

Adaptive Prepositioning and Emergency Scheduling of Mobile Microgrids in Constrained Active Power Distribution and Urban Transportation Networks

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Abstract—Considering the proliferation of distributed energy resources (DERs) in active distribution networks (ADNs) and electric vehicles (EVs) in urban transportation networks (UTNs), it is imperative to coordinate the ADN and UTN for enhancing the power grid operation in normal steady state and extreme conditions. One example of such coordination is the integration of mobile microgrids in ADNs in which mobile DERs would be situated in day-ahead and optimally deployed in real-time to enhance the ADN economics, reliability, resilience, sustainability, and security in a constrained UTN.

Index Terms—Active Distribution Networks, Urban Transportation Networks, Mobile Microgrids.

I. INTRODUCTION

In recent years, extreme events, including natural disasters and deliberate attacks have led to serious power outages and major economic losses [1]. Extreme weather events are rare but disastrous, potentially triggering extensive disruptions within a short time in power distribution systems. Such an inherent capability which exceeds the context of reliability is defined as resilience. Given the aging of already stressed power infrastructure, power distribution systems have been continuously threatened by such extreme weather events. Distribution system disruptions are estimated to account for roughly 90% of outages in the United States, when adverse weather is proved as the primary cause of these outages.

On September 6, 2017, Hurricane Irma, a Category 5 storm, struck Puerto Rico's northern coastline. Two weeks later, Hurricane Maria, another Category 5 storm, made its way up the Caribbean, bringing winds of over 150 miles per hour and dumping 25 inches of rain, resulting in catastrophic outages to various infrastructures and private properties. The hurricane knocked down 80% of Puerto Rico's utility poles and transmission lines, resulting in the loss of electric power essentially to all 3.4 million residents [2]. The NOAA estimate of damage in Puerto Rico and the U.S. Virgin Islands due to Hurricanes Irma and Maria was \$90 billion. At the end of 2017, nearly half of Puerto Rico's residents were still without power, and by the end of January 2018, electricity had been restored to about 65% of the island. The Puerto Rico's blackout was the worst in the US history with more than 3.4 billion kilowatt-hours of electricity lost,

surpassing damages reported by Hurricanes George in 1998 and Sandy in 2012. By April 2018, power was restored to 96% of the island, meaning that 53,000 households, between 100,000 and 200,000 people, still did not have access to electricity seven months after the large storm [3].

Likewise, the flooding in Hurricane Katrina left behind 3×10^{13} gallons of water in 2017, which caused subsequent outages to the electricity infrastructure in Texas. In addition to hurricanes, previous earthquakes and their aftershocks that would last for several weeks have imposed physical risks to large infrastructures. Cyber incidents throughout the world have also launched coordinated multi-stage attacks to impose extended damage to infrastructures. The Ukraine grid attack (which caused power outages by manipulating distribution switches) demonstrated the vulnerability of distribution power systems to malicious attacks.

Differences between reliability and resilience indicate that reliability measures the power system performance against potential high-probability/low-impact events (e.g., “N-1” or “N-2” contingencies); whereas resilience corresponds to extreme events that have a low probability but a high impact (e.g., “N-k” contingencies). In contrast to reliability, resilience is not a generic merit-based, which can be easily predicted, but a case-by-case property of a power system. The reliability of a power system is commonly measured by the frequency and duration of power outages (e.g., lasting longer than 5 minutes) experienced by electricity consumers. However, the evaluation of resilience focuses on changes in the system performance. In other words, reliability can be evaluated without specifying the threats, but resilience is always relative to a particular threat. In fact, the more an engineering system is designed to be resilient to a specific type of extreme events, the more it will become fragile and vulnerable to some other types of extreme events.

ADN and UTN are interdependent systems. This paper will focus on the day-ahead allocation and real-time deployment of mobile microgrids for enhancing the ADN resilience, including to integrate renewable generation, in constrained and coupled UTNs. Specifically, the following resources will be discussed:

a) *Mobile Microgrids and DERs*: Mobile microgrids coordinate the use of distributed generation (DG), including solar PV, and energy storage systems (ESSs) to bring into play the flexibility of MGs to control and enhance the performance of the damaged grid in real time. A lot of research has been done on its security and economy, and it has been explored as a means to enhance system resilience based on the above characteristics.

b) *ADN-UTN (ATN) coordination*: When extreme outage events occur in ADN, the following measures are necessary to quickly restore the power supply to critical loads: 1) Mobile microgrids need to be transported to the critical area using the existing UTN. 2) After completing the resilience tasks, mobile microgrid would need to return to the nearest EVCS/refueling stations quickly for recharging before they can resume their tasks.

