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Part I

Motivation

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1 Introduction

1.1 Basic concepts

Electrification is widely regarded as the single greatest engineering achievement of the twentieth century. The electrical power grid, the system that interconnects and distributes electrical energy, is the foundation of the built environment that supports modern societies and their economies. Yet, electric power grids are showing increased signs of deterioration due to aging equipment and usage that stresses these systems beyond their original design and safety margins. Simply stated, the current technology is inadequate to meet the evolving and growing needs of society. The last decade saw a number of poignant cases where problems in the energy system wreaked havoc and devastation. Singular instances, including the 2000 and 2001 California electricity energy crisis, the 2003 Northeast blackout, and widespread cases of expansive outages caused by natural disasters should all serve as wake-up calls for infrastructure improvement. Looking toward the future, simply patching the existing system will not alleviate the power-delivery congestion, which creates local markets with extremely high marginal pricing and prevents widespread penetration of renewable energy resources such as wind and residential-scale photovoltaic systems.

Many of the energy sources that powered the last century are dwindling. Even if new deposits of these finite energy resources are discovered, their conversion to electrical energy will remain one of the largest contributors to global greenhouse gas emissions and other environmental hazards. Nuclear power, once seen as an alternative to fossil fuels, has lost widespread support since the nuclear event at the Japanese Fukushima #1 Nuclear Power Plant. The move to more environmentally friendly technologies, so-called renewable energy sources, adds stresses to the electrical grid that were never previously considered and pushes existing electric systems to the edge of their design and operational envelope.

The design of current electric power systems is essentially unchanged from that of the first power grids developed over a century ago. This design is based on the centralized architecture illustrated in Figure 1.1, in which power is generated in relatively few large power plants from which it is delivered to many loads that can be hundreds and even thousands of miles away. Despite having mesh topologies and other sources of redundancy, this predominantly centralized architecture is relatively unreliable and inflexible because sensing, actuation, and control coordination does not generally permeate down to the distribution level, much less to individual loads. Even with recent

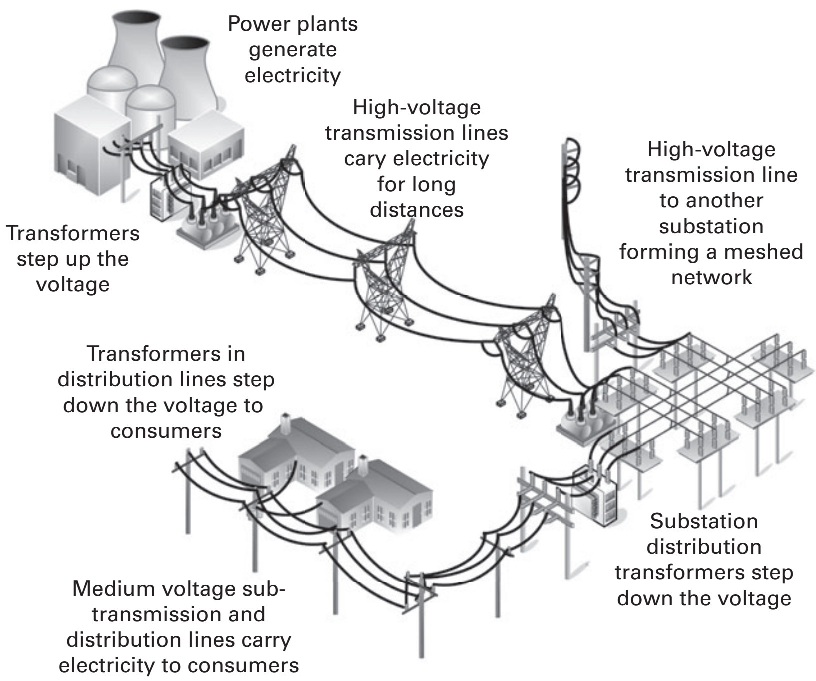

Figure 1.1 A traditional utility power grid. Power flows in sparse mesh networks from large, centralized generators into the distribution system and then radially outward to loads. Note: Some details, such as the use in the United States of pole-mounted transformers near consumers, may differ depending on different design practices around the world.

