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(导读版)

WIND ENERGY ENGINEERING

风能工程

Pramod Jain



科学出版社

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北 京

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ISBN 978-0-07-171477-8

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北京市版权局著作权合同登记号: 01-2013-2615

图书在版编目(CIP)数据

风能工程=Wind Energy Engineering:英文导读版/(美)杰恩(Jain, P.)著.—北京:科学出版社,2013.7

(国外洁净能源精品著作系列)

ISBN 978-7-03-038064-7

I. 风… II. ①杰… III. ①风力能源-资源开发-英文 ②风力能源-资源利用-英文 IV. ①TK81

中国版本图书馆 CIP 数据核字(2013)第 141188 号

责任编辑:吴凡洁 陈构洪/ 责任校对:陈玉凤
责任印制:张 倩 / 封面设计:耕者设计工作室

科学出版社出版

北京东黄城根北街 16 号

邮政编码: 100717

<http://www.sciencep.com>

源海印刷有限责任公司印刷

科学出版社发行 各地新华书店经销

*

2013 年 7 月第 一 版 开本: B5(720×1000)

2013 年 7 月第一次印刷 印张: 22 1/2

字数: 415 000

定价: 110.00 元

(如有印装质量问题,我社负责调换)



作者简介

Pramod Jain 博士是风能咨询公司 Innovative Wind Energy 的创始人兼总裁。他是风电场规划方面的国际知名专家,参与的项目遍布美国、加勒比海地区和拉丁美洲,有规模小到 100kW 的单机项目,也有装机容量超过 100MW 的风电场;客户包括财富前 100 的公司、美国政府、多所高校、电力部门、市政局与土地开发商。他也是 Wind Energy Consulting and Contracting 公司的合伙创始人兼首席技术专家。Pramod Jain 博士拥有加州大学伯克利分校机械工程博士学位、肯塔基大学硕士学位和孟买的印度理工学院的学士学位。

本书简介

本书详述了如何有效地利用风能这种可行和经济的能源。多学科方法是《风能工程》的特色,其涉及物理学、气象学、空气动力学、风测量、风电机组、电气和并网。书中还讨论了风电项目的规划、选址、成本估算、环境影响和项目管理,配有丰富的图表与数据,是一本关于目前和未来风能开发的权威参考书。

本书包括以下内容:

- ◇ 世界风能产业
- ◇ 风能基础
- ◇ 风与空气的气象学特性
- ◇ 风电叶片空气动力学
- ◇ 风的测量、数据管理与报告
- ◇ 风资源评估
- ◇ 风资源的高级评估,包括尾流、发电量损失与不确定性
- ◇ 风电机组组成部件
- ◇ 电气与电机基础
- ◇ 风电机组并网
- ◇ 风力发电工程的环境影响
- ◇ 风电项目的财务评价模型、规划与执行

(刘永前 译)

导 读

气候变化、化石能源资源枯竭和环境恶化是人类可持续利用能源的主要挑战,而规模化发展风力发电是应对这些挑战的一个必要措施。过去 10 年,全球风力发电产业持续高速增长,风电技术也取得了很大进步,风电正在成为许多国家的主力电源之一。在此背景下,大批工程师投身风电产业,迫切需要大量的关于风能工程的专业书籍。该书正是专门为风能工程师而作的好书之一。

作者 Pramod Jain 博士长期从事风电场的开发,亲身体会到风工程师的需求。更为可贵的是,他勤于思考并具备扎实的理论基础和宽广的知识面。该书具有以下几个特色。

(1) 跨学科。风能工程具有很强的跨学科特征,必须从多学科角度才能正确理解。书中涉及了风能工程中的五大主要学科:气象学、机械与航空工程、土木工程、电气工程和工程环境工程。单一专业背景的工程师可以从其他专业角度了解风能工程,从而更为系统地理解风能工程。

(2) 实用。该书介绍了风能资源测量与评估、风电机组、风电场电气系统、风电场环境评价与财务评价等多个技术领域的工程技术,特别是作者作为亲历者的亲身体会以及丰富的实际案例,可以直接指导风能工程实践。

