

NIKOS HATZIARGYRIOU

# Microgrids

## Architectures and Control



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# MICROGRIDS

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## ARCHITECTURES AND CONTROL

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**WILEY** |  **IEEE**  
IEEE PRESS

This edition first published 2014

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*Registered office*

John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, United Kingdom

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*Library of Congress Cataloging-in-Publication Data*

Microgrid: architectures and control / edited by professor Nikos Hatziargyriou.

1 online resource.

Includes bibliographical references and index.

Description based on print version record and CIP data provided by publisher; resource not viewed.

ISBN 978-1-118-72064-6 (ePub) – ISBN 978-1-118-72065-3 – ISBN 978-1-118-72068-4 (cloth)

1. Smart power grids. 2. Small power production facilities. I. Hatziargyriou, Nikos, editor of compilation.

TK3105

621.31–dc23

2013025351

A catalogue record for this book is available from the British Library.







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# Foreword

The idea of microgrids is not new. However, as new technologies are coming into existence to harvest renewable energy as well as more efficient electricity production methods coupled with the flexibility of power electronics; a new industry is developing to promote these technologies and organize them into microgrids for extracting the maximum benefits for owners and the power grid. More than 20 years ago, the Department of Energy has sponsored early research that laid the foundations for microgrids and explored the benefits. One key aspect is the ability and promise to address environmental concerns that have been growing in recent years. Today the microgrid concept has exploded to include a variety of architectures of energy resources into a coordinated energy entity that its value is much greater than the individual components. As a result the complexity of microgrids has increased. It is in this environment of evolution of microgrids that the present book is very welcome. It is written in a way that provides valuable information for specialist as well as non-specialists.

Chapter 1 provides a well thought view of the microgrid concept from the various forms of implementation to the potential economic, environmental and technical benefits. It identifies the role of microgrids in altering the distribution system as we know it today and at the same time elaborates on the formation of microgrids as an organized entity interfaced to distribution systems. In a refreshingly simple way identifies the enabling technologies for microgrids, that is power electronics, communications, renewable resources. It discusses in simple terms the ability of microgrids to minimize green house gases, help the power grid with load balancing and voltage control and assist power markets. While it is recognized that participation of the microgrids in power markets is limited by their size, it discusses possible ways that microgrids can market their assets via aggregators and opens the field for other innovations.

The book addresses two of the great challenges of microgrids: control and protection. Four chapters are devoted to these complex problems, three on control (Chapters 2, 3 and 5) and one on protection (Chapter 4). The multiplicity of control issues and their complexity is elaborated in a clear and concise manner. Since microgrids comprise many resources that are interfaced via power electronics the book presents the organization of the control problems in a hierarchical architecture that consists of local controllers that control specific resources, their operation and their protection as well as outer loop controllers that perform load-generation management, islanding operation as well as the interaction with up-stream controllers including power system control centers. It provides a good overview of approaches as well as the role of state estimation in controlling and operating a microgrid. In addition to conventional control methods, recent intelligent control approaches are also discussed. The specific issues and challenges of microgrid control are clearly elaborated. As an example, because the microgrid typically comprises many inverters connecting various resources to the microgrid it is possible to trigger oscillations due to inverter control interactions. Methods for solving these issues are clearly discussed in an easy to follow way. It is recognized that multiple microgrids can exist in a system and the issue of controlling and coordinating all the microgrids is very important from the point of view of managing the microsources as well as providing services to the power grid by coordinating all the resources. The services can be any of the ancillary services that are typically provided by large systems: frequency control, voltage control, power balance, capacitor reserves. The hierarchies involved in the control and operation of multi-microgrid systems are eloquently presented as a hierarchical control problem.

Protection of microgrids is a challenging problem due to the fact that microgrid resources provide limited fault currents. Detection of faults in microgrids is problematic at best because the grid side fault current contribution may be very high while the contribution from microsources is limited. Present protection schemes and functions are not reliable for microgrids. The book describes clever methods for providing adequate protection functions such as adaptive protection schemes, additional components that will provide temporarily high fault currents to enable the operation of protective relays, increasing inverter capacity and therefore fault current contribution. While the book provides some solutions it also makes it clear that there is much more work that needs to be done to reliably protect microgrids.

The basic approaches in designing, controlling and protecting microgrids are nicely complimented by a long list of microgrid projects around the globe that provide a picture of the evolution of microgrid design and lessons learned. Specific microgrid projects in Europe, United States, Japan, China and Chile are described and discussed. These projects provide an amazing insight into the lessons learned, challenges faced and issues resolved and issues outstanding. The examples span small capacity microgrids as well as some very large microgrids; grid-connected microgrids as well as stand-alone or island microgrids. The information provided is extremely useful and enables appreciation of the challenges as well as the rewards of these systems.

