OFFSHORE WIND ENERGY TECHNOLOGY

OLIMPO ANAYA-LARA | JOHN O. TANDE
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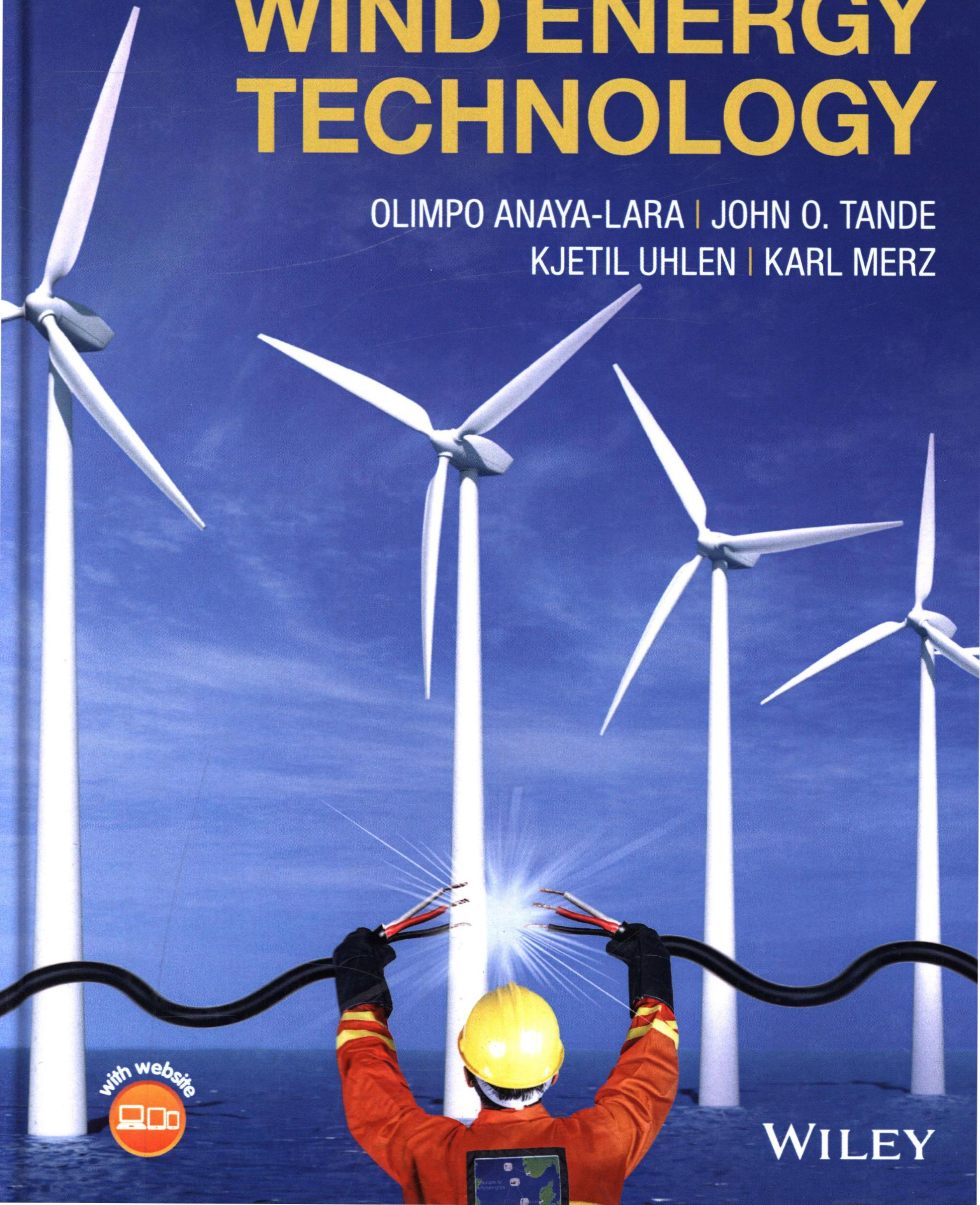

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A COMPREHENSIVE REFERENCE TO THE MOST RECENT ADVANCEMENTS IN OFFSHORE WIND TECHNOLOGY

Offshore Wind Energy Technology offers a reference based on the research material developed by the acclaimed Norwegian Research Centre for Offshore Wind Technology (NOWITECH) and material developed by the expert authors over the last 20 years. This comprehensive text covers critical topics such as wind energy conversion systems technology, control systems, grid connection and system integration, and novel structures including bottom-fixed and floating. The text also reviews the most current operation and maintenance strategies as well as technologies and design tools for novel offshore wind energy concepts.