II. BASICS OF MOBILE MICROGRIDS

Mobile microgrids depicted in Fig. 1 provide a linkage between ADN and UTN. Mobile microgrids are controllable and flexible trucks which include DG and battery resources and can deliver a fast response to extreme cases. Mobile microgrids will be prepositioned on day-ahead and deployed optimally in real-time to the fault area to restore the key load power supply. Previous studies have shown that mobile microgrids can provide load balancing, peak shaving, reactive power regulation, and enhance the renewable energy integration services in ADN [4],[5]. ADNs can strategically deploy flexible mobile microgrid to prevent grid failures caused by extreme events and mitigate disaster consequences. When EV aggregation is used as a power source to restore the grid resilience, the required time for aggregation is difficult to control, during which the power and energy are uncertain, and the service reliability is insufficient [6].

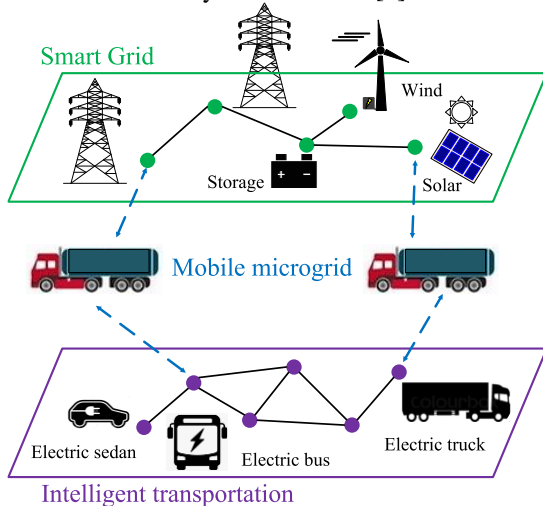


Figure 1. Coordinated Mobile Microgrid Operation

Unlike EVs, a mobile microgrid is a utility-scale DG and battery storage which is owned and fully controlled by a utility company. Compared with fixed microgrids, mobile microgrids can be transported to different power nodes to provide flexible local services to ADN. Mobile microgrids

can improve the utilization rate of renewable energy resources and enhance load transfers for managing the transmission congestion even at normal conditions [7]. It has the advantages of fast response, low maintenance and strong mobility. The mobile microgrids, typically deployed a mobile-mounted generator or battery storage, after an extreme event, considered 400 mobile-mounted generators delivered emergency services in the aftermath of Hurricane Sandy [8]. In practice, flexible mobile microgrids can enhance the ADN survivability when staged properly and deployed from secure locations.

III. ADN RECOVERY AND RESTORATION STAGES

Continuous situational awareness enables the comprehension of the current situation and the projection of future outages. Using situational awareness, an extreme event can be managed proactively by the ATN coordination rather than in a passive mode. In a cyber-physical power system, cyber subsystem outages render pertinent components in the physical subsystem unobservable and uncontrollable. The emergence of unobservable components hampers operators' situational awareness, when, as a compromise, operators utilize the last available component measurements to estimate operating conditions of the physical subsystem. In extreme weather events, such estimated operating conditions tend to diverge from actual system conditions. Uncontrollable components also complicate operators' decision-making process which is due to the limited availability of control variables. Hence, cyber subsystem outages could deteriorate the distribution system operation performance in extreme weather events.

In general, ADN resilience measures that would render the cyber-physical power system observable and controllable are comprised of the following elements:

- Robustness and preparedness before any extreme event (ADN must be planned properly and reinforced in advance so that it can be more resistant to a given set of unexpected disruptions. ADN operation must be optimized to achieve a higher flexibility for mitigating various types of extreme outages.)
- Responsiveness and survivability during any extreme event (Power system operators should respond to extreme outages in a timely and effective manner so as to preserve the ADN functionality and curb the decline in the power system performance.)
- Recoverability and rapidity after an extreme event (Power system performance must be recovered and restored quickly to the level prior to the occurrence of the extreme event.)