Finally, the last chapter elaborates on the technical, economic, environmental and social benefits of microgrids. The discussion is qualitative as well as quantitative. While the quantitative analysis is very much dependent upon specific areas and other conditions, the qualitative discussion is applicable to microgrids anywhere in the globe. Indirectly, this discussion makes the case for microgrids comprising mostly renewable energy resources as a big component in solving the environmental, economic and social issues that are facing a society that relies more and more in electric energy. The technical issues are solvable for transforming distribution systems into a distributed microgrid. The work presented in this book will be a fundamental reference toward the promotion and proliferation of microgrids and the accompanied deployment of renewable resources.

This book is a must read resource for anyone interested in the design and operation of microgrids and the integration of renewable resources into the power grid.

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# Preface

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The book deals with understanding, analyzing and justifying Microgrids, as novel distribution network structures that unlock the full potential of Distributed Energy Resources (DER) and thus form building blocks of future Smartgrids. In the context of this book, Microgrids are defined as distribution systems with distributed energy sources, storage devices and controllable loads, operated connected to the main power network or islanded, in a controlled, coordinated way. Coordination and control of DER is the key feature that distinguishes Microgrids from simple distribution feeders with DER. In particular, effective energy management within Microgrids is the key to achieving vital efficiency benefits by optimizing production and consumption of energy. Nevertheless, the technical challenges associated with the design, operation and control of Microgrids are immense. Equally important is the economic justification of Microgrids considering current electricity market environments and the need for a quantified assessment of their benefits from the view of the various stakeholders involved.

Discussions about Microgrids started in the early 2000, although their benefits for island and remote, off-grid systems were already generally appreciated. Nowadays, Microgrids are proposed as vital solutions for critical infrastructures, campuses, remote communities, military applications, smart utilities and communal networks. Bright prospects for a steady market growth are foreseen. The book is intended to meet the needs of practicing engineers, familiar with medium- and low-voltage distribution systems, utility operators, power systems researchers and academics. It can also serve as a useful reference for system planners and operators, technology providers, manufacturers and network operators, government regulators, and postgraduate power systems students.

The text presents results from a 6-year joint European collaborative work conducted in the framework of two EC-funded research projects. These are the projects “Microgrids: *Large Scale Integration of Micro-Generation to Low Voltage Grids*,” funded within the 5th Framework programme (1998–2002) and the follow-up project “More Microgrids, Advanced Architectures and Control Concepts for More Microgrids” funded within the 6th Framework Programme (2002–2006). The consortia involved were coordinated by the editor of this book and comprised a number of industrial partners, power utilities and academic research teams from 12 EU countries. A wealth of information and many practical conclusions were derived from these two major research efforts. The book attempts to clarify the role of Microgrids within the overall power system structure and focuses on the main findings related to primary and secondary control and management at the Microgrid and Multi-Microgrid level. It also provides results from quantified assessment of the Microgrids benefits from an economical, environmental, operational and social point of view. A separate chapter beyond the European projects, provided by a more international authorship is devoted to an overview of real-world Microgrids from various parts of the world, including, next to Europe, United States of America, Japan, China and Chile.

Chapter 1, entitled “The Microgrids Concept,” co-authored by Christine Schwaegerl and Liang Tang clarifies the key features of Microgrids and underlines the distinguishing characteristics from other DG dominated structures, such as Virtual Power Plants. It discusses the main features related to the operation and control, the market models and the effect of possible regulatory settings and provides an exemplary roadmap for Microgrid development in Europe.

Chapter 2, entitled “Microgrids Control Issues” co-authored by Aris Dimeas, Antonis Tsikalakis, George Kariniotakis and George Korres, deals with one of the key features of Microgrids, name

their energy management. It presents the hierarchical control levels distinguished in Microgrid operation and discusses the principles and main functions of centralized and decentralized control including forecasting and state estimation. Next, centralized control functions are analyzed and illustrated by a practical numerical example. Finally, an overview of the basic multi-agent system concepts and their application for decentralized control of Microgrids is provided.

Chapter 3, entitled “Intelligent Local Controllers,” co-authored by Thomas Degner, Nikos Soutani, Alfred Engler and Asier Gil de Muro, presents primary control capabilities of DER controllers. The provision of ancillary services in interconnected mode and the capabilities of voltage and frequency control, in case of islanded operation and during transition between the two modes are outlined. Emphasis is placed on the implications of the high resistance over reactance ratios, typically found in LV Microgrids. A control algorithm based on the fictitious impedance method to overcome the related problems together with characteristic simulation results are provided.