The text contains a wealth of mathematical derivations, tables, graphs, worked examples, and illustrative case studies. Authoritative and accessible, *Offshore Wind Energy Technology:*

- Contains coverage of electricity markets for offshore wind energy and then discusses the challenges posed by the cost and limited opportunities
- Discusses novel offshore wind turbine structures and floaters
- Features an analysis of the stochastic dynamics of offshore/marine structures
- Describes the logistics of planning, designing, building, and connecting an offshore wind farm

Written for students and professionals in the field, *Offshore Wind Energy Technology* is a definitive resource that reviews all facets of offshore wind energy technology and grid connection.

OLIMPO ANAYA-LARA is a Reader in the Wind Energy and Control Centre at the University of Strathclyde, Glasgow, UK.

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Offshore Wind Energy Technology

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Erin E. Bachynski has been an Associate Professor of marine structures in the Department of Marine Technology at the Norwegian University of Science and Technology (NTNU) since 2016. She holds bachelor and masters degrees in naval architecture and marine engineering from the University of Michigan, and a PhD from NTNU, with a thesis titled 'Design and Dynamic Analysis of Tension Leg Platform Wind Turbines.' Associate Professor Bachynski's main research areas are numerical and experimental modelling of offshore wind turbine structures, including hydroelasticity, nonlinear wave loads and structural response modelling. Previous projects include development of numerical simulation tools for offshore wind turbines, including consideration of the faults, drivetrain responses, and higher-order hydrodynamic loads, as well as real-time hybrid testing of a semisubmersible wind turbine.

David Campos-Gaona received his PhD degree in electrical engineering from Instituto Tecnológico de Morelia, Morelia, México, in 2012. From 2014–2016, he was a Postdoctoral Research Fellow with the Department of Electrical and Computer Engineering, University of British Columbia, Vancouver, Canada. Since August 2016, he has been a Research Associate with the University of Strathclyde, Glasgow, UK. His research interests include wind farm power integration, HVDC transmission systems and real-time digital control of power-electronic-based devices. Dr Campos-Gaona has been author/co-author of one book, seven journal papers and several conference papers in the area of electrical engineering and wind power systems.

Elin Espeland Halvorsen-Weare is a Research Scientist in the Maritime Transport Systems group at SINTEF Ocean, department of Maritime. She earned her MSc in Industrial Economics and Technology Management in 2007 and her PhD on Maritime Fleet Planning and Optimization under Uncertainty in 2012, both from the Norwegian University of Science and Technology (NTNU). Between 2011 and 2014 she held a position as postdoctoral fellow on the topic of discrete optimization methods for transportation problems at SINTEF ICT. Dr Halvorsen-Weare has mainly been working on optimization problems related to maritime logistics, but her interests also cover other related problems within transport and logistics. Her focus is on a broad range of solution methods, including exact optimization techniques, heuristics and multi-objective optimization and how to treat uncertainty in real-life logistic problems for the maritime industry.

Sung-ho Hur received a BEng degree in Electronics and Electrical Engineering (EEE) from the University of Glasgow in 2004 and an MSc (with Distinction) in EEE from the University of Strathclyde in 2005. He then worked as a research assistant in the Industrial Control Centre (ICC) within the Department of EEE at the University of Strathclyde before undertaking a PhD at the ICC in 2006. During his PhD, he conducted research on modelling, cross-directional control and fault monitoring of DuPont Teijin Films' plastic film manufacturing process. Since completing his PhD in 2010, he has been working as a Research Associate in the ICC, researching in control, modelling and anomaly detection of wind turbines and farms. Sung-ho Hur's primary research interests include control, modelling and condition monitoring, with particular interest in wind turbines and farms. Further interests include cross-directional processes, such as plastic film manufacturing processes.

