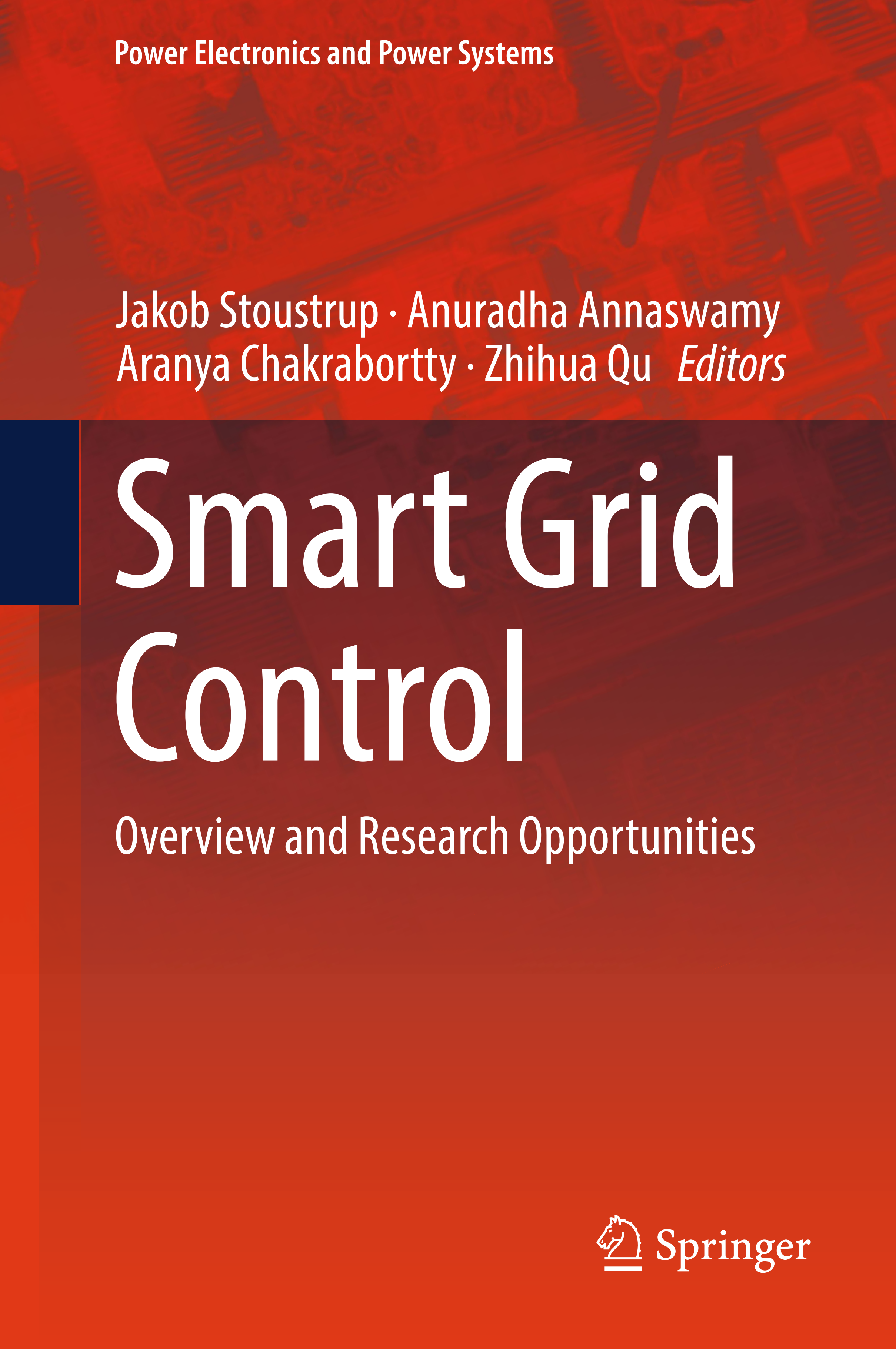

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Jakob Stoustrup · Anuradha Annaswamy
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Smart Grid Control

Overview and Research Opportunities

Springer

Power Electronics and Power Systems

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Foreword I: Smart Grid Control, A Power Systems Perspective

The accelerating shift of energy supply from large central generating stations to smaller producers such as wind farms, solar PV farms, rooftop solar PVs, and energy storage systems, collectively known as distributed energy resources, has far exceeded the expectation of power system experts. Simultaneous to the steep drop in costs of renewable equipment and installations which prompted this rapid pace, intelligent and low-end sensors to measure power variables are also becoming low cost. The confluence of sensors and pervasive computer networks allows for the monitoring and feedback control of power systems at a larger geographical scale and with finer granularity. Previous unobservable remote dynamics are now visible within fractions of a second.

