Power Systems

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Smart Grids from a Global Perspective

Bridging Old and New Energy Systems

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ISSN 1612-1287 ISSN 1860-4676 (electronic)
Power Systems
ISBN 978-3-319-28075-2 ISBN 978-3-319-28077-6 (eBook)
DOI 10.1007/978-3-319-28077-6

Library of Congress Control Number: 2015960431

Printed on acid-free paper

This Springer imprint is published by SpringerNature
The registered company is Springer International Publishing AG Switzerland

Power Systems

More information about this series at http://www.springer.com/series/4622

Foreword

This book represents a bold step toward formulating a number of questions that are crucial to a much-needed redefinition of the electric energy sector of engineering and system science. It should not be surprising to anyone that the initiative for this book came from the Groningen Energy Summer School (GESS), well known in the Netherlands as an institution that greatly values strong links between research and education. If you have not visited this country in person, I recommend that you do so, not only for education and gathering of information, but also for the ambience of the country itself and its relevance to electric energy. You will find yourself, as I did, faced with vast green spaces surrounding relatively small homes. By virtue of an invitation to a Dutch home, I quickly realized that sustainable fields and windmills are higher up in the value chain of the Netherlands than having large homes. This attitude cannot be found everywhere. The Netherlands has long nurtured nature preservation, which shows today in the way people value their environment.

It is also not surprising that several top Dutch schools, many of whose faculty are authors of this book, are very active in research and education sustainability programs. The oldest of them is Groningen where, as an example, a yearly Energy Summer School attracts groups of young unconventional minds meeting on an annual basis to think deeply and openly about evolving objectives of industry, their implications for society as a whole, and their impact on electric energy consumers in particular. I had the privilege of participating in a GESS a few years back. During that time, I reaffirmed my conviction that learning must be a lifelong experience. The GESS experience presented to me many aspects of problems that I had never thought of before. It impressed upon me that there would be much learning ahead if I had the opportunity to proactively interact with such a diverse group in the future. This book is simply another reflection of this deeply ingrained commitment by the Dutch universities to make the world a better place.

However, even as I write these thoughts, I cannot help but think of how challenging must be the entire process of making GESS work. It motivates me to look back at my own career and revisit how I coped with the challenge of going beyond a narrow specialization at different stages in my career. In hindsight (always easy!), I can recognize where I saw the challenge and how I chose my next steps.

As many of the authors in this book, I started with my own discipline-oriented education in electrical engineering and systems science. I was quite content with thinking about electric power systems as complex dynamical systems. Given a new technical problem, like the infamous voltage collapse which took French and Belgian grids into blackouts caused by phenomena previously unstudied, it became quite challenging and rewarding to learn from such legendary engineering leaders, Charles Concordia, John Zaborszky, and Lester Fink, how to look at a real-world problem, pose it mathematically, and design methods for solving it. These people were simply amazing, as they interpreted complex physical problems using clean elegant mathematics. Influenced by each of them, I gradually moved into thinking about electric power grids as complex dynamical systems, whose structures must be defined and used to make the grid work better by means of feedback control. I was working on "smarts" without identifying them with any special names. But, neither new technologies nor perceived needs were ready for their deployment. "Loads" were quite predictable during normal operation, and ICT was viewed more as a liability than as a help to a physical system. Supplying a load reliably had been the golden industry rule, and it was to remain so for years to come. Innovation for efficiency was secondary. So we wrote papers that went largely unused by the industry.

In the early 1990s, the electric utility sector entered the beginning of what was to become a turbulent period to this day. Utilities began the restructuring battle with non-utility-owned generation companies, and customers were assumed to be the only invariant. For all practical purposes, customers were to be captive since there was and still is only one electric connection from users to large energy sources. Needless to say, I began to question my own research direction. I was not formally trained in economics, financial engineering, public policy, or political science. You name the discipline of the day that was to magically transform the industry, and it was not what I knew.