Chapter 4, entitled “Microgrid Protection,” co-authored by Alexander Oudalov, Thomas Degner, Frank van Overbeeke and Jose Miguel Yarza, deals with methods for effective protection in Microgrids. A number of challenges are caused by DER varying operating conditions, the reduced fault contribution by power electronics interfaced DER and the occasionally increased fault level. Two adaptive protection techniques, based on pre-calculated and on-line calculated settings are proposed including practical implementation issues. Techniques to increase the amount of fault current level by a dedicated device and the possible use of fault current limitation are also discussed.

Chapter 5, entitled “Operation of Multi-Microgrids,” co-authored by João Abel Peças Lopes, André Madureira, Nuno Gil and Fernanda Resende examines the operation of distribution networks with increasing penetration of several low voltage Microgrids, coordinated with generators and flexible loads connected at medium voltage. An hierarchical management architecture is proposed and functions for coordinated voltage/VAR control and coordinated frequency control are analyzed and simulated using realistic distribution networks. The capability of Microgrids to provide black start services are used to provide restoration guidelines. Finally, methods for deriving Microgrid equivalents for dynamic studies are discussed.

Chapter 6, entitled “Pilot Sites: Success Stories and Learnt Lessons” provides an overview of real world Microgrids, already in operation as off-grid applications, pilot cases or full-scale demonstrations. The material is organized according to geographical divisions. George Kariniotakis, Aris Dimeas and Frank van Overbeeke describe three pilot sites in Europe developed within the multi-Microgrids project; John Romankiewicz and Chris Marnay provide an overview of Microgrid Project in the United States; Satoshi Morozumi provide an overview of the Japanese Microgrid Project; Meiqin Mao describes the Microgrid Projects in China and Rodrigo Palma Behnke and Guillermo Jiménez-Estévez provide details of an off-grid Microgrid in Chile. These projects are of course indicative of a continuously growing list, they provide, however, a good impression of the on-going developments in the field.

Chapter 7, entitled “Quantification of Technical, Economic, Environmental and Social Benefits of Microgrid Operation,” co-authored by Christine Schwaegerl and Liang Tao attempts to quantify the Microgrids benefits using typical European distribution networks of different types and assuming various DER penetration scenarios, market conditions, prices and costs developments for the years 2020, 2030 and 2040. Sensitivity analysis of the calculated benefits is performed. Although, the precision of these quantified benefits is subject to the high uncertainties in the underlying assumptions, the positive effects of Microgrids operation can be safely observed in all cases.

Next to the co-authors of the various chapters, there are many researchers who have contributed the material of this book by their knowledge, research efforts and fruitful collaboration during the numerous technical meetings of the Microgrids projects. I am indebted to all of them, but I feel obliged to refer to some names individually and apologize in advance for the names I might forget. I would like to start with Profs. Nick Jenkins and Goran Strbac from UK; I have benefited tremendously while working with them and their insights and discussions helped clarify many concepts discussed in the book. I am indebted to Britta Buchholz, Christian Hardt, Roland Pickhan, Mariam Khattab, Michel Vandenberg, Martin Braun, Dominik Geibel and Boris Valov from Germany; Mikes Barne Olimpo Anaya-Lara, Janaka Ekanayake, Pierluigi Mancarella, Danny Pudjianto and Tony Lakin from UK; Jose Maria Oyarzabal, Joseba Jimeno and Iñigo Cobelo from Spain; Nuno Melo and António Amorim from Portugal; Sjef Cobben from the Netherlands; John Eli Nielsen from Denmark; Peregrino Omar and Michelangeli Chiara from Italy; Aleksandra Krkoleva, Natasa Markovska and Iva Kungulovski from FYR of Macedonia; Grzegorz Jagoda and Jerszy Zielinski from Poland; my NTU colleagues Stavros Papathanassiou and Evangelos Dialynas; and Stathis Tselepis, Kostas Elmasidas, Fotis Psomadellis, Iliana Papadogoula, Manolis Voumvoulakis, Anestis Anastasiadis, Fotis Kanellos, Spyros Chadjivassiliadis and Maria Lorentzou from Greece. I express my gratitude to my PhD students and collaborators Georgia Asimakopoulou, John Karakitsios, Evangelos Karfopoulos, Vassilis Kleftakis, Panos Kotsampopoulos, Despina Koukoula, Jason Kouveliotis-Lysicatos, Alexandros Rigas, Nassos Vassilakis, Panayiotis Moutis, Christina Papadimitriou and Dimitris Trakas, who reviewed various chapters of the book and provided valuable comments. Finally, I wish to thank the EC DG Research&Innovation for providing the much appreciated funding for the research leading to this book, especially the Officers Manuel Sanchez Jimenez and Patrick Van Hove.