It has been recognized that current power system controls would not be entirely adequate to handle future smart power grid with very high penetration of renewables and long-distance transmission of such sustainable energy. System rotational inertias would be reduced such that frequency regulation would be more challenging. Renewable resources are taken as must-runs at the present time, but their variability poses additional cycling requirements from conventional generators. Allocating sufficient reserves to back up the renewables may be costly and not readily accommodated in electricity markets that were originally designed without considerations of renewable resources. Automation in power control functions also exposes its communication systems to cyber intrusion, with potentially severe consequences.

Recently, many control system researchers have taken a keen interest in examining the control issues in the future power grid and developing novel solutions. A “Smart Grid Vision” document was recently prepared by the IEEE Control System Society, outlining a number of potential control concepts and techniques that can be useful or should be explored to meet the challenges of the future power grid. This volume in the Springer Power Electronics and Power Systems Series is both an update of the earlier vision document, a necessity in this fast changing energy development environment, and an elaboration in more detail some of the areas in which controls can make contributions.

This Springer volume is fortunate to have four leading researchers on control applications in future power grid, Drs. J. Stoustrup, A. Annaswamy, A. Chakrabortty, and Z. Qu, to organize this effort. In addition to providing their own articles, they invited articles from over 20 renowned researchers, not only from control systems, power electronics, and power systems, but also from researchers who are grounded in signal processing, computer networking, optimization theory, and economics. The contributors have been asked to write provocatively and share their best ideas. The articles are divided into four topic areas, each containing a survey article, followed by in-depth discourses of more specific new results and ideas. A reader interested in future power grid control research may benefit from a careful study of one or more of these topic areas.

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Foreword II: Smart Grids and Controls: A Global Perspective

As the world grows more interconnected, we are becoming surrounded by complex networked systems. These systems consist of numerous components interlinked in complicated webs. As a result of the number of components and their intricate interconnections, complex networked systems are extremely difficult to design, analyze, control, and protect. Despite these challenges, understanding complex networked systems is becoming critical. It is in this context that I express my gratitude to the authors and editors of this volume of exceptional work. The *Smart Grid Control: Overview and Research Opportunities*, edited by distinguished colleagues Drs. Annaswamy, Chakrabortty, Qu, and Stoustrup—with peer-reviewed articles written by superb teams of researchers and leaders in this field, is a timely and lasting contribution to the field of smart grid.

From a broader context, worldwide, the electricity infrastructure and service requirements are being dramatically changed to meet the sustainable demand of the twenty-first century. Electricity distribution is generally being challenged worldwide by growing concerns of greenhouse emissions and sustainability, aging infrastructure, and increasing demands for digital quality power. As a result of digital technology and its digitization of society, the nature of electricity generation, transmission, and distribution is undergoing a profound shift emphasized by many smart grid case studies. A fully automated electronically engaged smart grid holds the potential of doubling the consumer service reliability level and significantly improving the energy efficiency. The envisioned smart grid architecture is enabling the electric power industry globally to evolve from the traditional model relying on large centralized power plants owned by utilities to one that is much more diverse in terms of electricity generation, ownership of the assets, and integration of new distributed energy resources.

Associated with this transformation are significant challenges. The resulting system is increasingly interconnected, complex, dynamic, distributed, and nonlinear, with intra- and interconnections with human owners, operators, markets, generating units, flexible consumers, smart storage devices, and smart meters. No single entity has complete control over its operation, nor does any such entity have the ability to evaluate, monitor, and manage it in real time. Performance specifications, as in any critical infrastructures, abound in a smart grid as well. Most notable are Security, Quality, Reliability, and Availability (SQRA) of the overall system. In addition to these, a smart grid needs to have the ability to self-heal following an outage through real-time monitoring by the grid operators to the precursors or signatures of impending faults, using advanced sensor technology including Phasor Measurement Units (PMUs). This provides the potential operators to react swiftly, through rapid isolation, or by restoring balance by manipulating various field devices to respond automatically. What makes the smart grid vision especially difficult to realize is that these performance metrics are linked to multiple operational, spatial, and energy levels distributed across the entire grid.