As though none of this had dealt enough bruises to my self-confidence, the "smart grid" wave blinded me during those several years. I watched many people rediscover many known technologies without assessing hidden assumptions that made them work. Storage became the main medicine for all, without having a holistic approach to how to value it relative to, say, a slower-responding resource equipped with model predictive control (MPC) software. But since there was enough extra reserve in the system that deploying lots of expensive storage was not an immediate need, some technically strong companies making large storage such as A123 failed financially.

Currently, we are experimenting with magic new technologies whose inventors are about to save the world. On the other hand, lots of wind power deployed in Germany gets "spilled" and wasted. The grid cannot deliver it to the right customers, and it has become too complex to fix the problem. Instead, we continue to reel out more transmission wires and ruin our beautiful large green fields. Nobody seems to be connecting the dots between new resources, customer needs, and the delivery service to make it all work. I think back to much of the early systems work, including my own, which was published but remained unused because it came before its time. Now, the technologies and needs are here, but we still fail miserably in technology transfer for well-understood functionality. The scary challenge is that many of these "smarts" by themselves do not have value. For example, storage has value in balancing intermittent generation, but the customer can also do this when adjusting its demand using MPC, for example. Technical solutions are non-unique and they must be evaluated in the context of many other factors communicated by the authors of this book.

It is probably safe to say that at the end of the day, the complexity will become so overwhelming that users are going to begin to disconnect from the grid and serve themselves. This is an idea that would have been considered suicidal back in the days of economies of scale, when the bigger power plants routinely meant lowering cost.

All I can say is that it is beginning to look like we are at the point of spiral death of the electric energy sector as we have known it. Everyone is inventing something, convincing government to subsidize its pilot deployment, and, almost as a rule, without supplying any new technologies deployed at scale. This is all done with little understanding of impacts on those who need electricity. Something is obviously wrong with this picture!

As the reader can conclude by now, it remains difficult for me to see that we are so far from posing the problem holistically. Doing this is easier said than done. Fundamentally, we do not have common problem formulations in different disciplines. Communicating differing views of the same complex problem in a way that can be unifying, and that will motivate a multidisciplinary team to solve the actual real-world problem holistically, has remained an elusive holy grail, I believe. This challenge continues to be seen as we attempt to formalize multidisciplinary educational and research programs.

This overall perception of the situation in the field, summarized as a lack of systematic well-defined approaches to multidisciplinary complex problems, brings to focus the major importance of this book. GESS is an emerging living laboratory where methods begin to be molded. It is only by doing it together and listening to each other with open minds and appreciation for the magnitude of the challenge set that we can make progress. Having taken this admirable approach, the authors of this book offer many different aspects of the underlying complex industry evolution. They explicitly question the objectives of industry evolution, keeping customers in the main focus; they are no longer captive predictable loads. Several book chapters make it very clear that our industry evolution is not only about designing economic incentives. It is much more about the sustainability attributes the late Elinor Ostrom envisioned. The key to sustainability is having proactive consumers who understand what can and should be done, ranging from adjustments, to cooperation through distributed aggregation, and/or to using embedded computer applications such as MPC to deal with the uncertainties in a stable way. Customers need to self-manage their own privacy and only exchange what is essential for them to align their characteristics with the characteristics of the others within a complex dynamical system. Fascinating is the concept of a "powerful network" put forward by a group of thinkers. Several authors recognize that it is no longer "one size fits all" but that culture, race, and religion that may jointly determine customers' approach to electric energy. Clearly stressed is that customers do not use watts, but they use heat, light, and computers and drive cars. Not every watt is equally important to all users.