(3) 易懂。为了让不同专业背景的工程师系统了解风能工程,作者用浅显、形象的语言介绍了风能工程涉及的基础理论,如物理学、流体、电气等。对有些难以理解的理论,作者以其独特的视角给出了浅显易懂的解释,如第 2 章中对贝茨极限的意义的讨论深刻而易懂。

该书第 1 章介绍了风能产业发展概况。第 2~6 章介绍风能工程的基本知识,包括风能与风力发电的基本概念、风能气象学基本知识、风电叶片空气动力学和风的测量等。这些内容是进一步理解风能工程技术的必要基础。第 7~14 章分领域介绍了风能工程专业技术。第 7 章和第 8 章讨论了风资源评估理论和方法。第 9 章介绍了风力发电机组的组成部件,包括风轮系统、机舱系统、塔架和基础系统等。第 10 章和第 11 章介绍了风电场电气工程,包括电与电磁的基本知识、应用于风电机组中的各种类型发电机、风电波动性对电网的影响、风电的并网标准、风电场中的保护要求和风电场集电系统拓扑结构等。第 12 章论述了风力发电项目对环境的影响。首先对比了风力发电与化石能源发电对环境的影响,然后论述了风电的各种环境影响:对野生动物的影响、噪声、视觉美感、阴影闪动等。另外,还讨论了对航空、雷达以及无线电通信的

影响。第 13 章论述了评价风力发电工程的财务模型,阐述了收入、投资和经常性成本的组成,详细介绍了激励政策,特别是美国的税收激励政策,对财务绩效的影响,最后,介绍了评价风力发电工程的财务绩效的方法。第 14 章介绍了风电项目的规划与执行。

该书主要目标读者有 4 类:一是风能产业的工程师,但他们仅专注于风能工程的较窄的专业和学科领域;二是想要进入风能领域的工程师;三是高校本科生和职业技术学校的学生,他们希望学习风力发电工程相关的多学科知识;最后一类是从事风能产业的商人和项目经理。

对于初涉风能产业的读者,建议首先阅读前 6 章,了解风能工程的基础知识和理论。这对于阅读后面的专业章节是必要的。对于在风能工程已经有一定工作经验的读者,可以选择第 7~14 章任何感兴趣的章节进行阅读,而不必按照顺序阅读。

该书不是工程技术手册,但在一些方面可以指导工程实践;不是教科书,但可以帮助读者系统地理解风能工程基本理论;不是学术著作,但在对风能工程理论与技术的理解方面有独到的见解。

刘永前

华北电力大学可再生能源学院

前 言

从研究生阶段起,我就对撰写科技短文产生了兴趣,但却不善此道。那时候,我写的都是晦涩难懂的文章,面向的读者是专家。当我开始为公司写作时,有了转变。而后我投身风能事业,经常撰写公司报告与博客,但是从没想过写一本书。我开始有想法写书要从我的一个挚友 Satya Komatineni 说起,他写了几本 Andriod 系统技术方面的书籍。他鼓励我向 McGraw-Hill 递交出书计划,由此我开始了九个月的写书奇旅。本书的写作过程好比怀孕和生产第一个孩子。尽管我没有体验过怀孕生子,但是我和有此经历的人生活在一起。那是一段兴奋、不安而又痛苦的时光,有时真的痛苦,而最后作品的诞生却会让你忘掉经历的痛苦。

我写这本书的动力源自市面上缺少面向风能工程师的书。我想专门为来自不同学科背景的风能工程师提供有关风能工程的多学科知识。本书旨在提供综合理解风能工程所需的五大相关学科的知识:气象学、机械与航空工程、土木工程、电气工程和环境工程。此外,本书设有与在风力发电工程中起关键作用的财务管理与项目管理两个商业学科相关的章节。

本书面向以下几类读者:一是风能产业的工程师和科学家,但他们仅专注于风能工程的较窄的专业和学科领域;二是想要进入风能领域的工程师与科学家;三是高校本科生和职业技术学校的学生,他们希望学习风力发电工程相关的多学科知识;最后一类是从事风能产业的商人和项目经理。