Besides these multitudinous levels, power systems are also multi-scaled in the time domain, from nanoseconds to decades. The relative time of action for different types of events, from normal to extreme, varies depending on the nature and speed of the disturbance, and the need for coordination. The timescale of actions and operations within the power grid (often continental in scale) ranges from: microseconds to milliseconds for wave effects and fast dynamics (such as lightning or from nanoseconds to microseconds for propagation of the EMP), milliseconds for switching overvoltages, 100 ms or a few cycles for fault protection, 1–10 s for tie-line load frequency control, 10 s–1 h for economic load dispatch, 1 h to a day or longer for load management, load forecasting, and generation scheduling, and several years to a decade for new transmission or generation planning and integration. Given the above compelling drivers for smart grids, the emergence of several new stakeholders, all of whom are highly interconnected, and the fact that they have to be coordinated, at multiple timescales, it is clear that controls take a center stage in smart grids. Control systems are needed across broad temporal, geographical, and industry scales—from devices to systems, from fuel sources to consumers, from utility pricing to demand response, and so on in order to realize the complete smart grid vision.

Across the globe, the foundational and transformative role of controls and systems science has long been recognized and acknowledged in multiple ways. A more recent one is the vision document that I had the honor of coediting with Drs. Anu Annaswamy, Tariq Samad, and Chris Demarco [1] published in 2013, which outlined research opportunities and challenges that smart grids have elicited from the controls community. The second is the articulation of domains and subdomains that come together to lead to the Smart Grid Vision [2] by the IEEE Smart Grid Initiative. Started in 2009, this initiative has become the most successful cross-society endeavor, where all Smart Grid activities carried out by a total of 14 IEEE societies are showcased and disseminated through peer-reviewed webinars, tutorials, monthly newsletters, web portals as tools for collaboration, and compendium of important articles that appear in transactions and magazines of various societies—with participation of over 155,000 members from over 190 nations and territories across the globe. It should be noted that in [2], the role of controls is clearly acknowledged as a foundational support system. I am therefore delighted to see that this important volume precisely captures this key foundational area. The overall volume together with the four areas of electricity markets, wide-area control, distributed control, and cybersecurity capture the loci of controls activities to make the smart grid vision a reality. Together, we can serve this transformative vision/modernization to meet the global needs of twenty-first-century societies. The twin pillars of controls and the broader areas of systems science, two foundational areas of smart grids, enable prosperity and power progress in responsible and sustainable ways, and need your committed engagement, feedback, and support.

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Foreword III: Smart Grid Controls—Visions of the Future

According to the U.S. National Academy of Engineering, electrification was the greatest achievement of engineering in the twentieth century. Electrification is enabled by the electric power grid, a marvel of large-scale, spatiotemporal engineered system that operates with impressive levels of reliability, efficiency, and economy. It is among the most critical civil infrastructures at the center of our way of living.

Indeed, infrastructures are essential to civilization and society. Historically, they have defined the level of development of societies. In addition to the electric grid, water supply and distribution, roads, airports, electric grids, oil and gas pipelines, communications, hospitals, and banking are excellent examples of infrastructures. The Internet is the latest in this collection of our civilization's infrastructures.

Infrastructures result from very large public and private investments. Infrastructure decisions have long-term impacts that stretch for decades and centuries. For example, our current social structure and lifestyle has been shaped by transport system infrastructure decisions made 100 years ago.

The infusion and integration of sensors, communications, networking, computing and control into the traditional hard physical infrastructures is a major transformation whose impact will be felt for decades to come. Among other ideas, "infrastructure-as-a-service" is a key to this transformation. Smart roads, smart cars, and smart electric grids are at the forefront of this transformation as cyber-physical-social infrastructure systems.

While we cannot know the way people will live and work in 2068, we do know that there will be major changes from the way we live and work now. Therefore, the potential for flexibility inherent in algorithm and software-driven cyber-physical-social infrastructures may well turn out to be the greatest value in this transformation.

The recent hurricanes that devastated Puerto Rico, Texas, and Florida are stark reminders of the vulnerability of the critical infrastructures to natural and man-made disasters. With global warming, it is likely that such disruptive events will be more frequent and more extreme. A great promise of the smart electric grids lies in their potential to make the electricity system more resilient. That is, the electric power system can be restored to a certain minimal level of operational performance much more quickly than the current practice. Monitoring and control systems for self-healing in smart grids will be a key to this increased resilience.

Transition to a low-carbon economy is critical for mitigating global warming. For the energy sector, which constitutes 8–9% of the global economy, this requires replacing fossil fuels with renewable sources of energy such as wind and solar electricity generation. These electricity production sources are inherently variable and uncertain and present enormous obstacle to their large-scale integration into the power systems. Whereas availability of cost-effective electric energy storage would be revolutionary and therefore is the focus of large numbers of research efforts, smart grid systems will be essential to the operation of power grids with large-scale deployment of wind and solar electricity and replacement of fossil fuel based energy sources.

