Part I

Fundamentals

1 Introduction

1.1 Empowering Smart and Connected Communities through Microgrids and Networked Microgrids

The keystone of smart and connected communities (S&CCs) is a resilient electric network capable of supporting critical infrastructures such as water, food, public safety, transportation, waste management, communication, and other functions that are vital for citizens [1].

Existing electric networks, however, cannot sustain growing communities' ever-increasing demands. According to the Department of Energy, US customers experienced power outages for an average of 198 minutes in 2015. One state even lost power for over 14 hours. Over the same period of time, customers in Japan and Korea only lost power for an average of less than 10 minutes and less than 12 minutes, respectively [2]. Furthermore, distributed energy resources (DERs), such as intermittent photovoltaics (PVs) increasingly installed in the United States communities, fail to improve electricity resilience, because they cannot ride through sustained grid contingencies. In addition to these challenges, extreme weather events and cyberattacks [3] can lead to catastrophic blackouts. Actually, in the United States, thousands of major blackouts have occurred in the past three decades causing over $1 trillion in damages and enormous social upheavals [4]. Of these outages, over 90% occurred along electric distribution systems under extreme weather events [5]. In light of this, academia [6, 7], industry [8, 9], and government [10] now share a strong consensus that enhancing distribution systems' resilience is an important focus of research [11, 12].

Microgrids offer a promising paradigm for increasing electricity resiliency for customers [42]. Normally, a microgrid is still a local power distribution grid, but it is an autonomous system rather than a traditional passive network. It is often designed to provide a more reliable and resilient electrical and heat energy supply for a community such as a commercial building, a residential area, a military base, a university campus, or a mix of these. A salient feature of a microgrid is that it operates not only when it is coupled with the main grid (grid-connected mode) but also when it is disconnected from the main grid during emergencies (islanded mode). Though microgrids are more similar than different, they can be defined in a variety of ways, a trend that is likely to increase with advancements in microgrid technology. As an example, the International Council on Large Electric Systems (CIGRE) C6.22 Working Group [13] has defined microgrids as follows:

Microgrids are electricity distribution systems containing loads and distributed energy resources, (such as distributed generators, storage devices, or controllable loads) that can be operated in a controlled, coordinated way either while connected to the main power network or while islanded.

In theory, the microgrid model provides a potent option for preventing power outages. Because microgrids can operate autonomously, accommodate renewable resources, and remain immune to weather damage, they promise to prevent local power outages. For example, the author's research [14, 15] has quantified the resilience benefits of microgrids for hardening critical infrastructures within 15 Connecticut cities/towns under various weather conditions (e.g. major storm; tropical storm; Categories 1, 2, and 3 storms). The resiliency and reliability of microgrids are also being proved in the real world. For instance, during the 2017 flooding of Hurricane Harvey in the Houston area, a handful of microgrids allowed the Texas Medical Center, as well as some local gas stations and stores, to continue operating despite severe utility grid outages [16].

The need for highly resilient and clean energy resources in important load centers calls for the adoption of microgrids in cities and smaller communities. For instance, large data centers, which are critical for the United States' growing digital economy, suffered from an average of $2.4 million in power outage costs per data center in 2015, an 81% increase compared to 2010 [17, 18]. Thus, in the coming decade, data centers are expected to represent up to 40% or more of the total microgrid market [19]. As the world's population becomes increasingly concentrated in urban centers, there will be a corresponding rise in the demand for electricity, a trend that will pose significant challenges to cities' aging power infrastructures. The power outage that occurred on July 13, 2019, in Midtown Manhattan and New York City's Upper West Side was a typical example of the daunting problems faced by America's aging electrical infrastructure. The author believes that, in order to achieve an adequate level of electrical resiliency, microgrids will be increasingly accepted and installed in cities or S&CCs with dense populations and critical loads. Although individual microgrids can surely provide electricity resilience to their own customers, they seldom are able to improve the reliability and resilience of the main grid [20]. On the other hand, our preliminary research has shown [20] that coordinated *networked microgrids* can potentially help restore neighboring distribution grids after a major blackout. Networked microgrids also promise to significantly enhance day-to-day reliability and performance by improving both the System Average Interruption Duration Index (SAIDI) and the System Average Interruption Frequency Index (SAIFI). Actually, as anticipated by the US Department of Energy, the research and development (R&D) of networked microgrids will lead to the next wave of smart grid research, which will help achieve the nation's grid modernization vision toward climate adaptation and resiliency [21].