William E. Leithead leads the wind energy research group and is the Director of the Industrial Control Centre at the University of Strathclyde. Professor Leithead is the Chair and Management Hub of the EPSRC Supergen Wind Energy Technologies Consortium. He is the Director of the EPSRC Centre for Doctoral Training in Wind Energy Systems and is also a member of the Executive Committee of the EPSRC Industrial Doctoral Centre in Offshore Renewable Energy. He is a member of the European Academy of Wind Energy Executive Committee, European Energy Research Alliance Joint Programme Wind Steering Committee, Scientific Advisory Board of the Norwegian Centre for Offshore Wind Technology (Trondheim), Scientific Advisory Board of the Norwegian Centre for Offshore Wind Energy (Bergen), Strategy Advisory Group of the Energy Technology Institute, Energy Technology Institute Wind Strategy Advisory Group and Wind Energy Coordinator of the Energy Technology Partnership. His research interests in wind energy include the dynamic analysis of wind turbines, their dynamic modelling and simulation, control system design and optimization of wind turbine design. Professor Leithead has strong links to all aspects of the wind energy industry and has been involved in many collaborative projects related to the design of controllers and wind turbines. He has been the recipient of more than 40 research grants and is the author of more than 200 academic publications.

Karl Merz has been a researcher in the field of offshore renewable energy since 2008. His PhD thesis was on the design of optimal stall-regulated rotors for offshore wind turbines. After joining SINTEF Energy in 2012, he has focused on the dynamics and control of offshore wind turbines and power plants. Highlights include the design of a control system for the Deepwind floating vertical-axis wind turbine and the development of the STAS wind power plant analysis program, which is a unified state–space model including aerodynamic, hydrodynamic, structural, electrical and control systems. Prior to his career in renewable energy, Karl Merz worked at Boeing Commercial Airplanes, where he developed analysis methods used to design and certify composite structures on the 787 aircraft.

Amir Rasekhi Nejad is an associate professor at the Marine Technology Department, Norwegian University of Science and Technology (NTNU). He lectures 'Machinery and Maintenance', 'Wind Energy' and 'mechatronics' courses at NTNU. Prior to joining NTNU, he worked in different industries, such as industrial machinery design, mechanical power transmission systems, gear industry, offshore oil and gas and third party design verification, for more than ten years. He has carried out extensive research on drivetrains in offshore wind turbines, both fixed and floating ones. His current research interests include design, dynamic modelling, reliability analysis, fault detection and condition monitoring of mechanical systems in marine and renewable applications. Dr Nejad holds a PhD in Marine Engineering, MSc in Subsea Engineering and BSc in Mechanical Engineering. He is a member of the 'Norwegian Standard committee on vibration and shock' and 'ISO committee on condition monitoring and diagnostics of wind turbines'.

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Lars Magne Nonås is a Senior Research Scientist in the Maritime Transport Systems group at SINTEF Ocean, department of Maritime. He holds an MSc in Optimization from the Department of Informatics, University of Bergen (2002), and gained his PhD in Operational Research at the Department of Finance and Management Science at the Norwegian School of Business (NHH). Lars Magne Nonås has over 10 years of national and international research experience within maritime transport and logistics problems (shipping, oil and gas, and offshore wind), and nine years within the offshore wind industry. His research interests and expertize include heuristics and optimization methods applied towards practical decision problems.

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Iver Bakken Sperstad is a Research Scientist in the Power System Asset Management group at SINTEF Energy Research, department of Energy Systems. He holds a PhD in theoretical and numerical physics from the Norwegian University of Science and Technology. Since joining SINTEF in 2012, he has been working on simulation modelling of operation and maintenance and logistics of offshore wind farms, and he has been the lead developer of the strategic decision support tool NOWIcob since 2014. He has also been involved in international collaborations on LCOE calculation (through IEA Wind Task 26 Cost of Wind Energy) and comparison, verification and validation of strategic operation and maintenance decision support tools. Other research interests include power system reliability, vulnerability and optimization of energy storage systems.

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John O. Tande is Chief Scientist with SINTEF Energy Research and Director of NOWITECH, a EUR 40 million (2009–2017) research cooperation on Offshore Wind Technology (www.nowitech.no). He is also heading the subprogramme on offshore wind energy within the European Energy Research Alliance and is a Steering Committee member of the European Technology and Innovation Platform ETIP wind. He has more than 20 years experience within the field of wind energy research, with a focus on grid integration and offshore technology. He graduated from the Norwegian University of Science and Technology in 1988 and has since worked in Denmark and Norway. He has been with SINTEF Energy Research since 1997.