"smart grid" initiatives to increase instrumentation and sensing, the central-grid model fundamentally lacks the necessary control intelligence and actuation to regulate individual loads. If this ability existed, system utilization could be improved in a targeted way because individual loads would be optimized instead of simply controlling an aggregated system in an average sense. Moreover, integration of alternative or renewable generation sources or load technologies, such as plug-in hybrid vehicles (PHEV) or inherently dc sources and loads, becomes in many cases complicated. Furthermore, the large and complex nature of electric grids leads to very high operational and maintenance costs, which eventually lead to a serious aging infrastructure problem. The electric grid aging problem has four contributing factors: aging power equipment – e.g., more than 50% of the US substation transformers are more than 35 years of age – outdated system layouts, outdated engineering, and obsolete problem characterization and solution approaches.

The technical solution to these problems is the integration of small, distributed generation sources into the grid. This is, basically, the same concept that Edison proposed in the late 1800s as a counterpoint to Tesla's concepts that prevailed into present power grids because, at that time, the technology was not sufficiently developed to implement Edison's concepts. Today, however, the technologies exist and Edison's concepts can now be practically implemented, thereby increasing operational flexibility, efficiency, and reliability while also lowering capital and operational costs. Some of the technologies that provide the necessary technical capabilities missing in Edison's systems include power electronic interfaces, energy storage, advanced loads, and intelligent controls. In particular, power electronic interfaces are arguably the main enabling technology for modern microgrids. Although power electronics is an engineering area that has attracted relatively enough recognition in the past, the main focus during its first development decades has been on circuits and controls for electromechanical systems – e.g., motor drives. Yet, the other main power electronics field, stationary applications, has traditionally seen a more limited attention, primarily in a few particular industries, such as telecommunications. Stationary power electronics systems – those used in distributed generation systems – started to gain more attention with the development of computers because of their challenging power conversion needs. This interest has accelerated considerably in the past decade as the power conversion needs for renewable energy sources have increased.

In the same way that the Internet revolutionized communication systems, integration of distributed generators powering relatively small power systems called microgrids may be the only option to truly address the problems affecting power grids. Formally, microgrids can be defined as "a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that act as a single controllable entity with respect to the grid" [1]. Hence, microgrids can be operated either connected or disconnected from a main grid. Thus, microgrids create local area power and energy systems (LAPES) that are independently controlled from the grid. Therefore, LAPES tend to be a concept that lies on the "customer side" of an electric meter, because owners of microgrids have control over all of their aspects, including technology planning and purchasing, and operations. Still, the vision for the grid of the future includes using advanced monitoring and control systems in order to interconnect many microgrids – hence, creating what are termed advanced smart grids, as opposed to basic smart grids, in which smart meters and associated systems are the only key technologies added to conventional grids, and distributed resources or areas with local independent controls are not added. Hence, increased attention on microgrids can be paired with advanced smart-grid development. The current development of advanced smart grids is motivated by the goal of improving electric power supply in two areas: the first being power availability, reliability and security, and the second integration of local renewable and alternative energy sources, and energy storage. Both of these areas can be considered to be related when microgrids are used in order to achieve ultra-high power-supply availability. In a conventional approach, applications that need power-supply availability higher than that provided by conventional grids rely on a combination of batteries and diesel engine generators in order to power the load when there is a grid outage. That is, the grid is the main source of power to the load, and energy is stored locally as a backup option when the grid fails. Hence, the conventional approach for loads that require high power-supply availability is an energy-based solution. Microgrids provide a different strategy for solving the same problem. Since microgrids should be able to operate without a power supply from the grid, LAPES's primary sources of power are local generators. A main grid can still be present but it is considered a secondary or complementary power source. Since local generators in microgrids convert energy from variable sources, such as solar radiation or wind, or depend on other infrastructures – called lifelines – for an energy supply (such as natural gas for microturbines or fuel cells reformers), microgrids require a diverse arrangement of generating technologies in order to achieve an ultra-high availability goal. Therefore, microgrids can be considered power-based solutions to achieve high power-supply availability. Nevertheless, local energy storage, such as batteries, can still be added in order to support further availability improvement provided by functional diverse local power generating units.