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# The Microgrids Concept

Christine Schwaegerl and Liang Ta

## 1.1 Introduction

Modern society depends critically on a secure supply of energy. Growing concerns for primary energy availability and aging infrastructure of current electrical transmission and distribution networks are increasingly challenging security, reliability and quality of power supply. Very significant amounts of investment will be required to develop and renew these infrastructures, while the most efficient way to meet social demands is to incorporate innovative solutions, technologies and grid architecture. According to the International Energy Agency, global investments required in the energy sector over the period 2003–2030 are estimated at \$16 trillion.

Future electricity grids have to cope with changes in technology, in the values of society, in the environment and in economy [1]. Thus, system security, operation safety, environmental protection, power quality, cost of supply and energy efficiency need to be examined in new ways in response to changing requirements in a liberalized market environment. Technologies should also demonstrate reliability, sustainability and cost effectiveness. The notion of **smart grids** refers to the evolution of electricity grids. According to the European Technology Platform of Smart Grids [2], a smart grid is an electricity network that can intelligently integrate the actions of all users connected to it – generators, consumers and those that assume both roles – in order to efficiently deliver sustainable economic and secure electricity supplies. A smart grid employs innovative products and services together with intelligent monitoring, control, communication and self-healing technologies.

It is worth noting that power systems have always been “smart”, especially at the transmission level. The distribution level, however, is now experiencing an evolution that needs more “smartness”, in order to

- facilitate access to distributed generation [3,4] on a high share, based on renewable energy sources (RESs), either self-dispatched or dispatched by local distribution system operators
- enable local energy demand management, interacting with end-users through smart metering systems
- benefit from technologies already applied in transmission grids, such as dynamic control techniques, so as to offer a higher overall level of power security, quality and reliability.

In summary, distribution grids are being transformed from **passive** to **active networks**, in the sense that decision-making and control are distributed, and power flows bidirectional. This type of network eases the integration of DG, RES, demand side integration (DSI) and energy storage technologies, and creates opportunities for novel types of equipment and services, all of which would need to conform to common protocols and standards. The main function of an active distribution network is to efficiently link power generation with consumer demands, allowing both to decide how best to operate in real

time. Power flow assessment, voltage control and protection require cost-competitive technologies and new communication systems with information and communication technology (ICT) playing a key role.

The realization of active distribution networks requires the implementation of radically new system concepts. **Microgrids** [5–11], also characterized as the “building blocks of smart grids”, are perhaps the most promising, novel network structure. The organization of microgrids is based on the control capabilities over the network operation offered by the increasing penetration of distributed generation including microgenerators, such as micro-turbines, fuel cells and photovoltaic (PV) arrays, together with storage devices, such as flywheels, energy capacitors and batteries and controllable (flexible) loads (e.g. electric vehicles [12]), at the distribution level. These control capabilities allow distribution networks, mostly interconnected to the upstream distribution network, to also operate when isolated from the main grid, in case of faults or other external disturbances or disasters, thus increasing the quality of supply. Overall, the implementation of control is the key feature that distinguishes microgrids from distribution networks with distributed generation.

From the customer's point of view, microgrids provide both thermal and electricity needs, and, in addition, enhance local reliability, reduce emissions, improve power quality by supporting voltage and reducing voltage dips, and potentially lower costs of energy supply. From the grid operator's point of view, a microgrid can be regarded as a controlled entity within the power system that can be operated as a single aggregated load or generator and, given attractive remuneration, also as a small source of power or ancillary services supporting the network. Thus, a microgrid is essentially an aggregation concept with participation of both supply-side and demand-side resources in distribution grids. Based on the synergy of local load and local microsource generation, a microgrid could provide a large variety of economic, technical, environmental and social benefits to different stakeholders. In comparison with peer microsource aggregation methods, a microgrid offers maximum flexibility in terms of ownership constitution, allows for global optimization of power system efficiency and appears as the best solution for motivating end-consumers via a common interest platform.

Key economic potential for installing microgeneration at customer premises lies in the opportunity to locally utilize the waste heat from conversion of primary fuel to electricity. There has been significant progress in developing small, kW-scale, combined heat and power (CHP) applications. These systems have been expected to play a very significant role in the microgrids of colder climate countries. On the other hand, PV systems are anticipated to become increasingly popular in countries with sunnier climates. The application of micro-CHP and PV potentially increases the overall efficiency of utilizing primary energy sources and consequently provides substantial environmental gains regarding carbon emissions, which is another critically important benefit in view of the world's efforts to combat climate change.