Kjetil Uhlen is Professor in Power Systems at the Norwegian University of Science and Technology (NTNU), Trondheim, and a Special Adviser at STATNETT (the Norwegian TSO). He has an MSc (1986) and PhD degree (1994) in control engineering. His PhD work was on design and control of autonomous wind–diesel systems with battery energy storage. Research on wind power integration in the power system was also a main activity while working for SINTEF Energy Research until 2009. As professor at NTNU his main responsibility has been research and education related to power system stability and control. Recent focus has been on the development and implementation of applications based on Phasor Measurement Units (PMUs) in operation and control. As special advisor at STATNETT, a main goal has been to enable the deployment of R&D results in this area into the control room environment. Kjetil Uhlen has been a member of the IEEE since 1993 and has been co-editor of the *IEEE Transactions on Power Systems*. He was the Norwegian member of CIGRE Study Committee C4, 'System technical performance' (2004–2012), convener of Advisory Group C4.6, 'Power system security assessment' (2004–2010) and CIGRE Working Group WG C4.603, 'Analytical techniques and tools for power balancing assessments' (2009–2015).

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Foreword

Wind energy is playing an increasingly vital role in the efforts to decarbonise European and international energy systems. Power grids have seen a strong increase in wind power penetration, enhanced through the development of very large offshore wind farms consisting of hundreds of multi-MW wind turbines. To optimally exploit these very valuable assets, all aspects of the design, operations and maintenance will need to be tightly integrated, and the strategies and algorithms required to achieve optimality will need to be developed.

Since its creation back in 2009, I have followed NOWITECH activities and given advice on its direction through my participation in its Scientific Committee. NOWITECH facilitated an intense cooperation between outstanding researchers (postgraduate students and academics) and strategic industry partners maintaining at all times a strong connectivity with research organisations and programmes in Norway and internationally.

Being an international precompetitive research cooperation with the required depth of experience and breadth of expertise on offshore wind technology, NOWITECH was ideally placed to successfully conduct innovative research on all relevant aspects of offshore wind technology aiming to maximise energy production, minimise downtime, reduce operational and maintenance costs and extend lifetime. This book presents first-class material on some of these aspects.

It gives me great pleasure to write the Foreword for this timely book. I am confident it will be of great value to students, practising engineers and the offshore wind industry as a whole.

Peter Hauge Madsen
Head of Department
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Preface

The motivation for this book is the rapid growth of offshore wind energy systems and the implications this has on power system operation, control and protection. Developments on wind turbine technology and power electronic converters along with new control approaches have enabled offshore wind energy systems performance to be improved. The authors identified the need for a book that covers up-to-date issues on this dynamic topic. This reference book is based on research material developed by the Norwegian Research Centre for Offshore Wind Technology (NOWITECH)[1] and teaching material developed by the authors over the last 20 years. It is useful to final year undergraduate and postgraduate students, and also practising engineers and scientists in the offshore wind industry. The book addresses offshore wind farm electric design, substructure and foundation design, operation and maintenance modelling, turbine and park control, offshore transmission and power system integration.

The book is organized into eleven chapters. In Chapter 1 the reader is presented with a brief overview on offshore wind developments and further introduced to the topics of the book. Chapter 2 provides a general description on the various topologies of wind turbine generators, main components and capacity sizes. Enhanced power electronic converters for wind turbine generators are also presented. A thorough review of modelling and analysis of drivetrains in offshore wind turbines are presented in Chapter 3 while support structures for offshore wind turbines, that is substructures and foundation, are covered in Chapter 4, which also provides a classification of wind turbine substructure based on water depth covering both bottom-fixed and floating support structures. Chapter 5 addresses the problem of controlling large bottom-fixed offshore wind turbines. In order to make the material broadly accessible, we stick to relatively simple control algorithms and focus on the interplay between the controls and the dynamic response of the wind turbine. Alternative electrical designs of an offshore wind farm are presented in Chapter 6, covering topologies and protection aspects. Chapter 7 provides an overview of, and a brief introduction to, operation and maintenance (O&M) modelling for offshore wind farms, including transportation and logistics for O&M.

1 NOWITECH's objective is international precompetitive (2009–2017) research cooperation on offshore wind technology established as part of the Norwegian Centres for Environment-friendly Energy Research (FME) scheme and cofinanced by the Research Council of Norway, industry and research partners. NOWITECH is hosted by SINTEF Energi AS with SINTEF Ocean, SINTEF Stiftelsen, Norwegian University of Science and Technology (NTNU) and Institute for Energy Technology (IFE) as research partners (www.nowitech.no).