In closing, each chapter in this book is like a breath of fresh air. It is not the sum of the ideas that helps progress in this real chaotic evolution. I can only hope that the GESS continues for years to come. We need hordes of young people with very diverse views spending time together and arriving at the common language needed to formulate the problem holistically. Perhaps it is my biased view, but systems thinking is essential. And it is not about one single method (Foster school of system dynamics; MPC; behavioral science, feedback control, industrial economics), but about being able to zoom out to wrap our hands around this monster problem and zoom back into different aspects of the problem (engineering, economic, social, political, ICT) studied by the discipline experts, and then zoom out again. Some sort of interactive thinking starting with a family of unique single discipline-based formulations and arriving at the holistic multidisciplinary problem formulation is badly needed. We are not quite there yet, but the thinking offered in this book is a big step in the right direction. I encourage young people to make it a routine pilgrimage to GESS where they once in a while step out of their own specialized way of thinking about the problem, and open themselves to learning about other aspects of the problem. And I would say not to get discouraged by what might seem at times an unmanageable roadblock. As I shared briefly with you my own path, this is bound to happen the minute one dares to zoom out into the real world. However, it can be tremendously rewarding. I am heartened by so many young people who, like the authors in this book, think of their work as having a much bigger mission beyond the boundaries of what they know best. I thank the authors for having provided much food for thinking to the readers.

November 2015

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Introduction—Smart Grids: Design, Analysis and Implementation of a New Socio-technical System

J.H. (Jaap) de Wilde, J. Anne Beaulieu and Jacquelien M.A. Scherpen

Self-Managing And Reliable Transmission electric grids—SMART Grids. According to many sources on the internet, including his own LinkedIn page, Andres Carvallo, "Energy Maven and Smart Grid Godfather", defined the term SMART grid on March 5, 2004" (Carvallo 2015). Johannes Kester (Chap. 12 in this book) found an older source. In a less bombastic manner, Khoi and colleagues defined SMART Grids as:

> The Self-Managing and Reliable Transmission Grid (SMARTGrid) is seen as the future of protection and control systems. It is an automated system of monitoring, control, and protection devices that improves the reliability of the transmission grid by preventing wide-spread break-ups (Khoi et al. 1997).

Beyond Carvallo's bravura and claims to precedence, there are more intriguing aspects to the term SMART Grid. 'Self-Managing' hints at an engine without a driver. Such a techno-fix is expected to help create a sustainable society without addressing questions like 'whose society?' and at 'which levels of welfare and well-being within that society?' This version of smart grids doesn't pause to ask: Will there be equal access for all—in the spirit in which the electricity grid was rolled out in Western countries in the last century—or will smart grids create new social stratification through differential access to energy? Given the way the social is excluded from such definitions, it is not surprising that a number of publications

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A. Beaulieu et al. (eds.), *Smart Grids from a Global Perspective*, Power Systems, DOI 10.1007/978-3-319-28077-6_1

on smart grids see the consumers and prosumers as the main obstacles to success. They are externalities and unknown factors in the equation. Not in this book.

In the run up to the preparation of this volume, we have noted again and again how the dominant paradigm in the literature on smart grids insists on the economic road to socialisation: pro- and consumers can be pushed into the desired directions by creating economic incentives. The pro- and consumers are expected to behave like a *homo economicus*, a rationally operating agent who attempts to maximize utility as a consumer and economic profit as a producer. There is also a *homo politicus* and a *homo ethicus*, with corresponding non-economic modes of reasoning, decision-making and behaving. These different dimensions are relevant for families, communities, nations, religions, and societies, and important also for firms, bureaucracies, armies and governments. All are part of complex socio-technical systems, and there is no single stimulus, economic or otherwise, that can bring about change.

If smart grids aim to contribute to a more sustainable production, transportation and use of energy *by design*, its 'self-management', 'reliability' and 'transmission' need to incorporate factors it has ignored so far. This book intends to open a window into that direction by merging a variety of approaches of smart grids. As such it builds on the four-year experience of the interdisciplinary Groningen Energy Summer School, run by the University of Groningen and Globalisation Studies Groningen (GSG). This School unites staff and Ph.D. students from a wide range of academic disciplines in one programme: engineers, lawyers, chemists, sociologists, physicists, philosophers, economists, geographers, psychologists, political scientists, historians, geologists and computer science experts. Over the course of two weeks, they try to incorporate the best of each other's expertise into their own. The Ph.D. students have to present each other's work: a lawyer needs to come to grips with algorithms that run distribution systems, or an engineer needs to understand how speech acts create social realities. This book as a whole represents that practice. The individual chapters, however, reflect the expertise of the authors. Some of them combine various disciplines, but the true transdisciplinary exposure of this book is the added value created by the sum of its parts. To strengthen this we have added Points for Discussion to each chapter, emphasizing the broader context, and helping readers from other fields understand the relevance of a particular kind of expertise for larger questions about smart grids. It is our hope that this book will be an instrument to rethink the boundaries of smart grids as a concept, making it more inclusive and reflexive, and therefore more adequate for shaping a sustainable energy future.