From the utility point of view, application of microsources can potentially reduce the demand for distribution and transmission facilities. Clearly, distributed generation located close to loads can reduce power flows in transmission and distribution circuits with two important effects: loss reduction and the ability to potentially substitute for network assets. Furthermore, the presence of generation close to demand could increase service quality seen by end customers. Microgrids can provide network support in times of stress by relieving congestion and aiding restoration after faults.

In the following sections, the microgrid concept is clarified and a clear distinction from the virtual power plant concept is made. Then, the possible internal and external market models and regulatory settings for microgrids are discussed. A brief review of control strategies for microgrids is given and

## **1.2 The Microgrid Concept as a Means to Integrate Distributed Generation**

During the past decades, the deployment of distributed generation (DG) has been growing steadily. DGs are connected typically at distribution networks, mainly at medium voltage (MV) and high voltage (HV) level, and these have been designed under the paradigm that consumer loads are passive and power flows only from the substations to the consumers and not in the opposite direction. For this reason, many studies on the interconnection of DGs within distribution networks have been carried out, ranging from control and protection to voltage stability and power quality.

Different microgeneration technologies, such as micro-turbines (MT), photovoltaics (PV), fuel cells (FC) and wind turbines (WT) with a rated power ranging up to 100 kW can be directly connected to the LV networks. These units, typically located at users' sites, have emerged as a promising option to meet growing customer needs for electric power with an emphasis on reliability and power quality, providing different economic, environmental and technical benefits. Clearly, a change of interconnection philosophy is needed to achieve optimal integration of such units.

Most importantly, it has to be recognized that with increased levels of microgeneration penetration, the LV distribution network can no longer be considered as a passive appendage to the transmission network. On the contrary, the impact of microsources on power balance and grid frequency may become much more significant over the years.

Therefore, a control and management architecture is required in order to facilitate full integration of microgeneration and active load management into the system. One promising way to realize the emerging potential of microgeneration is to take a systematic approach that views generation and associated loads as a subsystem or a microgrid.

In a typical microgrid setting, the control and management system is expected to bring about a variety of potential benefits at all voltage levels of the distribution network. In order to achieve this goal, different hierarchical control strategies need to be adopted at different network levels.

The possibility of managing several microgrids, DG units directly connected to the MV network and MV controllable loads introduces the concept of multi-microgrids. The hierarchical control structure of such a system calls for an intermediate control level, which will optimize the multi-microgrid system operation, assuming an operation under a real market environment. The concept of multi-microgrids is further developed in Chapter 5.

The potential impact of such a system on the distribution network may lead to different regulatory approaches and remuneration schemes, that could create incentive mechanisms for distribution system operators (DSOs), microgeneration owners and loads to adopt the multi-microgrid concept. This is further discussed in Chapter 7.

## **1.3 Clarification of the Microgrid Concept**

### **1.3.1 What is a Microgrid?**

In scope of this book, the definition from the EU research projects [7,8] is used:

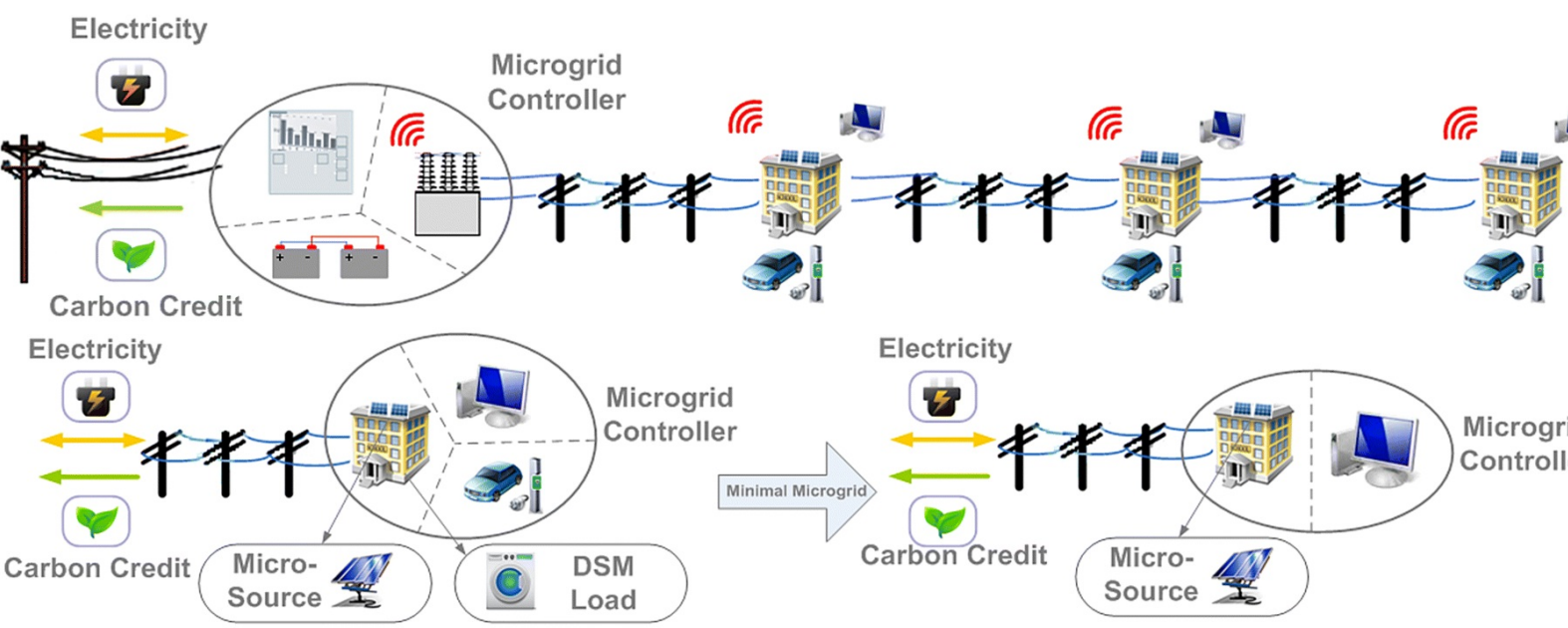
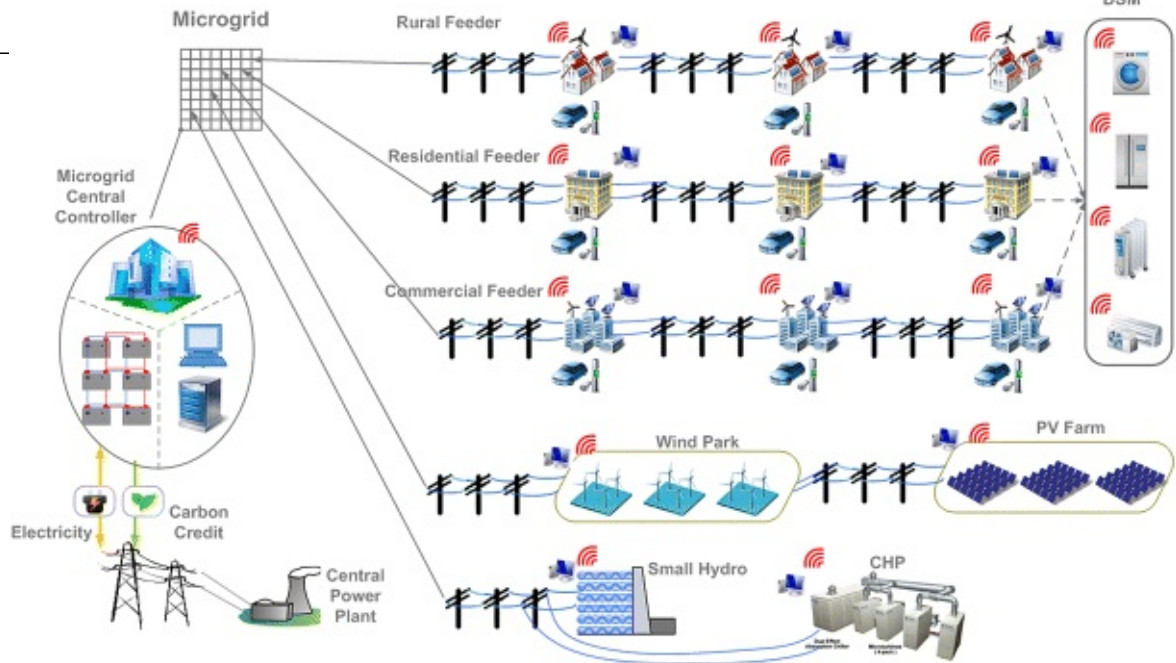
Microgrids comprise LV distribution systems with distributed energy resources (DER) (microturbines, fuel cells, PV, etc.) together with storage devices (flywheels, energy capacitors and batteries) and flexible loads. Such systems can be operated in a non-autonomous way, interconnected to the grid, or in an autonomous way, if disconnected from the main grid. The operation of microsources in the network can provide distinct benefits to the overall system performance, if managed and coordinated efficiently.