Infrastructure systems are not merely technological. They are deeply integrated into societal structures: homes, workplaces, public spaces and therefore in manufacturing, education, health care, entertainment, services, transport, agriculture, etc. Thus, human behavior, as individuals and in groups, is an essential driver of the behavior and performance of infrastructure systems. Smart electric grids are thus an excellent exemplar for "cyber-physical-human" or "cyber-physical-social" systems. Their analysis and design will require much greater integration of insights and knowledge from the social-behavioral-economic sciences for their analysis, design, and operation.

As the various chapters and articles in this book illustrate, control systems engineering and technology will play a central role in the realization of the benefits from investments into smart electric grids. The tutorial chapters provide a nice overview while challenge articles articulate significant challenges and opportunities. With increased uncertainty and variability, there are numerous control and decision challenges faced by market participants as well as system operators in electricity markets, for various energy and grid products and services, where advanced techniques from multistage stochastic control, estimation, prediction and optimization have great potential. With the proliferation of distributed renewable generation, storage, electric vehicles, and smart appliances along with pervasive sensing through (IoT based) sensing systems, there are very interesting and important opportunities for distributed control and optimization algorithms to extract value from these resources while supporting grid reliability and power quality. Wide-area control and monitoring will be enabled by improving communications and greater computing capability over large geographic regions. Finally, cybersecurity is very likely to remain a high priority and continuing and evolving challenge as the smart grid technologies are deployed in the field.

The electric power system is one of the largest engineered networked systems. As a result, the smart electric grid field will offer a rich set of problems and opportunities for networked control systems. Thus, there is great potential for smart electric grids to catalyze new fundamental contributions to the control systems field and contribute to its growth.

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Preface

A smart grid is an end-to-end cyber-enabled electric power system, from fuel source, to generation, transmission, distribution, and end use, that has the potential to (i) enable integration of intermittent renewable energy sources and help decarbonize power systems, (ii) allow reliable and secure 2-way power and information flows, (iii) enable energy efficiency, effective demand management, and customer choice, (iv) provide self-healing capability from power disturbance events, and (v) operate resiliently against physical and cyber attacks. Central to the realization of all of these goals is a control-centric approach. The increased deployment of feedback and communication implies that feedback loops are being closed where they have never been closed before, across multiple temporal and spatial scales, thereby creating a gold mine of opportunities for control. Control systems are needed to facilitate decision-making under myriad uncertainties, across broad temporal, geographical, and industry scales—from devices to systems, from fuel sources to consumers, from utility pricing to demand response, and so on.

The IEEE report [1], "Vision for Smart Grid Controls: A Roadmap for 2030 and Beyond," published in 2013, provided an overview of the role of smart grid control, its loci, possible impact, and research challenges. Fifteen different control topics were identified as those where controls play a dominant part. Given the tremendous state of flux in R&D in all things Smart Grid, it is not surprising that since the publication of the IEEE report, the frontiers of research in Smart Grid in general as well as Smart Grid Control in particular have changed significantly. This volume is an effort to capture the current landscape of this high-intensity research topic, and outline the available research opportunities.

Traditional control topics in power grids were for the most part prevalent in transmission and distribution problems, and focused on transient stability and steady-state optimization. Control problems such as Automatic Generation Control, and volt-VAR control were the most common centers of research activity. The emerging picture of smart grid control is significantly different. One of the biggest drivers of a smart grid is a high penetration of renewable energy resources. A complete integration of these resources introduces a host of challenges of coordination, analytics, information processing, monitoring, optimization, estimation, protection, and resiliency. All of these challenges are control-centric in nature, and require a significantly different set of tools compared to the traditional approaches used for solving control problems in transmission and distribution. These challenges have to be addressed at all subsystems of the grid, starting from generation, through transmission and distribution, to the end user. Faster decisions need to be made in markets, with accommodations of the stochastic elements introduced due to intermittencies and uncertainties in renewables. The underlying communication topology is changing with more stakeholders entering the picture, requiring frequent and reliable communication. The grid periphery is becoming more intelligent, with opportunities to measure, monitor, process information, and communicate decisions. And decisions need to be carried out at several points of the grid, and have to be addressed at multiple timescales, all the way from planning and economic dispatch at a longer time horizon of years, months, days, and minutes to operation at the faster timescales of automatic generation control, droop control, and sub-second transient stability phenomena. At the core of all of these challenges are decision-making, information processing, modeling, optimization, and control. These problems and the underlying approaches that lead to satisfactory solutions all lie completely within the purview of the activities of the Control Systems Society.