In the course of our discussions, participants often quipped about the relative smartness (or dumbness) of smart grids. Whether the system is seen as smart or not depends on how you define smartness, but also on how the problem that smart grids are meant to solve is defined. While this varies across regions and systems (see Beaulieu, this volume), two main framings of the problem dominate debates about anticipated problems with reliable supply of electricity to consumers, especially households, but also industries. The first focuses on how to incorporate and balance the often fluctuating production of renewable electricity into the grid. The second has to do with managing infrastructures and coping with the increasing electricity demand of societies, in particular peak demand. In both cases the answer is expected to come from ICT, by adding a layer of digital information to the operations of the grid and to the management of supply and demand. These starting points emphasize technology, but do so in relation to an existing infrastructure. Furthermore, the solutions proposed, even the most narrowly technological, always involve a suite of technologies (Shove 2007) rather than a single device. There will be no single 'killer app', but clusters of new technologies and practices. Solutions will necessarily be multiple and heterogeneous, if only because technological change involves the merging of the software of ICT and the hardware of energy infrastructures. The chapters in this book will further more demonstrate how transformations of infrastructures and technologies are intrinsically tied to social, economic, institutional and legal changes of our energy system. Furthermore, these changes will take place in a context where the very nature of 'energy' is shifting. In a near future, we may see transformations as far-reaching as the recent digital revolution, and the very concept of energy may be moving, from the provision of Kw/h to the provision of energy services.

In the first part of this volume, various approaches to changing energy systems are set out. Marco Aiello and Giuliano Andrea Pagani (Chap. 2) focus on energy distribution and the role that information and communication technology (ICT) can play. After a brief overview of the current role of ICT in energy distribution systems, they discuss the consequences of bi-directional energy flows. The electricity meter has to transform in such a way that it can help to predict energy consumption and can deliver a real-time view of both production and consumption anywhere in the distribution grid. They conclude that the current energy systems have to deal with two different constraints. Whereas ICT research and development must deal with a material infrastructure that is highly constrained by physical laws, power systems research and development faces the challenge of having to decentralize its operations and to make room for decision-making by more active end-users.

These decentralized decision refer to the new roles for consumers and prosumers in the grid. The passive and active roles of energy users are analysed by a research team of the Eindhoven University of Technology, led by Geert Verbong (Chap. 3). The authors develop a quadrant with four typical roles: users can be passive or active enablers of potentially sustainable innovation and they can be passive or active 'barriers' to such innovation. There can be organised protest to change or there can be organised grass root innovation projects, and anything in between. They conclude that there is a need for user-centred business models that enable desired roles, for which they sketch out a research agenda.

In Chap. 4, Ellen van der Werff, Goda Perlaviciute and Linda Steg put forth further psychological dimensions to analyse active roles of energy users. Using a review of psychological studies, they identify factors that stimulate so-called 'smart energy behaviour' by individuals and households. Little is known about how different incentives for smart energy behaviour affect each other. Both positive and negative spill-over effects are noted, leading to the 'enabler' or 'barrier' roles discussed in the work of Verbong and colleagues. The processes underlying these effects deserve more attention. Policies stimulating smart energy behaviour need to be aware of people's values, which the authors operationalize in four types: hedonistic, egoistic, altruistic and biospheric sets. The final point in this chapter points to the bridge between psychological and societal dimensions: addressing the biospheric values of individuals appears most effective, provided this is combined with a conducive context, including perceived distributive fairness and trust in the parties involved.