There are three major messages delivered from this definition:

1. Microgrid is an integration platform for supply-side (microgeneration), storage units and demand resources (controllable loads) located in a local distribution grid.
  - In the microgrid concept, there is a focus on local supply of electricity to nearby loads, thus aggregator models that disregard physical locations of generators and loads (such as virtual power plants with cross-regional setups) are not microgrids.
  - A microgrid is typically located at the LV level with total installed microgeneration capacity below the MW range, although there can be exceptions: parts of the MV network can belong to a microgrid for interconnection purposes.
2. A microgrid should be capable of handling both normal state (grid-connected) and emergency state (islanded) operation.
  - The majority of future microgrids will be operated for most of the time under grid-connection – except for those built on physical islands – thus, the main benefits of the microgrid concept will arise from grid-connected (i.e. “normal”) operating states.
  - In order to achieve long-term islanded operation, a microgrid has to satisfy high requirements on storage size and capacity ratings of microgenerators to continuous supply of all loads or it has to rely on significant demand flexibility. In the latter case, reliability benefits can be quantified from partial islanding of important loads.
3. The difference between a microgrid and a passive grid penetrated by microsources lies mainly in terms of management and coordination of available resources.
  - A microgrid operator is more than an aggregator of small generators, or a network service provider, or a load controller, or an emission regulator – it performs all these functionalities and serves multiple economic, technical and environmental aims.
  - One major advantage of the microgrid concept over other “smart” solutions lies in its capability of handling conflicting interests of different stakeholders, so as to arrive at a globally optimal operation decision for all players involved.

A microgrid appears at a large variety of scales: it can be defined at the level of a LV grid, a LV feeder or a LV house – examples are given in [Figure 1.1](#). As a microgrid grows in scale, it will likely be equipped with more balancing capacities and feature better controllability to reduce the intermittencies of load and RES. In general, the maximum capacity of a microgrid (in terms of peak load demand) is limited to few MW (at least at the European scale, other regions may have different upper limits, see Chapter 6). At higher voltage levels, multi-microgrid concepts are applied, implying the coordination of interconnected, but separate microgrids in collaboration with upstream connected DGs and MV network controls. The operation of multi-microgrids is discussed in Chapter 5.

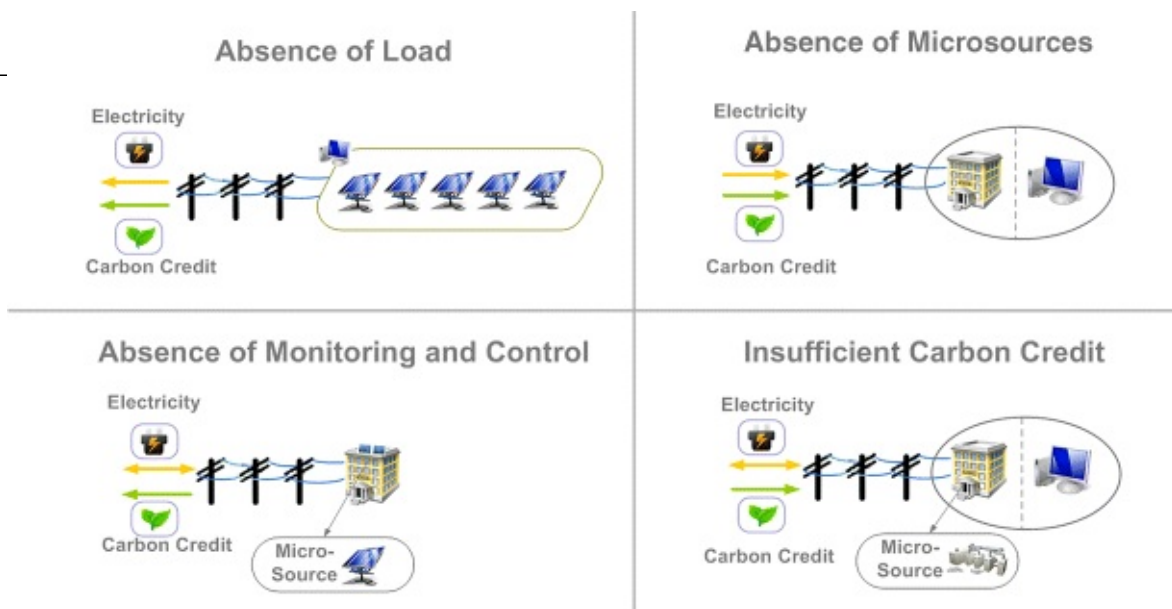
**Figure 1.1** (a) Microgrid as a LV grid; (b) Microgrid as a LV feeder; (c) Microgrid as a LV house



### 1.3.2 What is Not a Microgrid?

In [Figure 1.2](#), the microgrid concept is further clarified by examples that highlight three essential microgrid features: local load, local microsources and intelligent control. In many countries environmental protection is promoted by the provision of carbon credits by the use of RES and CHP technologies; this should be also added as a microgrids feature. Absence of one or more features would be better described by DG interconnection cases or DSI cases.