TABLE I. STAGES OF POWER GRID RESILIENCE IMPLEMENTATION

Period	Summary	Characteristic
Preparedness	Planning and design of ADN and UTN	Meet the UTN and PDN demand for resilient recovery
Responsiveness	Mobile microgrid positioning	Controllable, Flexibility, Fast response, Low maintenance, Strong mobility.

	Mobile microgrid deployment	Flexibility, Mobility, Better performance in power and energy density
Recovery	Recovery strategy	Optimal recovery of ADN and UTN resources and loads

The ADN performance in extreme conditions is depicted in Fig. 2 as a time-dependent evolution curve in the wake of an extreme event.

- After the occurrence of an extreme event at time t_0 , the performance remains at Q_0 until time t_1 due to the resistance to initial disruptions. The system will collapse between t_1 and t_2 .
- At time t_2 , the system performance has bottomed out at its lowest level and the system starts the responsiveness stage. The system starts to bounce back at time t_3 when the restoration and recovery efforts are initiated.
- The restoration process is completed at t_4 .

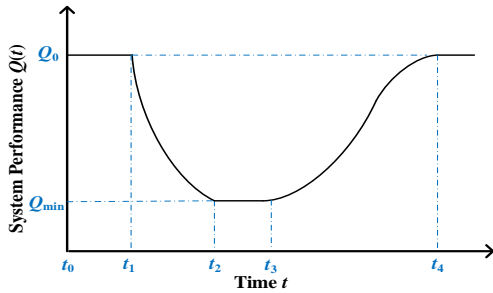


Figure 2. Performance Curve

A. Pre-event Planning for Preparedness

The planning and design of ATN system will affect the scheduling of mobile microgrids after extreme events. ADN resilience planning stage includes all measures to improve ADN resilience, including ATN hardware design and implementation. A reasonable ATN planning will improve the ADN resilience in response and recovery stages after extreme events. This multi-layer framework presents an inherent leader-follower relationship between infrastructural reinforcement and operational enforcement. In Fig. 3, in order to discover the optimal combination and the sequences for implementing the resilience enhancement measures, stochastic optimization or robust optimization problems can be formulated within this framework.

Infrastructural changes and hardware enhancement render the electricity grid more resistant to disruptions and easier to recover if disrupted. On the one hand, hardening aims at strengthening power system components to withstand disruptions so that hardened components are likely to retain adequate functionality during extreme events. Microgrid-based hardening measures could include utilizing more underground cables, strengthening existing power conversion devices, building additional power lines along more secure paths and fortifying the point of common coupling. On the other hand, planning considers both adding redundancy to the electricity infrastructure and driving the infrastructure to undergo structural changes. In this way, the infrastructure inherently gains more resilience to extreme events. Microgrid-based planning measures include refining

microgrid topology, introducing additional networked microgrids, and increasing the generation and energy storage capacity in networked microgrids.

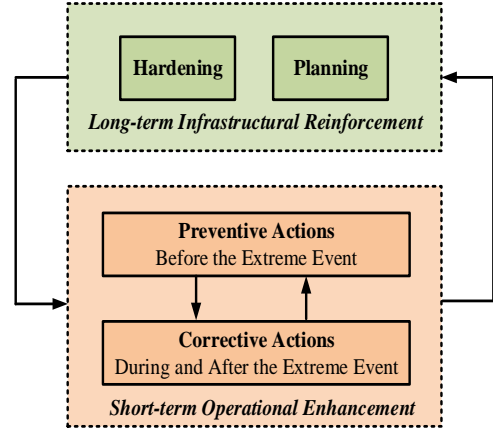


Figure 3. Preparedness Strategy

B. Resilience Responsiveness During and Extreme Event

The load recovery by mobile emergency resources includes prepositioning in the day-ahead and optimal deployment of a mobile microgrid after the extreme event, in which case the mobile microgrids are used as flexible resources to restore the power supply of ADN. The optimal deployment strategy of mobile microgrids will consider the ATN coupling which can effectively improve the grid resilience and outage mitigation. After extreme events, the mobile microgrid can be quickly transported in UTN to the outage area to restore the critical loads and power supply. Therefore, considering the UTN traffic flow is crucial to the optimal deployment of mobile microgrids. The optimal deployment strategy of mobile microgrid in real-time can improve the resilience of power grid and reduce the chance for large ADN blackouts.