Part 1 ends with Anne Beaulieu's epistemological analysis of smart grids (Chap. 5). Confusion about the nature of new energy systems and the role of smart grids therein is not merely a matter of the developmental stage of the new technologies and their application. Beaulieu discusses the roles of definitions, not by providing an authoritative once-and-for-all definition, but by demonstrating their function in the development of smart grids. "Definitions put forth a reality, foreground and background, include and exclude, assign active and passive roles," she argues. These diverse realities are described in terms of three functions: promissory work, creation of objects and boundary-work. This analysis provides insight in the power of framing inherent in definitions of smart grids, as well as very concrete tools for working across definitions, as is often the case in interdisciplinary work.

In the second part of *Smart Grids in Global Context*, we move from design to control and regulation of smart grids. In seven chapters technical, legal, economic, and societal aspects are discussed. Hassan Farhangi (Chap. 6) kicks off with an analysis of cybersecurity. Smart grids will existentially rely on ICT, and thus get on board the broad agenda of cybersecurity, running from software vulnerabilities for (e.g., hacking or data misuse) to hardware vulnerabilities of its material infrastructure for (e.g., sabotage, bombings or natural hazards). Farhangi moves beyond the general issues by investigating the cyber vulnerabilities in the British Columbia Institute of Technology (BCIT) Smart Microgrid. He analyses it as a potential site for cyber warfare, and concludes that, in face of attack scenarios on critical infrastructure, massive investments in cyber defence are unavoidable.

Part 2 ends with Johannes Kester's Foucauldian approach of the structures and practices that are empowered by the security dimensions of smart grids. "A smart grid is about the delivery *of* power, but there is power *in* and *behind* a smart grid as well," he argues in Chap. 13. He agrees with Farhangi that smart grids are essentially not about electricity but about the infrastructure to deliver it, and, he adds, its owners and operators. Although the smart grid seems to liberalize individual choices about production and consumption, the centralization of information in the energy system may very well move society into an opposite direction. Companies and governments will achieve new powerful positions in the new structures, for better or for worse. The chapters in-between these two analyses of how smart grids will shape vulnerabilities and power (in all sense of the word) further detail the dynamics of control, regulation, privacy and flexibility currently being designed.

Chapter 7, by Bao Nguyen, Desti Alkano and Jacquelien Scherpen, discusses how demand response regulation can be embedded in the market structure of the Universal Smart Energy Framework (USEF). Using distributed model predictive control (MPC) methods, they calculate how the balance between demand and supply can be optimized. Additionally they analyse how innovative storage options like Power-to-Gas can be successfully integrated into the system. With such integration, the electricity grid and the gas grid become physically intertwined. The next step would be to incorporate pricing mechanisms in the system, which are discussed in more detail by Machiel Mulder in Chap. 8.

Mulder focusses first on the present tariff-regulatory frameworks, which were mainly designed to stimulate competition and lower prices for consumers. Environmental and sustainability concerns were not part of the equation. Can they be sufficiently adapted to trigger network operators to make the desired investments to support a shift in the energy sector from a fossil-fuel based to a renewable-based industry? Provided the right circumstances in the wholesale and retail markets, Mulder is optimistic about one form of tariffs: yardstick regulation, a form of price-cap regulation. Experiences in the Netherlands are positive. Productive efficiency can be achieved without negative effects on the performance of the networks.

Energy prices and demand response regulation intend to balance the demand behaviour. But how much unpredictability can the energy system cushion itself? In Chap. 9, Sebastian Trip and Claudio De Persis take on the problem of frequency regulation in power grids in the presence of unknown and uncontrollable generation and demand. They formulate the problem of frequency regulation as an output agreement problem for distribution networks. This is a clear case in which the exchange of information between parts of the grid can lead to new approaches to its control. When the grid also becomes a communication network, new solutions become possible.