1.2 Challenges in Networked Microgrids

Networked microgrids – also referred to as coupling microgrids – consist of an interconnected cluster of microgrids in close electrical or spatial proximity to allow both coordinated energy management and interactive support and exchange [21–23].

Recently, studies have begun to investigate how power interchange among networked microgrids can help support more customers during situations of islanding or reduce power deficiencies in individual microgrids caused by intermittent renewables [22]. Other studies have proposed that decentralized dispatch be used to ensure the steady-state operation of networked microgrids [24]. Although promising results have been achieved for steady-state operations, dynamic performance under grid disturbances and faults remains an intractable challenge that compromises microgrids' resiliency, thus preventing the wide adoption of networked microgrids. Following is a summary of the three main problems that must be addressed before networked microgrids can be adopted more widely:

- *Understanding the dynamics of networked microgrids.* There is a methodological gap in computing the security indicators – including stability margin/region – for networked microgrids [25]. This challenge originates from the salient features of microgrids such as uncertainties, nonsynchronism, fast ramp rates, and low inertia. Therefore, a compelling question is this: *How can microgrid stability be assessed and enhanced for the improvement of networked microgrids' situational awareness and controllability? This question is key to determining whether networked microgrids can be used as dependable resiliency resources [26].*
- *Impact of high levels of microgrid penetration.* Although a high level of microgrid penetration is necessary to provide adequate capacity for preventing and mitigating grid outages [27], it creates a difficult dilemma. On the one hand, microgrids are designed to trip offline (or have their grid-interface converters change to zero power mode) and operate in islanding mode during grid contingencies. As a result, when many microgrids are interconnected, a grid disturbance can induce the sudden loss of a large number of microgrids, significantly increasing the risk of blackout in both distribution and transmission grids (see an ISO New England report [28]). On the other hand, forcibly coupling a network of microgrids with a disturbed main grid can lead to catastrophic mutual impacts, such as excessive fault current contributions into the main grid as well as large disturbances propagating into and out of the microgrids. This raises a fundamental question: *How can the fault responses of networked microgrids be managed so that they can provide critical ancillary support as required by the new Institute of Electrical and Electronics Engineers (IEEE) Standards 1547 and 2030 [29] without causing excessive (or inadequate) fault current magnitudes in the main grid, as well as internal and external instabilities*?
- *Bottleneck in the communication infrastructure.* Resiliency issues such as time delay, congestion, failures, and cyberattacks can significantly compromise the functionality of microgrids' communication networks, which are indispensable to microgrid stability control and fault management. Moreover, traditional cyberarchitecture has been found unable to adapt to the ever-increasing pace of functional and structural changes in microgrids and distribution grids [30, 31]. An essential problem is *how to design an innovative communication architecture to enable ultrafast microgrid control, respond to and mitigate threats and emergencies, and fully support scalable networked microgrids*.

This book aims to close the knowledge gap highlighted in the preceding so that reliable networked microgrids can boost distribution grid resiliency. The networked microgrid technologies discussed in this book are based on the author's study of microgrids and networked microgrids since 2010. In particular, this book summarizes several new findings from our recent research projects, including the following:

- EAGER: US Ignite: Enabling Highly Resilient and Efficient Microgrids through Ultra-Fast Programmable Networks, US National Science Foundation
- US Ignite: Focus Area 1: SD^2N: Software-Defined Urban Distribution Network for Smart Cities, US National Science Foundation
- Enabling Reliable Networked Microgrids for Distribution Grid Resiliency, US National Science Foundation
- SCC: Empowering Smart and Connected Communities through Programmable Community Microgrids, US National Science Foundation
- Formal Analysis for Dynamic Stability Assessment of Large Interconnected Grids under Uncertainties, US Department of Energy
- Academic Plan Level I: Software Defined Smart Grid, University of Connecticut

This book has three main objectives:

- *To establish a formal analysis method to tractably assess networked microgrid stability*. Modeling and analysis of uncertainties due to high levels of renewable generation will be addressed. A formal theory will be developed to increase situational awareness and unlock the potential of networked microgrids as primary resilience resources.
- *To devise a new concept of microgrid active fault management (AFM) through online distributed optimization*. The new approach allows networked microgrid riding through balanced and unbalanced grid disturbances, systematically enhancing grid resiliency rather than negatively impacting the disturbed grid. In the future, formal methods will be used to ensure provably correct AFM with guaranteed performance.
- *To build a software-defined networking (SDN) architecture to enable highly resilient networked microgrids*. As a new paradigm for computer networking, SDN provides run-time programmability and unprecedented flexibility in managing communication networks. SDN-based algorithms and a coordinated framework will be investigated to address communication challenges for networked microgrids, including time delays, network failures, service support quality, and cyberattacks.

As one of the first monographs on networked microgrids, this book is expected to serve as a reference for academia and industry. The contents will be useful for professors who plan to offer courses related to microgrids, active power distribution, and distributed energy resources. The topics discussed in this book will include power systems, power electronics, dynamics and stability, control theory, computer networking, and cybersecurity. Thus, readers who are inquisitive and curious about the integration of those techniques in the vibrant field of microgrids will find this book a useful introductory textbook. Reachability techniques will be devised to facilitate a deeper understanding of microgrid resilience under renewable energy's high penetration levels. The idea of an AFM-oriented power electronic control with distributed optimization will pave the way for a high penetration of microgrids without compromising grid reliability. The novel SDN-based architecture and techniques will open the door for innovations in devising secure, reliable, and fault-tolerant algorithms for managing resilient networked systems such as multiple microgrids and active distribution networks. Overall, the proposed new model-based and data-intensive technologies together will provide scalable, dependable, and intelligent solutions to traditionally intractable problems in integrating complex networked microgrids.

1.3 Overview of Topics

This book focuses on establishing several theoretical foundations for reliable networked microgrid operations and analysis in the face of various cyber and physical disturbances. It leverages our recent research in resilient microgrid control, ultrafast programmable networking, dynamical systems, cyberphysical security, and real-time hardware-in-the-loop microgrid testbeds to resolve the previously intractable problems posed by integrating scalable microgrids with a high penetration of renewable energy resources. The book includes the following chapters:

- Chapter 1. "Introduction"
  This chapter provides fundamental information about both microgrids and networked microgrids. It also previews the topics discussed in the rest of the book.
- Chapter 2. "Basics of Microgrid Control"
  This chapter covers the basics of hierarchical control for microgrids.
- Chapter 4. "Compositional Power Flow for Networked Microgrids"
  This chapter introduces a privacy-preserving, distributed power flow approach to networked microgrids' situational awareness.
- Chapter 4. "Resilient Networked Microgrids through Software-Defined Networking"
  This chapter discusses an SDN-enabled architecture that transforms isolated local microgrids into integrated networked microgrids.
- Chapter 5. "Formal Analysis of Networked Microgrids' Dynamics"
  This chapter establishes an innovative and tractable method called distributed formal analysis (DFA) for assessing the stability of networked grids under uncertainties.
- Chapter 6. "Active Fault Management for Networked Microgrids"
  This chapter devises a concept of AFM enabled through online distributed optimization.
- Chapter 7. "Cyberattack-Resilient Networked Microgrids"
  This chapter aims to understand, model, and mitigate the cybersecurity risks to the networked microgrids' operations.

- Chapter 8. "Networked DC Microgrids"
  This chapter focuses on a dynamic modeling and stability assessment of bipolar direct current (DC) microgrids and gives an introduction to the stability of networked DC microgrids.
- Chapter 9. "Software-Defined Distribution Network"
  This chapter introduces a future software-defined, hardware-independent microgrid infrastructure for smart and connected communities.
- Chapter 10. "Future Perspectives: Programmable Microgrids"
  This chapter provides the author's visions for next-generation microgrid research and development.