C. Post-event Restoration

The recovery stage of power grid resilience is the process of restoring the normal operation of ADN after extreme events and is the core stage of power grid resilience. The truck mobility in UTN will be instrumental in the prepositioning and real-time deployment of mobile microgrids for the recovery process in ADN. The safe and reliable operation of ADN is improved by utilizing a recoverable ATN after the extreme event by considering the coupling of ADN and UTN.

The recovery strategy considering the coupled ATN can further enhance the ADN resilience and improve its recoverability. Usually, emergency resource scheduling and load recovery decisions are arranged separately [9]-[10]. In [11], a two-stage optimal recovery strategy for critical load is proposed, which coordinates the flexible resources including emergency generators and battery storage devices to recover critical loads. After determining the optimal topology restoration at the first stage, the critical loads are recovered optimally at the second stage by deploying mobile microgrids. In [12], a coordinated recovery method of AC/DC hybrid ADN is proposed for load restoration with

mobile microgrids scheduled in a constrained UTN. In [13], an integrated optimization model for the restoration of unbalanced distribution systems after large-scale blackouts caused by extreme events is studied, and the optimal scheduling of maintenance personnel and mobile microgrids is proposed to make use of the recovery capability of the existing ADN. In [14] and [15], the recovery of key loads in ADN with mobile microgrid includes the grid reconfiguration in a coupled ATN.

The rolling integrated service recovery strategy is proposed in [16], which considers road repairs in ATN. The total cost of the system is minimized by coordinating the scheduling of vehicular mobile microgrids, resource scheduling of MGs and ADN reconfiguration of distribution systems. In [17], a multi-stage dynamic recovery strategy considering an ATN is proposed for post-disaster ADN, and the optimal path of mobile microgrid is obtained by using dynamic traffic assignment algorithm. In addition, the recovery strategy could include the ATN coupling which is also integrated with other energy systems such as hydrogen which can provide new opportunities to enhance grid recovery [18]. During the recovery period, maintenance personnel and mobile microgrids are regarded as flexible resources to repair faulty lines and support key power load recovery as the system benefits from the use of hydrogen-based generation system for expediting the recovery.

IV. ADAPTIVE FORMATION OF ISLANDED MICROGRIDS WITH MOBILE DEVICES FOR CRITICAL SERVICE RESTORATION IN EXTREME CONDITIONS

Typical ADN and UTN are depicted in Fig. 4. The previous studies on mobile microgrid applications for ADN service restoration indicate that these methods provided insight into the mobile microgrid-based service restoration problem; however, their applications can be limited considering the following challenges.

The existing recovery methods construct an ADN coverage by prepositioning and deployment of mobile microgrids. These approaches which could follow the traditional restoration principles, would not pertain to the flexibility of mobile microgrids or the ADN vulnerability to additional outages during the recovery stage, thereby risking the continuity of services to critical loads [19]. Specifically, the existing methods could risk the service restorations of critical loads in the following ways: 1) Loss of critical lines which provide a linkage to large non-critical loads could trigger large power imbalances which would cause extensive equipment damages due to frequency/voltage deviations, service interruptions when protection services would function, and a mobile microgrid service collapse due to voltage or frequency instability. 2) Mobile microgrids which are prepositioned and deployed away from critical loads might result in higher risks of inflicting additional critical outages during the recovery stage in which case the energized paths would encounter new damages in extreme events. 3) The mobile microgrid coverage for service restoration might end up with the operation of a large number of ADN switches which would lead to a more complicated and delayed

restoration. Besides, the limited DER capacity and fuel availability during the recovery stage would have to be optimized to serve critical loads more comprehensively in extreme conditions. Such a feature was encountered for supplying critical loads after the Hurricane Maria hit Puerto Rico.