Another incentive for studying various aspects of social and technological balancing potentials comes from a game changer in energy transition, which is expected from the massive use of electric vehicles, and electric transportation more generally. Together with distributed renewable energy sources, they add to the balancing problems noticed so far. In Chap. 10 Chris Develder, Matthias Strobbe, Klaas De Craemer and Geert Deconinck investigate demand-response strategies that will be needed to avoid peaks and support balancing in the energy systems. In two case studies they discuss the options for load flattening: the smart grid regulates the charging of electric vehicles, thereby reducing peak demand and moving it away from the present base load peak around 6 pm. The second case shows how the electricity demand of electric vehicles can be used to prevent over-voltage problems caused by irregular electricity supply from renewables. The chapter goes on to investigate three types of algorithms that can be used in these cases: centralized, distributed and aggregate and dispatch algorithms. In terms of scalability and optimality, the distributed algorithms perform best, be it in theory. The authors end by elaborating various simulation tools for further testing.

If Develder and colleagues seek a better interaction between mobility needs and the grid, Lukszo and Park Lee put forth a radical concept, a near fusion of mobility, grid and energy production. They present the ‘car as power plant concept that links mobility needs of drivers, the actual immobility of passenger vehicles that are stationary (parked) most of the time, and the need for flexible energy production. They review the feasibility in technical, organisational, economic and social terms of this use of fuel-cell powered cars, which has the potential for create a decentralised and 'detachable' energy production system.

Chapters 7–11 show that an optimally functioning electric smart grid profits from optimal data sharing and communication. Compared to the classical grids, the uncertainties in supply and demand are many. The more is instantly known about fluctuations or malfunctions, the more sophisticated the algorithms can become, and thus the higher the reliability of the system. This is clearly in the interest of society. Yet, as always, there is a downside: potential misuse of the data. Farhangi (Chap. 6) mentions the commercial interest in knowing consumer behaviour. Kester (Chap. 13) elaborates the more general problem of a society moving from the spectre of 'Big Brother is Watching You' (a centralized tyranny) to the nightmare of 'Many Little Sisters Are Watching You'—an image developed already in 1997 by Manuel Castells. These new forms of power are hard to control. The least we can do is provide legislation that helps to protect people from misuse.

Jonida Milaj and Jeanne Pia Mifsud Bonnici take up one dimension of this challenge in Chap. 12: how does privacy relate to law enforcement use of smart meter data? They investigate this in the context of the European Union and sketch a sobering overview of the existing shortcomings in European legislation. Simultaneously, the literature on the technical and engineering aspects of smart meters shows how tempting it will be for law enforcement agencies to exploit this source of information. Much can be detected from detailed knowledge of a household's electricity use, building a clear profile of a suspect, without the suspect's awareness. But mass surveillance can also be supported by using smart meter data. The EU aims at 80% smart meter use by 2020, but the legal safeguards established thus far by the laws, case law and the doctrine for both service providers and law enforcement authorities do not address the intrusive nature of smart meter data analysis.

In spite of (or should we say: in the face of?) such unsettled aspects of introducing smart grids, many experiments are initiated. Part 3 of this volume takes stock of the lessons learned so far. The authors are reporting field experiences in the Netherlands (Chaps. 14, 15 and 17) and in Denmark (Chap. 16).

Bas van Vliet, Joeri Naus, Robin Smale, and Gert Spaargaren (Chap. 14) present a sociological research agenda to guide existing pilots. They focus on the emerging energy practices in smart energy systems, which they call e-practices. By elaborating Social Practice Theory, they show that existing e-practices at the household level are much harder to change than is often assumed. They are routinized and reflect implicit sets of norms, values and principles which are difficult to address. Specifically relevant is to stop viewing a household as a closed entity or unitary actor. Instead it is "a set of different yet interdependent sub-systems that fulfil specific domestic tasks", including various human agents. This approach is used to analyse interviews with householders in a trial among 45 Dutch households, energy providers and consumer organisations, and survey and interview data on household involvement in two local energy cooperatives. They conclude that the changes in e-practices that did occur redefined the relationships within and between