Energy Storage for Smart Grids

Planning and Optimization for Renewable and Variable Energy Resources (VERs)

Pengwei Du, Ph.D. and Ning Lu, Ph.D.

ENERGY STORAGE FOR SMART GRIDS

Planning and Operation for Renewable and Variable Energy Resources (VERs)

Edited by

PENGWEI DU, NING LU

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PREFACE

First and foremost, both editors acknowledge Elsevier for being given this great opportunity to publish a book on energy-storage applications for smart grids. Energy storage is one aspect of the smart-grid revolution that it is taking place in all areas of electric-power systems. The application of advanced storage technologies presents many great opportunities. These include:

- Shaving peak demand, which makes more efficient use of the transmission and distribution systems.
- Facilitating maintenance of aging grid infrastructure and potentially deferring the need for future system improvements.
- Competitively hedging or reducing energy, capacity, and ancillary service costs to load customers (or improving revenues to owners of supply portfolios or storage devices).
- Improving environmental performance through the use of quick-start low-emitting resources.
- Assisting the successful integration of variable renewable resources by providing load following, frequency control, operating reserves, and voltage support.

As wind- and solar-power generation is growing quickly around the world, the variability of these renewable resources poses technical and economic challenges when integrated on a large scale. A variety of energy-storage resources can offer the advantage of flexibility to enhance the reliable, secure, and economic operation of a grid. Thus, energy storage will play a vital role in the integration of large-scale renewable resources, which is the main focus of this edition.

The application of storage technologies to the electric-power system has evolved over time, driven not only by energy-storage technology advancement itself but also by the challenges and issues they attempt to handle. Novel energy-storage technologies continue to emerge from sodium-sulfur batteries, thermal energy storage to other forms of energy capture-and-release technologies, i.e., the aggregation of electric vehicles. The diversity in the forms of energy storage and associated characteristics makes each storage suitable to address one particular challenge/issue imposed by renewable integration, and there is no single energy-storage technology that consistently outperforms the others in various applications.

Essentially, economics is key to storage applications. The economic performance of storage devices is dependent on many factors that affect their penetration and use. New business models should be invented to demonstrate that energy storage is fast, flexible, and more importantly, cost-effective. As the cost of energy storage ($/MW) drops, energy storage will become a more viable solution in a modern grid. On the other hand, we are experiencing the rapid advancement of technology at a time of uncertain structure of the electric-power industry. New market or regulatory rules could bring more dramatic changes to the path of energy storage in the future. For example, the state of California has approved a mandate that will require the state's big three investor-owned utilities to add 1.3 gigawatts of energy storage to their grids by 2020. Federal Energy Regulatory Commission (FERC) order 755 opens up competition in the regulation-service market to energy storage, and requires the non-discriminatory and just payment to all entities. There is also no doubt that reliability and economics are the two necessary ingredients for the successful application of energy-storage technology. To some extent, the reliability benefits from energy storage will be hard to quantify due to the lack of a comprehensive framework. However, this book puts some economic and reliability perspective on the applications of electrical energy storage and presents the latest advanced solutions for integrating energy storage in a smart grid.

This book covers a variety of subjects associated with the application of energy-storage technologies, from distribution systems to transmission networks and from cost-benefits analysis and market design to reliability evaluation. This book does not go into the details of energy-storage fundamentals or design, on which there are already several published books. The purpose of this book is to provide practical engineers a reference for the current state-of-the-art in this area, and thus the book was written for application engineers rather than for a detailed post-graduate college course. The book is organized as follows.

- Chapter 1: "Energy Storage for Mitigating the Variability of Renewable-Electricity Sources" presents a review of the state of technology, installations, and some challenges of electrical energy-storage (EES) systems. It particularly focuses on the applicability, advantages, and disadvantages of various EES technologies for large-scale variable renewable-electricity source (VRES) integration.
- Chapter 2: "Assessment of Revenue Potentials of Ancillary Service Provision by Flexible Unit Portfolios" discusses a new framework to

coordinate energy storage with a variety of other resources like generators and controllable thermal loads, which is collectively referred to as virtual power plants (VPPs).

- Chapter 3: "The Potential of Sodium-Sulfur Battery Energy Storage to Enable Further Integration of Wind" describes a research effort to examine the potential of sodium-sulfur batteries to enable integration of wind for a major utility that has installed a 1 MW/7.2 MWh sodium-sulfur battery in Luverne, Minnesota next to an 11.5 MW wind farm. The energy storage provides generation shifting to serve peak demand and to limit the wind-farm power-output ramp rate.
- Chapter 4: "Application of Energy Storage for Fast-Regulation Service in Energy Market" reviews recent efforts in North America for using energy storages for regulation services and its associated challenges, solutions, and issues.
- Chapter 5: "Impact of Energy Storage on Cascade Mitigation in Multi-Energy Systems" discusses the role of energy storage in preventing the cascade failure of a complex grid. This method proposes a bi-level cascade mitigation scheme within a multiple-energy hub framework that considers both the economic and security objectives in operation of the energy system.
- Chapter 6: "Incorporating a Short-Term Stored-Energy Resource into the MISO Energy and Ancillary Service Market and Development of Performance-Based Regulation Payment" analyzes various approaches to incorporating short-term stored-energy resources (SERs) into the MISO co-optimized energy and ancillary service market.
- Chapter 7: "A Novel Market Simulation Methodology on Hydro Storage" presents a study performed by MISO to evaluate the economic benefits of using a hydro system to facilitate large-scale wind integration. In this study, a simulation methodology is proposed to model the long-term operations of hydro systems in the day-ahead and real-time markets.
- Chapter 8: "Power-System Reliability Impact of Energy-Storage Integration with Intelligent-Operation Strategy" is focused on discussing the reliability improvement of the bulk-power system from the utilization of energy storage in local distribution systems.
- Chapter 9: "Electric Vehicles as Energy Storage: V2G Capacity Estimation" describes how to aggregate electric vehicles as smart energy storage (SES) for leveling the intermittent outputs of renewable-energy sources.

