this regard would be their high maintenance cost, failing which they become unreliable. In addition to that, during disasters, diesel supply chains can be crippled, leading to their unavailability when needed. While natural gas-based generators are relatively unaffected by the ground-based supply chain, as discussed, those generators can suffer outages due to the breakdown of gas transportation infrastructure (Girgin & Krausmann, 2014). While numerousness of available local resources solves the problem of a single backup generator, and early-adopters have significantly reduced the deployment cost of μ-grids, such a solution is still very expensive due to the utilization of multitude of switches, controllers and communication infrastructure. Nevertheless, multiple retailers can participate in a symbiotic fashion to avail the economy of scale, and such an aggregation model is not cost-prohibitive for small retailers, leading us to μ-grids-as-a-service (MaaS) model (Maloney, 2020). Here, the retailers do not directly bear the cost of μ-grids; rather, it is borne by the developer. This facilitates the retailer to advertise their electricity supply to be superior to the others. The third-party investors or the developers also earn a return on their investment by selling power directly into the wholesale market, when the isolated μ-grid service is no longer needed by the retailer. While a single small μ-grid may be too small to participate in the bulk power market, the aggregation approach with multiple operators facilitates that. Therefore, although disaster-related power outages have become common in recent year, investment into μ-grids are still dependent on carefully looking into possible revenue stream and deployment cost and following conduction of cost-benefit analysis.

5.2 Business models, regulatory barriers, and policy requirements

Higher cost has been demotivating factors for the procurement of μ-grids by the retailers, and consequently, multiparticipation MaaS or reliability-as-a-service (RaaS) models have flourished (Metelitsa, 2018). While μ-grids have proven their efficacy in improving the resiliency of the grid during multiple hurricanes and wildfires in the United States (Maloney, 2020), only fewer cities around the world are leading their way to enable resiliency in their power grid (York & Jarrah, 2020). To the developers, the current rate structure is so marginal that a small variation in price can potentially negate the economic benefit from μ-grid deployment (Borghese et al., 2017). Nevertheless, the European Union, the United States, Australia, and Japan are a few countries worldwide leading in terms of μ-grid-related policies. Especially, Japan, following the Fukushima disaster, has taken an early lead in improving their power grid's resiliency through μ-grid deployment (Marnay et al., 2015).

As reported in the literature, there exist a multitude of business models that can be adopted for the development and operation of μ-grids, and each of the business models has its own set of challenge (KEMA, 2014). Consortium for Electric Reliability Technology Solutions (CERTS) demonstration project has been one of the earliest demonstration projects for utility-owned μ-grid project. However, in many cases, utility companies are not allowed to own generation assets as a part of deregulation, limiting its applicability. Customers owning CHPs, or small generating facilities can be allowed to develop μ-grid, but is often cost-prohibitive due to increased investment in monitoring and protection. One of the recent models has been a multiuser model, where the possible challenge could be franchise right. The hybrid model involves shared responsibility, where the μ-grid authority owns generation, but the loads can be managed by the distribution utility. Under this paradigm, challenges would arise in managing resources when multiple participants are competing for them during the resource-poor condition. Nevertheless, identifying the value stream, contribution partners, ownership and revenue sharing, and overall control has been the major factor for determining the suitable business models for μ-grid (Asmus & Lawrence, 2016).

While newer business models are appearing, increasing the affordability of the μ-grids (Asmus & Lawrence, 2016), and countries are updating their μ-grid related policies (Ali et al., 2017; Wood, 2020b), the regulation is not uniform across the world. As discussed, this has been especially challenging with the multiparticipation framework, existing interconnection process and requirements, existing rate structures, and utility involvement in managing customer demand (Hoffman & Carmichael, 2020; KEMA, 2014). As an example, in case a distribution company has a fixed service territory, and no other entity can serve the power within such predefined territory, the μ-grid operator has to accept the rate structure provided by the distribution company, which can marginalize the profitability of the μ-grid operator. Additionally, in a certain service territory, if the μ-grids generates power for sale, the μ-grid operator might be treated as a public utility and subject to significant regulation, discouraging them from embarking into a μ-grid related project. While the MaaS structure allows multiple μ-grid to remain connected during the emergency condition, and day-to-day management will be carried out by the distribution utility, improving quality proposition for the retailers (Maloney, 2020), a significant reduction in the value-stream will also be discouraging for the μ-grid developers. Furthermore, such a multiplayer structure does not fit well if the utilities are vertically integrated with centralized resources, however, they fit well in the deregulated environment (Hoffman & Carmichael, 2020). Since μ-grids contains a fantastic proposition through resiliency improvement, some utilities may not be supportive of these ventures.

While the progress has been very slow, regulators around the world are legalizing μ-grid development. As an example, California Public Utilities Commission (CPUC) has published their standards, protocols, guidelines, methods, rates, and tariffs that serve to support and reduce barriers to microgrid deployment to emphasize immediate action plans for the utilities to develop μ-grids (John, 2020).

6. Summary

μ-grids provide a unique opportunity for resource-constrained distribution networks to adopt key strategies of resilience by ensuring survivability of critical loads, dampening of impacts of LPHI events, and improving system robustness. With the increased proliferation of distributed energy resources, the formation of self-sustainable μ-grids allows for proactive management of resources to reduce downtime of critical loads through reconfiguration, scheduling of DERs and energy storage, and shedding faulty portions of the system. Even in systems where the impact and duration of LPHI events are not known in advance, feasible islanding and formation of μ-grids take advantage of the uneven distribution of damage in the system to reduce critical loads lost. Utilizing energy storage, distribution automation, data analytics, and situational awareness, μ-grids can employ operational strategies in all stages of the event progression—proactive scheduling and control before the event, resilient mode of operation during the event, and corrective reconfiguration after the event. This book chapter provides the multistage resilience framework for the evaluation of resilience metrics for each stage. The argument for μ-grids as a resilience resource is reinforced through the elaboration of resilience-enabling strategies. The barriers in implementing μ-grids, include but are not restricted to the uncertainty of renewable DERs, communication infrastructure, cybersecurity cost of implementation, and regulatory roadblocks that every utility needs to elicit with stakeholders and customers for the correct action plan. In addition to improving the resilience behavior of the system, μ-grids also provide improved economic operation, socio-economic benefit, improved reliability, and reduced system loss. The operational configuration of μ-grids is varied, and careful consideration of the different options for implementing μ-grids to achieve resilience can be assessed through the μ-grid resilience evaluation framework presented in this chapter.

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