Based on the above considerations, this study takes into account the ADN vulnerability and the mobile microgrid survivability and proposes an optimal critical service restoration (CSR) strategy for serving critical loads in extreme events. Our proposed CSR strategy will form islanded microgrids with mobile microgrids for managing the supply continuity to critical loads. In CSR, we investigate an appropriate load switching sequence for restoring critical loads whose dynamics could involve frequency deviations when picking up large loads. A proper load switching sequence in CSR will consider the mobile microgrid dynamic performance for an optimal recovery stage.

A. CSR Strategy

To undertake the above challenges, this section proposes a mobile microgrid-based CSR strategy to ensure the highest service to critical loads when ADN encounters outages and damages under extreme events such as natural disaster and physical and cyber incidents. The CSR method partitions an ADN into islanded microgrids supplied by mobile devices with the objective of maximizing the sum of restored loads.

The CSR strategy (consisting of optimal mobile microgrid prepositioning and deployment as well as load switching sequence steps) focuses on restoring critical loads that deliver vital society services, e.g., hospitals, police and fire stations. CSR serves critical loads by forming islanded microgrids with radial and looped topologies by properly prepositioning mobile microgrids while taking into account the ADN survivability in extreme events. A proper load switching sequence strategy is developed in CSR by considering the relationship between switching actions and frequency deviations which includes a necessary condition for satisfying the dynamic frequency nadir limit.

V. CONCLUSIONS

Today's power grids are facing an increasing frequency and a higher intensity of extreme outages caused by natural disasters like Hurricane Sandy, and the threat of terrorism (both physical and cyber). The impacts of extreme events on power grids underscore the need for enhancing the resilience, which is defined as the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from extreme outages. Integrating renewable generation to support resiliency is key. In this context, LUMA Energy has recognized mobile microgrids as a very promising solution to resilience enhancement and service restorations after extreme events in Puerto Rico and created integration plans. When mobile microgrids are prepositioned and deployed optimally by the proposed maximum-coverage criterion for CSR, they will energize the maximum number of ADN components for service recovery within a reasonable operation time.

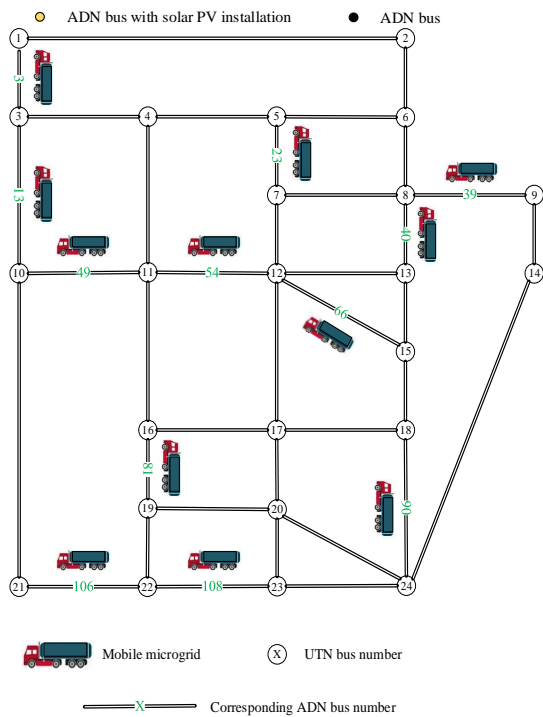
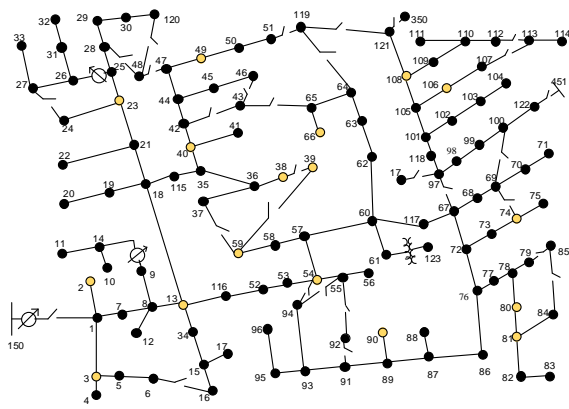


Figure 4. Typical ADN and UTN

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