Modeling and Analysis of Doubly Fed Induction Generator Wind Energy Systems

Lingling Fan
Zhixin Miao

Modeling and Analysis of Doubly Fed Induction Generator Wind Energy Systems

Lingling Fan and Zhixin Miao

ELSEVIER

AMSTERDAM • BOSTON • HEIDELBERG • LONDON
NEW YORK • OXFORD • PARIS • SAN DIEGO
SAN FRANCISCO • SINGAPORE • SYDNEY • TOKYO
Academic Press is an imprint of Elsevier

AP

Academic Press is an imprint of Elsevier
125 London Wall, London, EC2Y 5AS, UK
525 B Street, Suite 1800, San Diego, CA 92101-4495, USA
225 Wyman Street, Waltham, MA 02451, USA
The Boulevard, Langford Lane, Kidlington, Oxford OX5 1GB, UK

British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library

Library of Congress Cataloging-in-Publication Data
A catalog record for this book is available from the Library of Congress

ISBN: 978-0-12-802969-5

For information on all Academic Press publications
visit our website at http://store.elsevier.com/

Modeling and Analysis of Doubly Fed Induction Generator Wind Energy Systems

DEDICATION

To our parents

ACKNOWLEDGMENTS

We are fortunate to have the opportunity and time to write this monograph. Through our career development, we are blessed with the encouragement and support from mentors, colleagues, and friends. Our thanks go to Naihu Li, Guangxiang Lu, Haifeng Wang, Xiao-Ping Zhang, Mariesa Crow, Yilu Liu, Elham Makram, Dagmar Niebur, Fang Z. Peng, Jian Sun, and Kevin Tomsovic.

Our research in wind energy grid integration started from our years at Midwest ISO and spanned through time spent at North Dakota State University. We would like to acknowledge our mentors and collaborators at MAPPCOR, MISO, and North Dakota State University: Dale Osborn, Jeff Webb, Larry Brusseau, Terry Bilke, Jerald Miland, Subbaraya Yuvarajan, and Rajesh Kavasseri. Their help is enormous.

The research in wind energy grid integration is closely related to power electronics, a fairly new area to us when we started our investigation. There are many outstanding researchers in the field whose papers we digested and benefited a great deal. Profs. Jian Sun and Fang Z. Peng are sources of inspiration.

Our thanks also go to the former and current graduate students at University of South Florida Smart Grid Power Systems Lab. Their contributions and team spirit make USF Smart Grid Power Systems Lab a great place to work at. Haiping Yin's work in DFIG modeling and unbalanced mitigation control contributed to this book. Javad Khazaei developed a few examples in Matlab/SimPowerSystems for this book. Ling Xu, Lakshan Piyasinghe, and Javad Khazaei have extended the modeling techniques to other systems.

Our thanks go to Bikash Pal. Without his recommendation to Elsevier, this book would not be possible.

CONTENTS

Acknowledgments viii

Chapter 1 Introduction 1

1.1 Wind Energy Integration Issues 1

1.2 Objectives of This Book 3

1.3 Structure of the Book 4

References 6

Chapter 2 AC Machine Modeling 8

2.1 Space Vector and Complex Vector Explanation 8

2.2 Derivation of an Induction Machine Modeling in Space Vector and Complex Vector 13

2.3 DFIG Modeling 21

2.4 Examples 23

References 33

Chapter 3 Modeling of Doubly Fed Induction Generation (DFIG) Converter Controls 34

3.1 Rotor Flux-Oriented Induction Machine Control 35

3.2 DFIG Rotor Side Converter Control 40

3.3 GSC Control 46

3.4 Complete DFIG Modeling Blocks 48

3.5 Examples 49

References 54

Chapter 4 Analysis of DFIG with Unbalanced Stator Voltage 55

4.1 Steady-State Harmonic Analysis of a DFIG 55

4.2 Unbalanced Stator Voltage Drop Transient Analysis 64

4.3 Converter Control to Mitigate Unbalance Effect 67
References 73

Chapter 5 State-Space Based DFIG Wind Energy System Modeling 74
5.1 State-Space Model of a Series Compensated Network 75
5.2 State-Space Model of DFIG Wind Energy System.................... 76
5.3 Integrated System Model 78
5.4 Application of SSR Analysis 80
Appendix 92
References 93