The book adopts a cyber-physical system (CPS) approach, presenting a rigorous unification of the theoretical underpinnings behind the emerging field of networked microgrids. It draws on a diverse set of cyber-physical system methods to tackle open challenges in the operation and analysis of networked microgrids. It includes a power flow algorithm for islanded networked microgrids without any slack buses, formal methods via reachable set calculations for evaluating networked microgrids stability regions, online distributed optimization for microgrid inverters to ride through faults, active defense strategies to detect and mitigate deception attacks on microgrids, stability of bipolar DC microgrids, software-defined networking solutions to network individual microgrids, and resilience enhancement for physical and cybernetworks.

The book is suitable for classroom use or as a reference for professionals. It consists of accurate modeling details for microgrid components as well as test cases for networked microgrids. The book can be used for a semester-long course aimed at senior undergraduates or graduate students in electrical and computer engineering. It can be used as training material for continuing education purposes (e.g., power engineering graduate certificate programs) for electrical engineers. Power industry professionals will find the algorithms and architectures provided in this book useful for solving some challenges in their job duties. Based on the models provided in this book, researchers and professionals will be able to integrate our solutions to existing commercial tools and develop new tools. In general, this book can serve as a guide for industry and military professionals to understand the principles of microgrid operations and provide valuable tools for the planning, design, operation, and protection of microgrids.

References

[1] M. La Scala, S. Bruno, C. A. Nucci, S. Lamonaca, and U. Stecchi, *From Smart Grids to Smart Cities: New Challenges in Optimizing Energy Grids*. John Wiley & Sons, 2017.

[2] Department of Energy, "Transforming the Nation's Electricity System: The Second Installment of the Quadrennial Energy Review," Jan. 2017.

[3] T. Flick and J. Morehouse, *Securing the Smart Grid: Next Generation Power Grid Security*. Elsevier, 2010.

[4] D. T. Ton and W. T. Wang, “A More Resilient Grid: The US Department of Energy Joins with Stakeholders in an R&D Plan,” *IEEE Power and Energy Magazine*, vol. 13, no. 3, pp. 26–34, 2015.

[5] R. J. Campell, “Weather-Related Power Outages and Electric System Resiliency,” Washington, DC: Congressional Research Service, 2012. https://fas.org/sgp/crs/misc/R42696.pdf.

[6] S. Martin, G. Deffuant, and J. M. Calabrese, “Defining Resilience Mathematically: From Attractors to Viability,” in *Viability and Resilience of Complex Systems*, G. Deffuant and N. Gilbert, eds. Springer, 2011, pp. 15–36.

[7] C. Folke, S. R. Carpenter, B. Walker, M. Scheffer, T. Chapin, and J. Rockström, “Resilience Thinking: Integrating Resilience, Adaptability and Transformability,” *Ecology and Society*, vol. 15, no. 4, p. 20, 2010.

[8] A. Rose, “Economic Resilience and Its Contribution to the Sustainability of Cities,” in *Resilience and Sustainability in Relation to Natural Disasters: A Challenge for Future Cities*, P. Gasparini, G. Manfredi, and D. Aprone, eds. Springer, 2014, pp. 1–11.

[9] L. Molyneaux, L. Wagner, C. Froome, and J. Foster, “Resilience and Electricity Systems: A Comparative Analysis,” *Energy Policy*, vol. 47, pp. 188–201, 2012.

[10] J. Inglis, S. Whittaker, A. Dimitriadis, and S. Pillora, “Climate Adaptation Manual for Local Government: Embedding Resilience to Climate Change,” Australian Centre of Excellence for Local Government, University of Technology, Sydney. https://opus.lib.uts.edu.au/handle/10453/42120, 2014.

[11] M. McGranaghan, M. Olearczyk, and C. Gellings, “Enhancing Distribution Resiliency: Opportunities for Applying Innovative Technologies,” *Electricity Today*, vol. 28, no. 1, pp. 46–48, 2013.

[12] J. Carlson, R. Haffenden, G. Bassett, W. Buehring, M. Collins III, S. Folga, F. Petit, J. Phillips, D. Verner, and R. Whitfield, “Resilience: Theory and Application.” Argonne National Laboratory (ANL), Tech. Rep., 2012.

[13] C. Marnay, S. Chatzivasileiadis, C. Abbey, R. Iravani, G. Joos, P. Lombardi, P. Mancarella, and J. von Appen, “Microgrid Evolution Roadmap,” in *Smart Electric Distribution Systems and Technologies (EDST), 2015 International Symposium on*. IEEE, 2015, pp. 139–144.

