

WIND TURBINES

In the multi-disciplinary field of wind energy, students and professionals can often be uncomfortable outside their own specialist areas. This essential textbook explains, in a single readable text, the key aspects of wind turbine technology and its application. Covering a broad range of multi-disciplinary topics, including everything from aerodynamics to electrical and control theory, structures, planning, economics, and policy, this reference is an excellent toolkit for undergraduate students, postgraduate students, and professionals in the field of wind energy. Key concepts, including more challenging ones, such as rotational sampling of turbulence, vortex wake structures, and reactive power management, are explained using clear language and simplifying illustrations, including experimental graphs, photographs, and line drawings.

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WIND TURBINES
Theory and Practice

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PREFACE

This book offers a broad overview of wind energy technology, explaining the principles underlying the design, manufacture, and operation of modern wind turbines. The scope and content are based on a master's course I have taught at Edinburgh University since 2009, which has been continually updated in an attempt to keep pace with the evolution of the technology. To write a book about 'contemporary' wind turbines is, however, to offer a hostage to fortune. By the time it is published, it will be out of date, so references to the most powerful turbine, the longest blade, or the largest offshore array must carry the proviso 'at the time of writing'. So be it; but over the past few decades, the evolution of wind turbine technology and the increase in its worldwide reach have been quite breathtaking, and they show little signs of slowing. Wind power has firmly passed from alternative to mainstream.

The target readership for this book is the undergraduate or postgraduate student, professionals new to the field of wind energy, or anyone already working in it who seeks background reading outside his or her own specialism. Although a reasonable understanding of physics or engineering is required for some of the material, the level of mathematics is not severe, with illustrations and graphics used to clarify difficult concepts. I have tried where possible to illustrate key topics with examples from my own experience in the wind industry, in which I am fortunate to have been working since the mid 1980s. In this time I am privileged to have worked for the first UK manufacturer of large wind turbines, one of the earliest businesses to install a turbine for its own use, and the first community in Scotland to develop and own a grid-connected windfarm. These experiences have all been drawn on in the book, and I hope that in each chapter, the reader will either learn something new or understand better something already known.

CHAPTER OVERVIEW

Note. If this book is to be used as a course text, then the chapters should ideally be read in order, although the first and last can be read in isolation. There are example exercises at the end of each chapter; most are of exam standard, but a few (based on real situations) are included as examples in problem solving. For general readers or researchers who wish to explore more deeply the topics touched on in the book, there is a comprehensive reference list at the end. The following is a chapter summary.

Chapter 1 is a brief review of the trajectory of wind power from the pre-electric era through to the modern day. A recurring theme is that development of the technology has historically been driven by energy security. The chapter also relates how sophisticated measurements of rotor aerodynamic loads were being made 70 years before Michael Faraday built the first electric generator. Chapter 2 describes the origin and characteristics of the wind. Topics such as wind

shear and turbulence are illustrated with site measurements, and the chapter includes an example of some thought provoking wind conditions recorded during a severe storm in the Outer Hebrides.

Chapter 3 is a refresher on aerodynamic theory. It includes the basic mathematical development of blade element momentum theory and a qualitative description of the more complex but also more physically realistic vortex wake theory. There is a comparison of wake measurements from full-scale and model wind turbines; vorticity data from the latter verify the predictions of vortex wake theory with images that would not be out of place in a gallery of modern art. Chapter 4 extends the aerodynamic discussion to show how net rotor loads (thrust, torque, and power) and the dimensionless C_p, λ curve are derived. The relationship between optimum blade solidity and tip speed ratio and the influence of blade pitch are explained, leading to the broader discussion of rotor aerodynamic control in Chapter 6.

Chapter 5 meantime deals with electrical issues and is broadly divided in two. The first half explains the operating principles of the different types of generator (there are several) found on wind turbines and their influence on dynamics and electrical power quality. The second half deals with electrical networks and further examines the issue of power quality; the role of reactive power, and how generators can manipulate it (some better than others) to aid voltage stability, is explained. The role of statcoms, SVCs, and pre-insertion resistors is discussed. Chapter 6 then examines the subject of wind turbine control, drawing together material from the preceding three chapters. The main topic is real-time power limiting, with explanations of stall regulation, constant-speed variable pitch (CSVP), and variable-speed variable pitch (VSVP) control. A comparison of the control accuracy of CSVP and VSVP strategies is made using power measurements from full-scale wind turbines.

The subject of Chapter 7 is structural loading and response. A recap on the dynamics of a single degree of freedom system leads into a discussion of multi-DOF systems and modal analysis. The cyclic loads affecting a wind turbine structure are described, with explanations of stochastic and deterministic loading and the principle of aerodynamic damping. The last part of the chapter draws on an early experimental campaign in which the dynamic loading on a full-scale wind turbine was measured and compared with a modal simulation. Results from these trials also demonstrated the difference in rotor loading arising from positive and negative pitch control. The chapter concludes with a brief summary of fatigue prediction.

Chapter 8 is an overview of rotor blade technology, covering structural design, manufacture, and testing. The material properties of glass fibre- and carbon fibre-reinforced plastics and wood-epoxy laminate are compared, and their superiority to metals is explained. Blade stresses are analysed using a simple cantilever beam model, with bending moment theory modified for composite structures. Blade manufacture using the vacuum resin infusion (VRIM) process is illustrated and described, and different blade root attachment methods are compared. The chapter concludes with a look back at the ten-fold scaling of wind turbine rotors that has occurred in the modern era and how it was achieved without subverting the fundamental laws of physics.

Chapter 9 steps away from the wind turbine to consider the external factors involved in siting and construction for onshore wind projects. The measure-correlate-predict (MCP) procedure

for site wind assessment is described, and analytic models for wake loss and added turbulence are illustrated with experimental data from large and small arrays. The second half of the chapter looks at construction: topics include foundations, transport and access, and wind turbine erection. Some novel examples include rock anchor foundations that require almost no concrete and turbines that have been winched into place without using cranes.

Chapter 10 is an overview of the planning and environmental issues that attend onshore wind turbine developments, including ecological factors (birds and mammals), public acceptance (noise, visual impact), and safety. Examples are given of the type of information required in UK planning submissions but of generally wider application. The origins and treatment of wind turbine noise are dealt with in detail, and some simple rules are given for noise prediction. The chapter also considers impacts on other human activities, including radio-frequency communications, aviation, and radar. The principle of a radar-absorbing ‘stealth’ blade is described: such blades have recently been developed and put into windfarm service.

The final chapter (Chapter 11) addresses economic and political aspects; it is not overtly technical and may hold some interest for those working in the field of energy policy. The standard formula for the cost of generation, the levelised cost of energy (LCoE), is given in full and simplified forms. Historic installation costs from the UK onshore and offshore sectors are presented from 1990 to the present day and used to calculate LCoE at representative capacity factor and discount rates. A section on ownership considers two case studies. One examines the economics of self-supply for a business whose electricity demand is largely met by its own windfarm; the statistics for consumption, export, and balancing for this case usefully predict the impact of wind power at a national level. The second case study considers the Isle of Gigha community windfarm, which is an interesting technical story in itself, but informs a wider debate about ownership and public acceptance. The concluding section is on UK wind energy policy, past and (at the time of writing!) present.