Evidently, the success of any new technology cannot be decoupled from its economic effectiveness. This is a requirement that is also true for microgrids, because high costs are, arguably, the most important concern associated with the development of LAPES. The high costs associated with microgrids typically originate in their distributed generation sources. Hence, it is important that these sources achieve high energy-conversion efficiency. Where applicable, as with microturbines, a way of improving efficiency is to use waste heat in combined heat and power cycles. It is also important that these sources require little maintenance and occupy a reduced footprint so associated costs can be reduced. Furthermore, it is also important that local distributed resources are utilized as much of the time as possible in order to reduce the accounting impact of costs associated with depreciation of unused equipment. In a number of applications, all of these cost factors make microgrids an option that currently may not be as cost competitive as conventional solutions. Cost-wise, microgrids tend to be better options than conventional power supply choices in applications in which other goals in addition to equipment cost are important. For example, microgrids tend to be more effective than conventional solutions to powering medium-to-high-power critical loads that require a highly available power supply [2]–[4], because the high cost associated with backup batteries with a low utilization factor is avoided [4] [5]. Microgrids also tend to be more cost effective than conventional grids when they are used to power isolated locations, such as many villages in Alaska [6]. Other applications in which microgrids may be more cost effective than conventional solutions are those systems in which thermal processes – either heating or cooling processes – are important. In these cases, microgrids are cost effective only when combined heat and power cycles are considered [7]. However, the cost of many existing sources of high costs that originate in distributed generators, such as photovoltaic modules, are expected to drop as microgrids are used more extensively. Therefore, it is expected that microgrid use will become more widespread, so the study and further understanding and development of the technology will become not only an important part of the formation of future power and energy professionals, but also a reference for current technicians and engineers in those areas.

1.2 Architectures and system components

The aforementioned microgrids definition also refers to its system components, which are displayed in Figure 1.2. The first set of components comprises distributed energy resources (DER), which can be defined as “sources of electric power that are not directly

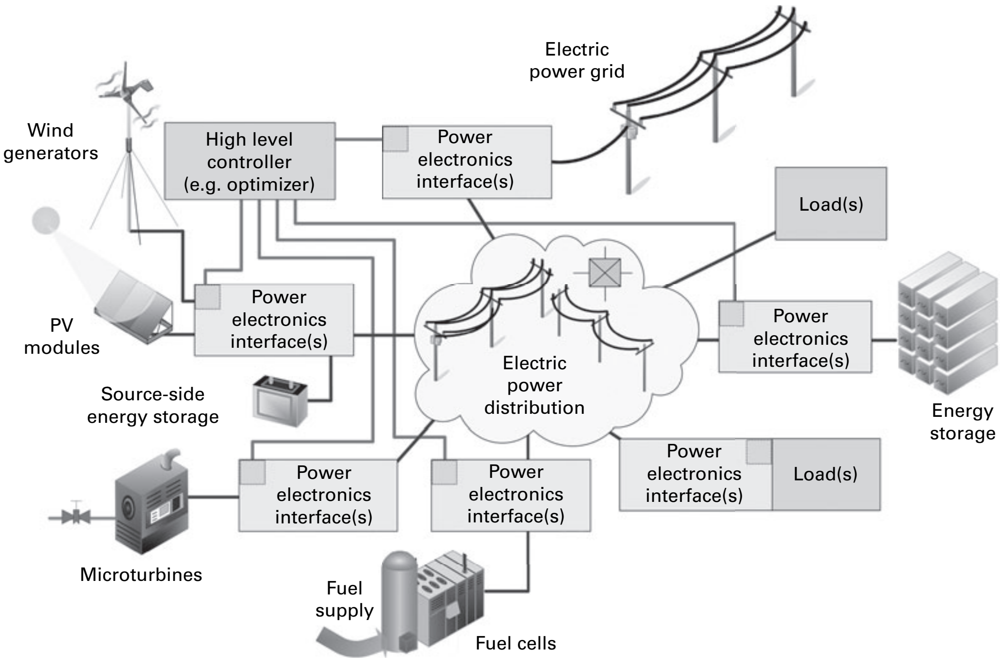

Figure 1.2 Main system components in a microgrid.

connected to a bulk power transmission system. Distributed energy resources include both generators and *energy storage technologies*" [8]. Many technologies have been proposed as suitable distributed generators, and among those mentioned more often are photovoltaic modules, small wind generators, fuel cells, microturbines, and internal combustion engines. Except for photovoltaic modules and small wind generators, these distributed generation technologies require some source of energy, such as natural gas, provided by a lifeline in order to operate. A detailed discussion of these primary energy sources (such as gasoline, natural gas, and biofuels) and their corresponding lifelines are outside of the LAPES domain and are therefore out of the scope of this book. Local energy storage is, however, part of LAPES. There are several energy storage technologies suitable for use as DER in microgrids. Among them, the most widely considered suitable options are batteries, flywheels, and ultracapacitors. When an electrolyzer is added to certain types of fuel cells, bidirectional power flow can be achieved, so energy contained in hydrogen molecules can be stored, making certain types of fuel cells also energy-storage devices. Hence, fuel cells can be considered a hybrid technology that could be considered both a generation and energy-storage resource.