Chapter 6 Frequency-Domain Based DFIG Wind Energy Systems Modeling 94
6.1 Introduction of Impedance Model and Its Application in Stability and Resonance Detection 95
6.2 Impedance Models of DFIG in Various Reference Frames 96
6.3 Negative-Sequence DFIG Impedance Model.......................... 103
6.4 Inclusion of DFIG into Torque-Speed Transfer Functions 106
6.5 Examples 111
References 127

Chapter 7 Multi-Machine Modeling and Inter-Area Oscillation Damping 128
7.1 Steady-State Calculation for a DFIG 129
7.2 Interconnection of DFIG Model in Power Systems.................. 132
7.3 Application of the Model: Interarea-Oscillation Damping Through DFIG Wind Turbines 133
Appendix 144
References 145

CHAPTER 1

Introduction

1.1 WIND ENERGY INTEGRATION ISSUES 1
1.2 OBJECTIVES OF THIS BOOK 3
1.3 STRUCTURE OF THE BOOK 4
REFERENCES 6

1.1 WIND ENERGY INTEGRATION ISSUES

Integration issues related to wind energy can be roughly categorized into two types based on time scales: operation issues and dynamic issues. Operation issues relate to a long-term time scale, e.g., hours, days, or weeks. Operating the system and dispatching synchronous generators while accommodating intermittent wind energy at hourly base or daily base is an example. For this type of research, wind farms' generation profiles of hours and days are of study interest. This type of problems belongs to the category of operations research. Optimization problems are usually formulated and solved. Example research can be found in [1–3]. In [1], a 24-hour unit commitment problem based on hourly generation, load, and wind profiles is formulated to evaluate the impact of wind penetration on market price. An economic dispatch problem with wind energy is presented in [2], where the stochastic nature of wind power is modeled based on wind speed Weibull probability distribution function. In [3], a short-term forward electricity market clearing problem is formulated with uncertain wind.

Compared to operation issues, dynamic issues are of very short time scales. For example, the time-scale of inter-area oscillations and electromechanical resonances is tens of seconds. The time scale of electric resonances is be even shorter.

Based on the above classification, many issues related to wind energy grid integration are dynamic issues, e.g., low voltage ride through, subsynchronous resonances (SSR), frequency support from wind, and control coordination of wind and high voltage direct current (HVDC) delivery

Modeling and Analysis of Doubly Fed Induction Generator Wind Energy Systems.
http://dx.doi.org/10.1016/B978-0-12-802969-5.00001-9

systems. Dynamic modeling of wind energy system is important to approach this type of research. For example, in [4, 5], dynamic models of an induction machine are used to investigate the effect of stator voltage drop on transients in rotor voltages and currents. In our research on SSR in Type-3 wind farms with series-compensated networks [6], dynamic models of a Type-3 wind energy system and the grid were built. Analysis and simulation were conducted based on this model. In [7], frequency support schemes from wind energy system are validated through dynamic model-based simulation in the time scale of tens of seconds. Dynamic model-based simulation is also employed when designing DFIG (doubly fed induction generator) and HVDC control coordination [8].

To be able to investigate the aforementioned issues, we need a good understanding of the dynamic models of wind energy systems as well as the grid. Compared to conventional power systems where synchronous generators are the main source, wind energy systems include both rotating machines and power converter interfaces. Thus, modeling has to capture power converter control dynamics as well as the electromagnetic and electromechanical dynamics of AC machines. In conventional power systems, electromechanical dynamics (e.g., low-frequency oscillations) and torsional interactions between the turbine mechanical systems and the electric systems are expected. In wind energy systems, inclusion of converters could introduce resonances due to converter-grid interactions and machine-converter interactions. Investigation of emerging dynamic phenomena requires adequate dynamic models of wind energy systems.