[Figure 1.2](#) What is not a microgrid? Sample cases



In the following section, some typical misconceptions regarding microgrids are clarified:

- Microgrids are exclusively isolated (island) systems.
  - ⇒ Microgrids have the capability to shift to islanded operation in emergency situations, thus increasing customer reliability, but they are mostly operated interconnected to the upstream distribution network. Small island systems are inherently characterized by coordinated control of their resources, thus, depending on their size and the extent of DER penetration and control, they can be also termed as microgrids.
- Customers who own microsources build a microgrid.
  - ⇒ DG penetration is indeed a distinct microgrid feature, but a microgrid means more than passive tolerance of DG (also known as “fit and forget”) and needs active supervision, control and optimization.
- Microgrids are composed of intermittent renewable energy resources, so they must be unreliable and easily subject to failures and total black-outs.
  - ⇒ A microgrid can offset RES fluctuation by its own storage units (when islanded) or external generation reserves (when grid-connected). Moreover, the microgrid's capability of transferring from grid-connected to island mode actually improves security of supply.
- Microgrids are expensive to build, so the concept will be limited to field tests or only to remote locations.
  - ⇒ DER penetration is increasing worldwide. Financial support schemes for RES and CHP have already ensured the basic profitability of such distributed resources; future cost reductions of microgeneration and storage can make microgrids commercially competitive. In any case, the additional cost for transforming a distribution line with DER into a microgrid involves only the relevant control and communication costs. These are easily compensated by the economic advantages of coordinated DER management.
- The microgrid concept is just another energy retailer advertising scheme to increase his income.
  - ⇒ Even if an end-consumer chooses not to install photovoltaic panels on his rooftop or hold a share in the community-owned CHP plant, he can still benefit from having more choice of energy supply and of sharing carbon-reduction credits in his bill.
- The microgrid controllers will force consumers to shift their demand, depending on the availability of renewable generation, e.g. to switch on the washing machine at home only when

the sun is shining or the wind is blowing.

⇒ Demand side integration (DSI) programs in normal commercial and household applications should apply a “load follow generation” control philosophy only to long-term stand-by appliances (such as refrigerators and air-conditioners) or time-insensitive devices (such as water heaters).

- A microgrid is such a totally new idea, that system operators need to rebuild their entire network
  - ⇒ Although new metering, communication and control devices would need to be installed, conversion of a normal “passive” distribution grid to a microgrid does not actually incur too much infrastructure costs on the network operator side – on the contrary, a microgrid can actually defer investment costs for device replacement.
- Microgrid loads will never face any supply interruptions.
  - ⇒ “Smooth” (i.e. no loss of load) transition to island operation is only possible with large storage or generation redundancy within a microgrid, thus an islanded microgrid will very probably have to shed non-critical loads according to the instantaneous amount of available resource.

### 1.3.3 Microgrids versus Virtual Power Plants

A **virtual power plant** (VPP) is a cluster of DERs which is collectively operated by a central control entity. A VPP can replace a conventional power plant, while providing higher efficiency and more flexibility. Although the microgrid and the VPP appear to be similar concepts, there are a number of distinct differences:

- **Locality** – In a microgrid, DERs are located within the same local distribution network and they aim to satisfy primarily local demand. In a VPP, DERs are not necessarily located on the same local network and they are coordinated over a wide geographical area. The VPP aggregated production participates in traditional trading in normal energy markets.
- **Size** – The installed capacity of microgrids is typically relatively small (from few kW to several MW), while a VPP's power rating can be much larger.
- **Consumer interest** – A microgrid focuses on the satisfaction of local consumption, while a VPP deals with consumption only as a flexible resource that participates in the aggregate power trading via DSI remuneration.

Following on from the definition of a VPP as a commercial entity that aggregates different generation, storage or flexible loads, regardless of their locations, the technical VPP (TVPP) has been proposed, which also takes into account local network constraints. In any case, VPPs, as virtual generators, tend to ignore local consumption, except for DSI, while microgrids acknowledge local power consumption and give end consumers the choice of purchasing local generation or generation from the upstream energy market. This leads to a better controllability of microgrids, as shown in [Figure 1.3](#), where both supply and demand resources of a microgrid can be simultaneously optimized leading to better DG profitability.

[Figure 1.3](#) Microgrid benefit over commercial and technical VPP due to supply side integration



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