One of the key enabling technologies of microgrids is power electronic circuits. These circuits are formed by conventional electric components, such as capacitors and inductors, and by semiconductor switches, such as IGBTs, MOSFETs, and diodes. The main function of these circuits is to convert electric power from one form into another form. If we consider that electric power is produced or consumed in ac or dc circuits, then the power electronic circuits most commonly used in microgrids are those that convert from dc power to dc power, from dc power to ac power, and from ac power to dc power. Power electronic circuits that convert ac power to dc power are called rectifiers. The power electronic circuits that produce the inverse power conversion, i.e., from dc to ac, are called inverters. The third type of converter, i.e., one that converts dc power to dc power, is called a dc-dc converter. Power electronics technology also includes circuits called cycloconverters, which convert ac power directly into ac power, but these circuits are rarely used in microgrids. The most common use of power electronic circuits in microgrids is as interfaces between system components – distributed generation sources, local energy storage, and loads – and the power distribution grid. For example, rectifiers are typically used at the output of small wind turbines or microturbines. Dc-dc converters are used, for instance, to interface photovoltaic modules and achieve their maximum power operating point. Power electronic circuits can also be used in the power distribution network in order to provide some operational flexibility by, for example, realizing active nodes that can regulate electric variables, such as voltage, current, or power, in all its ports. However, this application is less common when compared to their use as system components interfaces.

One essential aspect of the aforementioned definition of LAPES is that microgrids must be able to operate independently of the grid. That is, all microgrids must have their own control systems that allow them to operate as stand-alone LAPES. Hence, although it is possible – and in many cases even desirable, due to reliability and economic reasons – to have microgrids connected to a main bulk grid, a grid tie is not required for microgrids operation. In cases in which microgrids are tied into a main grid, the bulk grid is a secondary source of power. In this way, during a mains outage, a microgrid can still operate normally with its distributed resources feeding its loads. Microgrid controllers may serve several purposes. Usually, controllers will regulate microgrid bus voltages and they will typically have a user interface for system configuration and for alarms and warnings display. Controllers may also regulate distributed generation sources output; for example, to achieve photovoltaic modules' maximum power operating point. When interfacing energy storage, controllers can regulate charge and discharge processes. In some cases, controllers can also be used to manage loads in order to optimize system performance. Another important function of controllers is to achieve stable operating points; for example, by regulating active and reactive power in ac microgrids or by compensating for destabilizing actions of constant-power loads in dc microgrids. In some cases, achieving stable operating points may be a challenging problem because of a few common characteristics of most microgrids: dynamic response mismatches between loads and sources, generated power capacity close to nominal load, and reduced added energy storage in generator rotors.

Some microgrids have a centralized controller that controls power flow from each source and monitors overall system condition [9]. Other microgrids have a decentralized – also called autonomous – control strategy in order to prevent potential system outages, as may happen if the controller fails in a centralized scheme. Some control schemes require a communication link among their distributed controllers in order to coordinate their actions. However, although having a communication link reduces control complexities, it may also become a single point of failure that may impact system availability in a negative way. In order to avoid this disadvantage of a communication link, decentralized control strategies are designed with autonomous capabilities, in which each distributed controller, or agent, is able to make decisions without communicating with other system components by estimating system and component conditions from locally measured variables. Yet autonomous control strategies tend to be more complex than other control approaches. Hence, one of the challenges of realizing such decentralized autonomous control schemes is to avoid increasing complexity to the point where such added complexity increases chances for a failure to happen. Some examples of microgrids with decentralized autonomous controllers include [10] and [11].