Of these large set of problems, four broad topics are worth noting, around each one of which there has been a tremendous level of research activity, and make up this volume. These topics are electricity markets, wide-area systems, distributed control, and cyber-physical security. Markets address planning and operations issues related to economic dispatch, those in wide-area control address large-scale dynamics that arise due to spatial interconnections, those in distributed control address decision-making across the entire grid as its edge intelligence grows, and those in security address all aspects of grid security that need to be addressed as more and more portals open up in the grid to collect information and make decisions. The major R&D challenges in these four topics are outlined below, and form the subject matter for the 17 articles that follow.

1. Markets

Increasing penetration of renewables necessitates new approaches and solutions to the design of electricity markets, many of which are centered around a dynamic perspective. The volatility inherent to wind power producers (WPPs) has posed challenges to the operations of RTOs which have gradually modified their regulations as their reliance on wind power increases. The variability and uncertainty of renewable generation will substantially increase the need for operational reserves to balance supply and demand instantaneously and continuously. Under low adoption of wind power, RTOs have opted for limited regulation and control over the power output of WPPs, allowing them to inject their generation when available, and treating them as negative load. As wind volatility becomes a more significant part of the energy balance problem and causes high congestion costs and significant reliability challenges, this practice has begun to change, with a need for evaluating dynamic market mechanisms to carry out market dispatch.

Another forthcoming challenge is that the total system inertia and contingency reserve capacity decrease as non-dispatchable renewable generation displaces conventional generation. This results in the reduction in the amount of critical operating decisions that need be made from minutes to seconds or even sub-seconds. Therefore, it is becoming extremely difficult for system operators to maintain the stability and reliability of their networks. In order to facilitate the paradigm shift to achieve higher energy efficiency in the future, more flexible and fast acting resources are needed to handle the uncertainties and variabilities introduced by such uncontrollable and intermittent energy resources. Design of forward markets that help guard against risks due to large forecast errors may be needed. How storage can be introduced into the market structure so as to alleviate these forecast errors needs to be investigated.

A prevailing trend to combat the uncertainties on the generation side is to reduce uncertainty on the load side through Demand Response (DR) including methods such as direct load control and transactive control. Systems and control tools that can provide guidelines and foundations for these emerging trends are therefore imperative. An overall framework including models and methods for the quantification and realization of performance metrics such as robustness, resilience, and reliability needs to be developed. The successful demonstration projects on transactive control by the Pacific Northwest National Lab as well as the promising approaches of renewables indicate that there are a number of opportunities for the controls community to develop such a rigorous theoretical framework for integration of DR and renewables into the electricity market. Yet another challenge pertains to the setting up of a retail market, where varied issues need to be addressed including the services provided by aggregators, both of distributed generation and flexible demand, appropriate coordination that ensures economic and physical goals of the distribution grid, and accommodates demand response structures of direct load control and transactive control.

2. Distributed Control

To effectively integrate rooftop PV, storage devices, controllable loads, and other Distributed Energy Resources (DERs), their dynamic changes need to be monitored and, when possible, appropriately controlled or coordinated as much as possible. The changes of renewable generation are stochastic and may be on different timescales than other DERs, and as such the coordination of DER devices requires both spatial diversity and temporal diversity in order to reduce the spinning reserves in the overall power system. In vastly expansive distribution networks, Advanced

Metering Infrastructure (AMI), Internet of Things (IoT), and communication networks can provide local information to enable distributed optimization and controls. Distributed optimization can maximize individual objective functions as well as provide voltage support and other ancillary services. Distributed cooperative control can utilize all the available information to coordinate local control/optimization actions so that a common system optimization/control can be reached. DERs may suffer from issues of low inertia and harmonics, necessitating a systematic deployment of distributed controls to compensate for these shortcomings. The challenges and benefits of designing distributed controls are to take full advantage of local information and achieve the grid-edge intelligence of addressing the distinct prosumers' interests and grid operational requirements.

3. Wide-Area Control

The US Northeast blackout of 2003, followed by the timely emergence of sophisticated GPS-synchronized digital instrumentation technologies such as Wide-Area Measurement Systems (WAMS) led utility owners to understand how the interconnected nature of the grid topology essentially couples their controller performance with that of others, and thereby forced them to look beyond using only local feedback and instead use wide-area measurement feedback. Some of the challenges lie in designing suitable communication networks so as to be able to collect and process very large volumes of real-time data produced by such thousands of PMUs. But several other challenges correspond to control-centric challenges. For example, the impact of the unreliable and insecure communication and computation infrastructure, especially long delays and packet loss uncertainties over wide-area networks, on the development of new WAMS applications is not well understood. Uncontrolled delays in a network can easily destabilize distributed estimation algorithms for wide-area oscillation monitoring using PMU data from geographically dispersed locations. Another major challenge is privacy of PMU data as utility companies are often shy in sharing data from a large number of observable points within their operating regions with other companies. Equally important is cybersecurity of the data as even the slightest tampering of Synchrophasors, whether through denial-of-service attacks or data manipulation attacks, can cause catastrophical instabilities in the grid. What we need is a cyber-physical architecture that explicitly brings out potential solutions to all of these concerns, how data from multitudes of geographically dispersed PMUs can be shared across a large grid via a secure communication medium for successful execution of critical transmission system operations, how the various binding factors in this distributed communication system can pose bottlenecks, and how these bottlenecks can be mitigated to guarantee the stability and performance of the grid.