[14] P. Zhang, G. Li, and P. B. Luh, “Reliability Evaluation of Selective Hardening Options,” State of Connecticut, Tech. Rep., May 2015.

[15] G. Li, P. Zhang, P. B. Luh, W. Li, Z. Bie, C. Serna, and Z. Zhao, “Risk Analysis for Distribution Systems in the Northeast U.S. under Wind Storms,” *IEEE Transactions on Power Systems*, vol. 29, no. 2, pp. 889–898, March 2014.

[16] Harvey’s Devastation Shows the Need for Distributed Energy, Microgrids during Disasters. [Online]. Available: www.greentechmedia.com/articles/read/harveys-devastation-shows-the-need-for-distributed-energy-microgrids-during.

[17] Ponemon Institute and Emerson Network Power, “Cost of Data Center Outages,” Ponemon Institute, Tech. Rep, Tech. Rep., 2016.

[18] Eaton, “Blackout and Power Outage Tracker,” http://powerquality.eaton.com/blackouttracker/.

[19] Navigant Research, “Data Centers and Advanced Microgrids,” Navigant Research, Tech. Rep., 2017.

[20] Z. Bie, P. Zhang, G. Li, B. Hua, M. Meehan, and X. Wang, "Reliability Evaluation of Active Distribution Systems Including Microgrids," *IEEE Transactions on Power Systems*, vol. 27, no. 4, pp. 2342–2350, November 2012.

[21] K. Cheung, "DOE Perspective on Microgrids," keynote presentation, 2015 Applied Power Electronics Conference and Exposition, March 2015.

[22] F. Shahnia, S. Bourbour, and A. Ghosh, "Coupling Neighboring Microgrids for Overload Management Based on Dynamic Multicriteria Decision-Making," *IEEE Transactions on Smart Grid*, vol. PP, no. 99, pp. 1–1, 2015.

[23] Z. Wang, B. Chen, J. Wang, M. M. Begovic, and C. Chen, "Coordinated Energy Management of Networked Microgrids in Distribution Systems," *IEEE Transactions on Smart Grid*, vol. 6, no. 1, pp. 45–53, 2015.

[24] Z. Wang, B. Chen, J. Wang, and J. Kim, "Decentralized Energy Management System for Networked Microgrids in Grid-Connected and Islanded Modes," *IEEE Transactions on Smart Grid*, vol. PP, no. 99, pp. 1–1, 2015.

[25] G. Strbac, N. Hatziargyriou, J. Carvalho Lopes, C. Moreira, A. Dimeas, and D. Papadaskalopoulos, "Microgrids: Enhancing the Resilience of the European Megagrid," *IEEE Power and Energy Magazine*, vol. 13, no. 3, pp. 35–43, May 2015.

[26] Presidential Policy Directive, "Critical Infrastructure Security and Resilience," *Department of Homeland Security Std*, 2013.

[27] J. Li, X.-Y. Ma, C.-C. Liu, and K. P. Schneider, "Distribution System Restoration with Microgrids Using Spanning Tree Search," *IEEE Transactions on Power Systems*, vol. 29, no. 6, pp. 3021–3029, 2014.

[28] M. Henderson, "Impacts of Transmission System Contingencies on Distributed Generation – Overview." DG Forecast Working Group Meeting, ISO New England, Tech. Rep., December 2013.

[29] T. S. Basso, *IEEE 1547 and 2030 Standards for Distributed Energy Resources Interconnection and Interoperability with the Electricity Grid*, 2014.

[30] M. Tahir and S. K. Mazumder, "Self-Triggered Communication Enabled Control of Distributed Generation in Microgrids," *IEEE Transactions on Industrial Informatics*, vol. 11, no. 2, pp. 441–449, 2015.

[31] L. Ren, Y. Qin, Y. Li, P. Zhang, B. Wang, P. B. Luh, S. Han, T. Orekan, and T. Gong, "Enabling Resilient Distributed Power Sharing in Networked Microgrids Through Software Defined Networking," *Applied Energy*, vol. 210, pp. 1251–1265, 2018.