Electric power distribution choices may determine microgrid performance as much as other technology options already mentioned in this subsection. Power distribution alternatives may be characterized based on various criteria that include topological considerations, power conversion approaches, and electrical parameter aspects (such as type and level of voltage). In terms of topologies, the most common and simple design is a radial architecture in which power from different sources is combined in a single network node from where it is distributed to all loads through various circuits. However, radial power architectures are subject to potential availability issues because there is only one power path from generation to any given load, so any problem in such a single path may lead to power supply outages for the load being fed through a given circuit. That is, the power path to any load is a single point of failure for that given load. One way of partially avoiding this availability issue is to provide a redundant circuit to every critical load. This is a solution implemented in almost all communication sites in which loads are fed through "duplex" redundant "A" and "B" circuits. However, although duplex circuits facilitate maintenance and installation works on live plants, the single node where all paths from generation sources are combined is still a single point of failure. Moreover, if redundant circuits are run together, as it is often done in many practical applications (such as the communication sites mentioned above), a fault may affect both circuits simultaneously. One option implemented in microgrids that occupy a relatively large space, such as military outposts, is to provide spatially diverse power paths, so that redundant circuits do not run on the same path. Some common power architecture designs with diverse power distribution paths that are discussed in this book include ring-type distribution networks [12] [13] and ladder-type distribution networks [5] [14]. Another way of characterizing power distribution architectures is based on how power conversion is performed. If power conversion is performed at a single power electronic interface, then the power distribution architecture is centralized. If, instead, power conversion functions are spread among converters [15], then the microgrid is said to have a distributed power architecture. Distributed architectures may lead to parallel or cascade structures [15], which are further discussed in Chapter 7. When the focus of the design is to improve availability, parallel structures are used. Cascade structures are used to improve point-of-load regulation, reduce cost, and improve system efficiency [15] [16]. They have at least two conversion stages among three or more voltage levels.

One important source of controversy when designing microgrid power architectures is the decision about which type of voltage system to use: ac (either at conventional frequencies of 50 or 60 Hz, or “high” frequencies of up to 400 Hz) or dc. This controversy arose even at the origin of power systems design in the late 1800s. Direct current supplied by relatively low-power generators to loads located nearby was the technology chosen in the first power distribution systems in Edison’s microgrids [17]. Yet dc-based power distribution architectures were soon overshadowed by Tesla’s ac systems, which led to the present bulk power grids. One of the fundamental reasons why ac prevailed over dc for power distribution systems was that an ac power supply was better suited for feeding a key load of the Second Industrial Revolution: induction motors. In addition to better load compatibility, voltage transformation was significantly simpler with ac, so that longer distance transmission necessitated ac. Better economic outcomes yielded by large power plants complemented these other advantages of ac electric systems over dc systems, and has made ac power the standard for power transmission and distribution for the last 130 years. One of the few exceptions can be found in telecommunications power systems, because traditional telephone service networks are low-power 48 Vdc grids. However, the advent of power electronic interfaces used to convert dc power has altered the ac paradigm for distribution. Presently, dc power distribution architectures are more suitable to integrate diverse power sources and loads. This is true even for generators producing ac power (such as the output of a gas turbine) or loads requiring an ac voltage (such as induction motors) because power electronics allow for adjusting the ac power frequency, and thus enable a more flexible operation. Direct current systems also enable a simpler integration of energy-storage devices, such as batteries, ultracapacitors, and flywheels, to meet both energy and power buffer needs. Other advantages of dc architectures over ac indicated in [18] include potential higher availability, efficiency, and power density. Parallel distributed architectures are also simpler to realize in dc because the unnecessary frequency control and phase synchronization required in ac systems makes parallel components connections simpler. Since frequency control is not necessary in dc systems, unwanted harmonic content may by easier to filter too. However, lack of phase information in dc power architectures may make implementation of autonomous controls more difficult in dc than in ac systems [10] because in the former, system-wide state information can only be inferred from main bus voltage levels. Although dc power systems are exempt from the stability control issues found in ac systems that are related to reactive power and frequency control, dc systems still present stability challenges. In dc systems, stability issues are inherently related to the need for energy conversion through power electronic interfaces in order to achieve different voltage levels – a necessity when integrating sources, loads, and energy-storage devices with different characteristics, and an unavoidable outcome when realizing distributed power architectures. Hence, dc microgrids have typically cascade-distributed power architectures in which power electronic converters act as interfaces between system portions with different voltages. In these architectures stability issues appear because point-of-load converters act as instantaneous constant-power loads that introduce a destabilizing effect into the system [19] [20]. Although the same stability issue is also observed in ac microgrids, it is more