4. Cyber-Physical Security and Control

While wide-area controls are typically implemented within SCADA, an isolated industrial control system (ICS) with dedicated communication network, a more open and network-enabled control architecture of cyber-physical-human system will become prominent due to the proliferation of PMUs, micro-PMUs, AMI and other IoT/networking technologies, to the expansion of electricity market from the bulk transmission network to distribution networks, and to distributed controls and optimization. The ever-increasing uses of information technology and communication technology make the grid vulnerable to cyber intrusions, false data attacks, and coordinated control/measurement attacks. Various scenarios such as inside attack, denial-of-service attack, switch/breaker attack, interdiction attack, data alteration, and spoofing attack have to be investigated. For each of these potential attacks, defense mechanisms such as enhanced passive/active state estimation algorithms against data attacks should be developed. A systematic design with a layered approach is needed to address monitoring and optimization/control functions at the levels of physical layer, control layer, communication layer, network layer supervisory layer, and market layer. And finally, resilient architectures such as competitive control need to be developed to ensure the overall system dynamic stability in the presence of potential attacks, especially during the period when multilevel monitoring is active and attacks are present but yet to be identified. As attack strategies evolve with more sophistication, defense mechanisms have to be more advanced. All of these challenges fall under the fourth category of cyber-physical security and control.

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Part I
Electricity Markets

Electricity Markets in the United States: A Brief History, Current Operations, and Trends

**Thomas R. Nudell, Anuradha M. Annaswamy, Jianming Lian,
Karanjit Kalsi and David D'Achiardi**

Abstract The global energy landscape is witnessing a concerted effort toward grid modernization. Motivated by sustainability, skyrocketing demand for electricity, and the inability of a legacy infrastructure to accommodate distributed and intermittent resources, a cyber-physical infrastructure is emerging to embrace zero-emission energy assets such as wind and solar generation and results in a smart grid that delivers green, reliable, and affordable power. A key ingredient of this infrastructure is electricity markets, the first layer of decision-making in a smart grid. This chapter provides an overview of electricity markets which can be viewed as the backdrop for their emerging role in a modernized, cyber-enabled grid. Starting from a brief history of the electricity markets in the United States, the article proceeds to delineate the current market structure, and closes with a description of current trends and emerging directions.

1 Introduction

An electricity market enables trade of electricity between suppliers and consumers. An efficient market is one where electricity is traded at a price that minimizes the cost of generation while supplying the demand. The overall market goals are to ensure efficient pricing of electricity generation, incentivize enhanced grid services and infrastructure maintenance. The outputs of the electricity market can, therefore, be viewed as set-points for the actual units that generate or consume electricity. As electricity cannot be stored in large quantities at the current cost of energy storage, the amount of electricity generated must match the demand at every instant of time. It is, therefore, not surprising that electricity markets range over a broad timescale, from years to seconds, to accommodate planning as well as operations. Examples include markets for Forward Capacity, Energy, and Ancillary Services.

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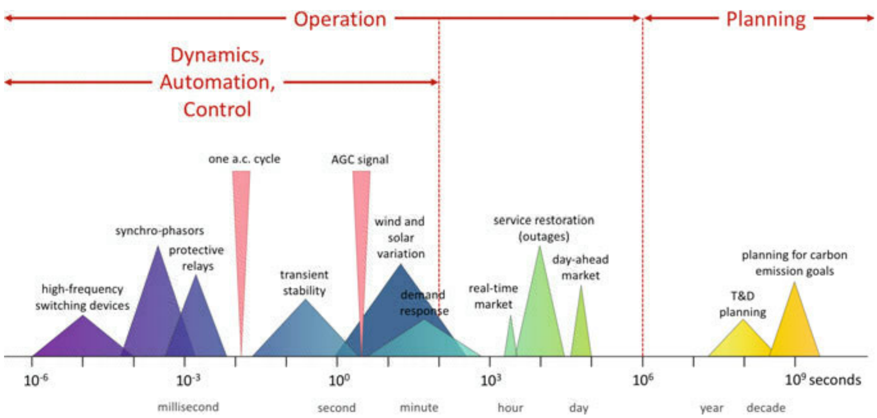