The main focus of the chapter is on strategic O&M modelling. Chapter 8 describes the main objectives of supervisory control, namely: maximize energy production; minimize fluctuating loads; provide ancillary services; handle faults; and global optimization, including enhanced control to reduce O&M costs. The design of enhanced controls to achieve these objectives is explained, including modelling-related issues. The connection to shore is addressed in Chapter 9, which presents the various technologies currently used by industry. The chapter discusses AC transmission, VSC-HVDC and gives an overview of low-frequency AC transmission (LFAC). Chapter 10 discusses aspects of operation and control of power systems with high penetration of wind power and explores the possibilities for offshore wind power plants to provide power system operation support. Chapter 11 presents economics, regulatory and policy issues related to offshore wind power developments.

The authors would like to thank the following authors for their contributions to this book: Dr Amir Rasekhi Nejad (Chapter 3 in full), Dr Erin E. Bachynski (Chapter 4 in full), Dr David Campos-Gaona (main parts of Chapter 6), Morten D. Pedersen (contribution to Chapter 5) and Dr Thomas Michael Welte, Dr Iver Bakken Sperstad, Dr Elin Espeland Halvorsen-Weare, Dr Øyvind Netland, Dr Lars Magne Nonås and Dr Magnus Stålhane (Chapter 7).

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Acronyms

AC	Alternating current
AEP	Annual energy production
AGC	Automatic generation control
AGMA	American Gear Manufacturing Association
ALS	Accidental limit state
BEM	Blade element momentum
BP	Band-pass
BTB	Back-to-back
CAPEX	Capital expenditure
CB	Circuit breaker
CDF	Cumulative distribution function
CFD	Computing fluid dynamics
CM	Condition monitoring
CMS	Condition monitoring system
CSC	Current source converter
CTV	Crew transfer vessel
DC	Direct current
DECC	Department of Energy and Climate Change
DFIG	Doubly-fed induction generator
DMC	Direct matrix converter
DOF	Degree of freedom
DTU	Danish Technical University
ENTSOE	European Network of Transmission System Operators, ENTSO-E
EPSRC	Engineering and Physical Sciences Research Council
FC	Flying capacitor
FC/TCR	Fixed capacitor/thyristor-controlled reactor
FCR	Frequency containment reserves
FCS	Frequency control support
FE	Force element
FEM	Finite element method
FFT	Fast Fourier Transform
FLS	Fatigue limit state
FORM	First-order reliability method
FR	Frequency restoration
FRC	Fully-rated converter

FRR	Frequency restoration reserves
FRT	Fault-ride through
FSIG	Fixed-speed induction generator
FWT	Floating wind turbine
GBS	Gravity-based structure
GDW	Generalized dynamic wake
GRC	Gearbox reliability collaborative
GSC	Generator-side converter
GTO	Gate turn-off thyristor
HPSTC	Highest point of single tooth contact
HTS	High-temperature superconducting
HV	High voltage
HVAC	High-voltage alternating current
HVDC	High-voltage direct current
Hz	Hertz
I	Current
IEC	International Electrotechnical Commission
IGBT	Insulated-gate bipolar transistor
IGCT	Integrated gate-commutated thyristor
iPMSG	Ironless permanent-magnet synchronous generator
L	Level
LCC–HVDC	Line-commutated converter HVDC
LCOE	Levelized cost of energy
LDD	Load duration distribution
LES	Large-eddy simulation
LFAC	Low-frequency alternating current
LPSTC	Lowest point of single tooth contact
LV	Low voltage
MBS	Multibody simulation
MC	Matrix converter
MOSFET	Metal–oxide–semiconductor field-effect transistor
MPPT	Maximum power point tracking
MV	Medium voltage
MW	Megawatt
NOWITECH	Norwegian Research Centre for Offshore Wind Technology
NPC	Neutral-point clamped
NREL	National Renewable Energy Laboratory
NSC	Network-side converter
NTNU	Norges Teknisk-Naturvitenskapelige Universitet
O&M	Operation and maintenance
OPEX	Operational expenditure
ORT	Offshore reference turbine
OWT	Offshore wind turbine
PAC	Power adjusting controller
PCC	Point-of-common coupling
PEX/XLPE	Cross-linked polyethylene insulated cable
PI	Proportional-integral