对于工程师关心的每个技术领域,本书力求翔实。对于涉及的数学知识的水平,我力求控制在工程师可以接受的程度;对于需要复杂的数学方法的地方,我力图提供其内在关系。

和所有书的撰写过程一样,我不得不在书的内容上做出取舍。在本书中没有关于气候变化与能源政策方面的深入探讨和辩论。尽管这些问题对于理解大背景具有重要的意义,但本人不具备撰写这方面内容的特别资质。不过在书中合适的地方,我也简要地讨论了这两个方面的问题。本书不是一本指导风电机组设计的书籍。在风电机组方面,本书局限于阐述主要部件及其功能,不包含复杂的载荷和位移计算,也没有部件的设计。

本书的开篇介绍风能产业,尤其是其爆炸式的增长。尽管这种爆炸式的增长率很难长期保持,但是我依然相信风能产业将会在未来十年保持 15%~20% 的年增长率。基于这一保守的估计,未来几年风能产业将需要大量的工程师、技术员、科学家、项目经理和财务人员。

第2章介绍风能与风力发电的基本概念,讲述了风中蕴含着什么形式的能量、量值是多少,以及有多少能量可以被风电机组吸收利用。

第3章从气象学的角度描述了风的特性。先讲述风是如何形成的,接着描述风速的统计特性、高度对风速的影响,最后阐述了风能随空气密度的变化关系,以及空气密度随气温、气压与空气湿度的变化规律。

第4章应用风电叶片空气动力学,描述了如何将空气中的动能转化为风轮的机械能的原理。这对理解风电机组功能有重要意义。

第5章进一步详细介绍风电叶片空气动力学和如何获得风力机功率曲线。

第6章从能量和空气流动的知识转到测量风的知识。风速测量是风力发电工程中的关键环节,因为任何规模的风力发电工程都需要,同时也是风电项目中历时最长的环节。风的测量是降低风电项目财务评价不确定性的关键步骤。

第7章讨论风资源评估。它是风电项目开发阶段另一个关键步骤。该章介绍了不同的风资源评估方法,如基于公共数据而无现场测量数据的评估方法和对测量数据沿三维空间轴和时间轴外推的方法。

第8章介绍高等风资源评估项目,如极端风速计算、复杂地形及尾流的模型。该章还包括各种风资源评估步骤中引起的发电量损失和不确定性等内容。

第9章介绍风力发电机组的组成部件,包括各种大型风电机组的风轮系统、机舱系统、塔架和基础系统的组成部件。

第10章主要阐述风力发电中的电气部分。在介绍电与电磁的基本知识的基础上,描述了应用于风电机组中的各种类型发电机。

第11章主要阐述风电并网。包括风电波动性对电网的影响、风电的并网标准和风电场中的保护要求。另外介绍了几种风电场集电系统拓扑结构。

第12章主要论述风力发电项目对环境的影响。首先对比了风力发电与化石能源发电对环境的影响,然后论述了风电的各种环境影响:对野生动物的影响、噪声、视觉美感、阴影闪动等。另外,还讨论了对航空、雷达以及无线电通信的影响。

第13章论述了评价风力发电工程的财务模型,阐述了收入、投资和经常性成本的组成,详细介绍了激励政策,特别是美国的税收激励政策,对财务绩效的影响,最后,介绍了评价风力发电工程的财务绩效的方法。

第14章(最后一章)阐述风电项目的规划与执行。这一章将为风电场工程项目管理者在项目开发、施工、试运行与正式运行工作中提供技术指导。

我在写这本书的过程中学到很多。许多我以前认为肯定是对的事情,最后发现是错误的;而许多我曾经自信地向同事与顾客解释的东西,现在看来漏洞百出。因此,我希望这本书同样能帮助您更好地理解风能的利用。

Pramod Jain
(刘永前 译)

致 谢

首先,感谢我的家人。没有我妻子 Shobhana 还有两个可爱的女儿 Suhani 和 Sweta 的支持这本书根本无法完成,我的家庭为此书的写作付出了很多;我感激他们对我全心全意的支持。同时我想感谢我的母亲与两个姐妹 Savita 和 Rekha,感谢她们对我的帮助。