Fig. 1 Illustration of typical planning and operation market timescales (adapted from [55])

While economic theory is the underlying tool utilized in order to govern the principles of electricity markets, such a tool alone is not sufficient, as the products and services transacted in electricity markets have to interact with the physical grid and satisfy its constraints. That is, electricity markets lie in the intersection of two systems, the financial and the physical, which makes their analysis and synthesis highly challenging. What makes it even harder is the current transformation that the grid is witnessing, toward modernization, toward a cyber-enabled architecture, toward a smart grid. This transformation is, therefore, providing a cause for revisiting the electricity market structure, its mechanisms, and its overall coupling with the physical power grid.

Figure 1 shows typical timescales of commonly found markets in the US with respect to other power system planning and operation processes. Because of the multi-year lead times for building electric power plants and transmission projects, planning markets exist in many places in the US in order to ensure that the overall supply of electricity will be able to meet projected demand. Markets that govern operation, termed day ahead (DA) and real-time (RT) markets, ensure that the instantaneous supply of and demand for electric power are balanced in a least-cost manner. The DA market clears a day prior to operation for 24 hourly intervals, while the RT market clears an hour ahead of operation for 5–15 min intervals. Whether in planning or in operations, these markets operate following certain rules and guidelines, which are set by regional transmission operators (RTOs), in accordance with regulators appointed by the government.

In order to set the stage for the impact of the Smart Grid Vision on the market structure, in the following sections, this tutorial seeks to provide an overview of electricity market structure in the United States. A brief history of the electricity market is provided in Sect. 2. An overview of the market structure is delineated in Sect. 3. Some of the major changes that the smart grid paradigm has precipitated are discussed in Sect. 4.

2 A Brief History of Electricity in the US

Since the invention of electricity in the eighteenth century, the evolution of the electricity market can be organized into three parts, the War of Currents and rise of the vertically integrated firm (1880s–1930s) leading up to a viable business model for generating and delivering electricity, the regulated utility (1930–1970), and subsequent deregulation (1970–1990). Each of these parts are described in the sections below.

2.1 War of Currents and Rise of the Vertically Integrated Utility

Subsequent to the understanding of the generation of electricity, the technological battle that ensued pertains to the use of AC (championed by Nicola Tesla) versus DC (championed by Thomas Edison) for power generation and transmission. Edison's support for DC stemmed from the fact that his well-known invention of the light bulb needed a distribution network as a foundation for large-scale expansion, and he believed that low-voltage (110 V) direct current (DC) was the only safe way to distribute electric power. On December 17, 1880, he founded the Edison Illuminating Company and went on to establish the first investor-owned electric utility in 1882 at the Pearl Street Station. From the Pearl Street Station, Edison operated a low-voltage DC "microgrid", which provided 110 V DC to 59 customers in lower Manhattan in New York City [1]. A foil to this technology came from Tesla, who had initially worked for the Continental Edison company tasked with the redesign of Edison's DC generators, and came to believe that many of the DC generators' demerits could be overcome with AC-transmission. The subsequent battle of ideals, now famously dubbed as the War of Currents, would be won by Tesla, and led to a series of US patents that laid the foundation for the AC-alternative to Edison's DC system. These patents were then sold to the Westinghouse Electric Company in 1888. Its owner, George Westinghouse, took advantage of the limited transmission range of low-voltage DC-power, and expanded transmission to beyond urban centers. Subsequently, Westinghouse and his AC distribution system prevailed. The War of Currents ended when Thomas Edison, facing shrinking profits relative to his AC rivals, merged his company with a more successful AC firm, the Thomas-Houston Electric Company, to form General Electric in 1892. Battles between GE and Westinghouse continued for the next few years.

The next step in the development of modern electricity markets in the US was entrepreneurial rather than technological. This step can be attributed to Samuel Insull, who introduced a demand-adjusted billing system in which there were two tiers of prices: one for low demand times and one for high demand times. This strategy increased profits by increasing overall power consumption, allowing the continuous running of base-load plants leading to better returns. Insull's holding companies grew in value to $500 million with a capital investment of only $27 million [68]. The stock market crash of 1929 and the ensuing Great Depression, however, introduced several singularities into the picture leading to a collapse of Insull's enterprise.