- Chapter 10: "Decentralized Energy Storage in Residential Feeders with Photovoltaics" addresses the role of decentralized energy storage in residential feeders with photovoltaics (PV).
- Chapter 11: "Operation of Independent Large-Scale Battery Storage Systems in Energy and Reserve Markets" considers a scenario where a group of investor-owned independently operated storage units seek to offer energy and reserve in the day-ahead market and energy in the hour-ahead market, which is formulated as a stochastic programming framework.

The application of energy storage will continue to expand as it offers many benefits to the grid. Hopefully, this book will stimulate the development of new solutions/applications and hence enable further exploitation of new revolution for energy storage.

Last but not least, we acknowledge the innovative work contributed by all of the authors in this increasing important area, and appreciate the professional organization – IEEE Power Engineering Society – as a source of invaluable information made available through tutorials, working groups, and panel sessions.

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CHAPTER ONE

Energy Storage for Mitigating the Variability of Renewable Electricity Sources

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1. INTRODUCTION

This chapter provides a survey of applying electric energy storage (EES) for facilitating the large-scale integration of variable renewable electricity sources (VRES), such as wind and solar power, into electric power systems. Large-scale integration of VRES introduces significant uncertainty into operation and planning of electric power systems. Electric energy storage is considered a tool for mitigating the impacts of VRES uncertainty [1] and [2].

In general, several criteria are analyzed when considering and choosing EES technologies for a specific application [3–5]. Those criteria include lifetime, life cycle, power and energy, self-discharge rates, environmental impact, cycle efficiency, capital cost, storage duration, and technical maturity. Based on these criteria, the appropriateness of EES for various applications has been evaluated in the literature, such as, for flexible alternating current transmission systems, small-medium-large-scale applications, system efficiency, emissions control, peak shaving, and deferring facility investments in peaking generators [3–8]. A limited amount of the reported research focuses on the necessary characteristics of EES specifically for VRES applications [4–6]. Nevertheless, other energy-storage literature can be applied for this purpose [8–11]. However, these references can either have a limited scope of EES or be outdated [4,9], and [10]. For example, [4,6], and [10] do not elaborate on battery types, and [4,8,11] are limited to bulk EES only.

In the present chapter, the previous literature is extended by providing an updated review of the state of technology and installations of a broad

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range of EES technologies. The main focus is on applications and appropriateness of each EES technology for mitigating the variability of renewable electricity generation sources. This chapter also includes discussions on important criteria for understanding the potential future of EES technologies, considering the impact of distributed generation, maturity and timing, and world metal resources on EES penetration for VRES applications.

The remainder of this chapter is organized as follows: Section 2 provides an overview of variable renewable electricity sources. Section 3 presents the current state of EES systems, which includes information on current worldwide installations, cost of the technology, and current applications. Section 4 discusses the appropriateness and competitiveness of EES for VRES applications. Finally, Section 5 provides a summary of the chapter.

2. AN OVERVIEW OF VARIABLE RENEWABLE ELECTRICITY SOURCES

With growing concerns about the environmental impacts of the electricity sector, there has been increasing interest to invest in wind and solar power. The 121 GW of global wind-installed capacity in 2008 produced 260 TWh of electricity and saved 158 million tons of CO_2 [12]. It is estimated that the worldwide wind cumulative capacity reached 318 GW in 2013 [12]. In the same year of 2008, nearly 6 GW of new photovoltaic and thermal solar to power installations contributed to the cumulative installed capacity of 14.7 GW [13]. In recent years, installed solar to power capacity has been growing very fast (e.g., 8% growth in 1992 and 46% in 2008), and reached 139 GW in 2013. However, the variable nature of these renewable resources introduces a new source of uncertainty in the operation and planning of electric power systems.

Variations in VRES depend on the size of the evaluated system and the timescale of wind variations. Proportionately, small wind farms tend to have larger expected hourly variation than variations from an entire area. For example, in Western Denmark, it can be reasonably expected that wind power may vary by 3% of its 2400 MW capacity, whereas a 5 MW wind farm in the same area may vary by 12% [14]. VRES timescale variations can be characterized as microscale, mesoscale, and macroscale. Microscale variations primarily affect regulation (seconds to minutes), while mesoscale variations affect the load-following timescale (minutes to hours), and macroscale variations affect the unit-commitment timescale (hours to days). While microscale fluctuations are smoothed to a significant extent across a typical wind-power array, mesoscale and macroscale fluctuations can be