其次,我要感谢 Wind Energy Consulting and Contracting 公司的同事。感谢 Wayne Hildreth,是他把我带进了风能行业。感谢 Glenn Mauney 和 Mike Steinke 帮助我销售我的产品以及给我许多锻炼的机会,感谢其他所有的同事!我在 EMD 的 Per Nielsen 身上学到了不少东西,他总能回答我千奇百怪的问题。帮助我学习风能产业知识的还有:Tim Printy, Kirk Heston, Mark Tippet, Craig White 和 Ralph Wegner。

再者,我要感谢向本书提供数据与图片的公司和机构:Alan Henderson of P&H, Vergnet, Vensys, Bosch-Rexroth, SKF, Vestas, GE, Wind Power Monthly, 世界风能协会, 美国风能协会, Lawrence Berkeley 国家实验室和美国国家可再生能源实验室。

我还要感谢 IEC 委员会允许我复制 IEC 61400-1 ed. 3.0 (2005) 标准,该标准版权属于瑞士日内瓦的 IEC 委员会,详细内容见 www.iec.ch。IEC 对作者复制的摘录和内容的安排及语境不负有责任,并对这方面的其他内容和准确度不负有任何责任。

最后,我感谢 McGraw-Hill 出版社接受我的出书计划,并帮助我编辑和出版。

(刘永前 译)

Preface

I have been interested in writing short technical articles from my graduate school days. I was never good at it. In those days, I supposedly wrote dense stuff, and the audience I had in mind were experts in the field. This changed as I wrote for a corporate audience. When I got into the wind business, I wrote white papers and blogs regularly but never considered writing a book. The idea of writing this book came to me from a dear friend Satya Komatineni, author of books on Android. He encouraged me to send a proposal to McGraw-Hill about the book. This led me down to a nine-month long adventure. The best metaphor to describe the adventure is that writing a book is akin to the nine-month process of gestation and birthing of the first child. Although I have not personally experienced it, I have lived with someone who has. It is exciting, uncomfortable, painful, at times really painful, and in the end, the product makes you forget the pain.

The impetus for writing this book was the lack of books on the market that targeted engineers. Specifically, I wanted to write a book that would give an engineer, from any discipline, sufficient knowledge about the multidisciplinary field of wind energy. This book intends to bring to bear at least five disciplines in order to provide a reasonably comprehensive understanding of the field of wind energy. The five disciplines are meteorology, mechanical and aeronautical engineering, civil engineering, electrical engineering, and environmental engineering. In addition, to these core engineering disciplines, the book has chapters on finance and project management, two business-related disciplines that are key to wind energy.

I wrote the book with the following audiences in mind. First are engineers and scientists in the wind industry but who practice in a narrow segment of the industry that covers their specific discipline. Second are engineers and scientists who want to enter the wind industry. Third are undergraduate engineering students and technical college students who want to learn about the various disciplines in

wind energy engineering. Finally, another intended audience is comprised of business people and project managers who work in the wind energy industry.

Engineers will find sufficient detail about each of the topics. I have kept the math to a level that would be comfortable for a practicing engineer. In areas that require sophisticated math, I have attempted to provide insights into the relationships.

As with any endeavor, I had to make decisions about what to include in the book and what to leave out. I chose to leave out of the book discussions and debates about climate change and energy policy. Although these are critical to understanding the big picture, I am not particularly qualified to write about these issues. Wherever appropriate, I have briefly discussed these two topics. This book is not an engineering design manual for turbines. The exposition on turbines is limited to describing the major components and their functions; it does not cover the complexity of computing forces and displacements nor design and engineering of the components.

The book starts with a brief description of the wind energy business with an emphasis on the explosive growth witnessed by the wind energy industry. Although such an explosive growth rate is difficult to sustain for long periods, I believe that the wind industry will experience sustained 15 to 20% growth over the next decade. On the basis of this conservative estimate, there will be a healthy demand for engineers, technicians, scientists, project managers, and financiers for years to come.

The second chapter of the book introduces readers to the concepts of energy and power, what kind and how much energy is contained in wind, and how much of it can be captured by a wind turbine.

The third chapter describes properties of wind from a meteorological perspective. It starts with a description of how wind is generated. Next, the statistical nature of wind speed is described, followed by the impact of height on wind speed. The chapter then concludes with dependence of wind energy on air density and dependence of air density on temperature, pressure, and humidity.