The above discussions indicate that economies of scale combined with concerns over reliability led to a firm establishment of the current grid infrastructure of AC generation and transmission. Large, vertically integrated utilities that generated, transmitted, and distributed power—and which were natural monopolies—arose to capture the economies of scale. After the collapse of Insull's company, it also became clear that these natural monopolies required regulatory oversight. This, in turn, led to Congress passing the Public Utility Holding Company Act (PUHCA) in 1935, which enabled state regulation of electric utilities, and gave federal oversight responsibilities to the Securities and Exchange Commission (SEC) and the FPC.

2.2 NERC, FERC, and Deregulation

The rapid expansion of electricity demand over the next few decades led to frequent brownouts in the 1960s, culminating in a massive blackout across the eastern seaboard in 1965, led to the creation of the National Electric Reliability Council (NERC) in 1968 that subsequently became the North American Reliability Corporation [29]. NERC divided North America into several interconnected regions and oversaw these entities to fulfill its mandate of ensuring reliability of the power system.

The energy crisis in the 70s, caused in part by the oil embargo, led to a shortage of natural gas, and rising oil prices. Due to the inefficient oversight of the FPC, Congress reorganized it as the Federal Energy Regulatory Commission (FERC), an independent commission within the newly formed Department of Energy in 1977. FERC worked to develop simpler approval procedures and eliminated the direct oversight of utilities, regulating instead the transmission grid, wholesale markets, and approvals of important mergers and acquisitions in the energy sector.

As a direct response to the energy crisis, Congress enacted the Public Utility Regulatory Policies Act (PURPA) in 1978, which promoted conservation, domestic energy production, and development of efficient co-generation and non-fossil fuel resources. PURPA also opened the market to non-utility generators or independent power producers (IPP) who could produce power at a lower cost than the vertically integrated utility, in which case the utility was mandated to buy this cheaper power and pass the "avoided cost" savings to their customers. This was an important first step toward broader restructuring of the electricity industry [56].

The late 1970s and 1980s saw continued, but gradual, deregulation of the energy sector. The Energy Policy Act of 1992 gave FERC the authority to mandate that a utility provides transmission access to eligible wholesale entities, including wholesale buyers such as large industrial customers and exempt wholesale generators (merchant generators). This was an important step in the development of bulk electricity markets in the US. It is important to note that retail competition and consumer choice, are not, and never were, under the authority of FERC, rather these decisions belong to state legislatures and regulators. Finally, in the 1990s, FERC issued a series of orders that led to modern-day wholesale electricity markets.

FERC Order 888, often referred to as the "open access" rule required utilities to unbundle wholesale generation and power marketing, identified ancillary services required to operate a bulk power system. To achieve the goal of open access, five non-profit Independent System Operators (ISOs) were created, California Independent System Operator (CAISO), New York ISO (NYISO), Electric Reliability Council of Texas (ERCOT), Midcontinent Independent System Operator (MISO), and ISO New England (ISO-NE). FERC Order 889 created the Open Access Same-time Information System (OASIS), which specified standards of conduct that would allow the transmission customers described in Order 888 to have nondiscriminatory access to the transmission grid, which was ensured by wholesale electricity markets run by the ISOs. FERC Order 2000 established guidelines that a transmission entity must meet to qualify as a regional transmission operator (RTO) and required that all public utilities that own, operate, or control transmission networks must "make certain filings with respect to forming and participating in an RTO" [23]. Every US ISO is also designated as an RTO—additional, non-ISO RTOs include PJM Interconnection (PJM) and Southwest Power Pool (SPP)—whose role of RTOs is largely similar to ISOs, but with additional responsibility for the reliable operation and expansion of the transmission grid.

FERC continues to issue rulings to improve market operation and ensure that consumers receive the lowest cost for reliable electricity, notable examples being Order 745 (in 2011) and Order 825 (in 2016). These are discussed in the subsequent sections, and are related to oversight of the emerging concepts of Demand Response and Settlement Reform, respectively.

3 An Introduction to Wholesale Energy Market Operation

Every RTO in the US operates multiple wholesale electricity markets, where various products and services are bought and sold, including bulk energy, financial transmission rights, and ancillary services. In this section, we focus on wholesale *energy* markets. We start by describing market objectives, followed by an introduction to day ahead (DA) and real-time (RT) energy market operation, typical unit commitment and economic dispatch (UC and ED) problem formulation, and, finally, an overview of typical settlement rules. This section is not meant to be a comprehensive guide to market products or operation in any particular RTO, but rather an overview of the energy market operation. The goal of this section is to provide a flavor of the kinds of problems that ISOs formulate and solve today. For details of the DA and RT markets as well as markets for forward capacity and ancillary services, we refer the reader to the publicly available best practice manuals and user guides published by the each [35, 57, 58, 62, 66].