The fourth chapter describes the mechanics of how wind energy is converted into mechanical energy using aerodynamics of blades. This is important in order to understand the functioning of a wind turbine. The fifth chapter presents a more detailed exposition on the aerodynamics of blades and how power performance curves of turbines are created.

The sixth chapter switches from the science of energy and airflow to the science of measurement. Measurement of wind speed is a crucial step in a wind project because all utility scale projects require it, and

in most cases, it is the longest duration task. Measurement is a key step in reducing uncertainty related to the financial performance of a wind project.

The seventh chapter deals with wind resource assessment. It is another pivotal step in the development phase of a wind project. In this chapter, different methods of assessment are covered, from methods based on publicly available wind data and no onsite measurements, to methods that extrapolate measured data along three spatial axes and the temporal axis. In the eighth chapter, advanced wind resource assessment topics such as computation of extreme wind speed, and modeling of rough terrain and wake are described. Losses and uncertainty associated with the various components of wind resource assessment are also covered in this chapter.

The ninth chapter describes the components of a wind turbine generator. The rotor system, nacelle, and tower and foundation systems are described. The components of these three systems are described for different types of utility scale turbines.

The tenth chapter deals with the electrical side of wind energy. Basic concepts of electricity and magnetism are covered followed by description of various types of generators used in wind turbines. In the eleventh chapter, the integration with an electricity grid is described. It covers how the variability of wind energy is incorporated in the grid, the grid interconnection standards, and the protection systems required in a wind farm. In addition, several topologies of wind farm from an electrical standpoint are explained.

The twelfth chapter covers the environmental impact of wind projects. It begins by setting the context for relative impact relative to fossil fuel-based generation. In the chapter, each of the environmental impacts: wildlife, noise, esthetics, shadow flicker, and others are described. In addition, impact on aviation, radar, and telecommunications are described.

The thirteenth chapter describes financial models used to evaluate wind energy projects. In this chapter, the various components of revenue, capital costs, and recurring costs are described. The impact of incentives, in particular tax incentives in the United States, on the financial performance is detailed. Finally, the financial performance measures used to evaluate wind projects are described.

The fourteenth and final chapter describes planning and execution of wind projects. This chapter will serve as a guide to project managers of wind energy projects during development, construction and commissioning, and operations.

I learned a lot while writing this book. There were quite a few things that I was certain were true but which turned out to be not so

true. There were more things that I had explained with confidence to colleagues and clients, which turned out to be full of holes and superficial, at best. I hope the book serves a similar purpose in helping you to better understand wind energy.

PRAMOD JAIN

Acknowledgments

The first acknowledgment goes to the family. This book would not have been possible without the support of my wife Shobhana and two wonderful daughters Suhani and Sweta. The book took a significant toll on the family; I am grateful for their wholehearted support and backing. I also want to thank my mother and sisters Savita and Rekha for their support.

The second acknowledgment goes to my colleagues at Wind Energy Consulting and Contracting, Inc. I am grateful to Wayne Hildreth, who got me into the wind industry and Glenn Mauney and Mike Steinke for helping me to sell the products to clients and giving me the opportunity to hone my skills and to all the other colleagues. I learned a lot from Per Nielsen of EMD, who always responded to my strangest queries. Other people that helped me learn about the various facets of wind industry are Tim Printy, Kirk Heston, Mark Tippet, Craig White, and Ralph Wegner.

The third acknowledgment goes to companies that shared pictures and data for the book including Alan Henderson of P&H, Vergnet, Vensys, Bosch-Rexroth, SKF, Vestas, GE, WindPower Monthly, World Wind Energy Association, American Wind Energy Association, Lawrence Berkeley National Lab, and National Renewable Energy Lab.

Next, I would like to thank the International Electrotechnical Commission (IEC) for permission to reproduce Information from its International Standard IEC 61400-1 ed.3.0 (2005). All such extracts are copyright of IEC, Geneva, Switzerland. All rights reserved. Further information on the IEC is available from www.iec.ch. IEC has no responsibility for the placement and context in which the extracts and contents are reproduced by the author, nor is IEC in any way responsible for the other content or accuracy therein.

Finally, I want to thank McGraw-Hill for accepting my proposal for the book and helping me with the editing and publishing process.

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