Wind turbines are classified into four types based on AC generator type and converter type [9]. Type-1 systems deploy induction machines and work at a fixed wind speed. Type-2 wind turbines use wound rotor induction generators with rotor resistance control. Type-3 and Type-4 wind turbines are called variable speed fixed frequency wind generators. These generators can work at variable wind speed and produce fixed frequency electricity. Type-3 wind generator uses doubly-fed induction generator (DFIG) with a partial converter interface, which connects the rotor side to the grid through a back-to-back converter (a rotor-side converter (RSC) and a grid-side converter (GSC) connected via a DC-link capacitor), as shown in Fig. 1.1. Type-4 wind generator uses permanent magnet synchronous generator with a full-converter interface.

The state-of-the-art wind energy systems adopt voltage source converter-enabled wind turbines: Type-3 and Type-4. Type-3 occupies more market

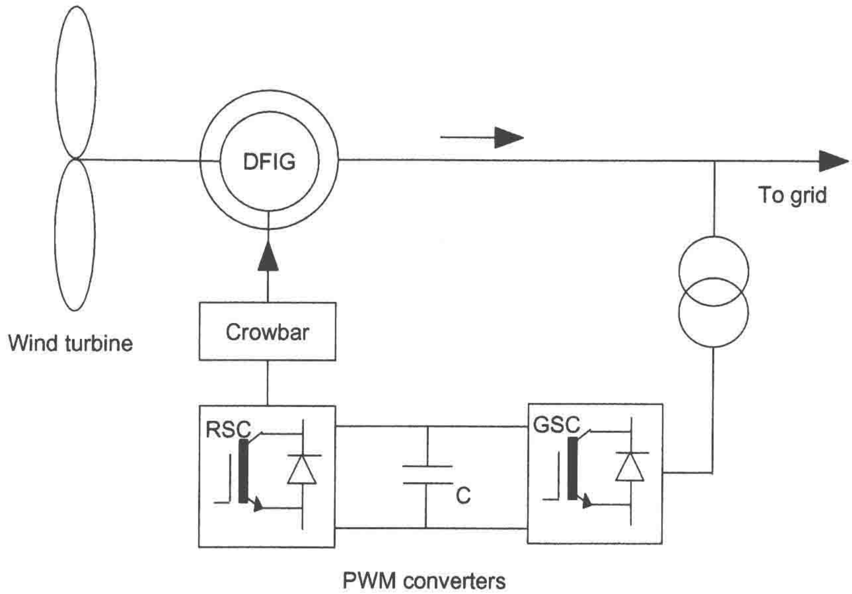

Figure 1.1 Type-3 wind energy system.

than Type-4. GE Wind's 1.5/1.6 MW wind turbine (Type-3) was the most popular wind turbine in the U.S. market in 2012 [10].

The focus of this book is Type-3 wind energy systems. Dynamic modeling of DFIG-based wind energy system and its applications in dynamic studies will be elaborated in this book.

1.2 OBJECTIVES OF THIS BOOK

With the focus on Type-3 or DFIG wind energy systems, throughout this book, analytical DFIG models will be derived and applied in various studies. Currently, there is a lack of monographs on systematic treatment of DFIG wind energy system in terms of modeling, analysis, and control.

There are classic textbooks on modeling and analysis of AC machines and drives, e.g., Krause's *Analysis of Electric Machinery* and Bose's *Power Electronics and AC Drives*. These books focus on drive systems. There are significant differences in control objectives for an AC drive system and a grid integration system. In drive systems, machine control focuses on flux and torque control, while grid integration focuses on real and reactive power control. In addition, many grid integration dynamic phenomena are system-level phenomena, e.g., SSR. System models including wind generation are required. These phenomena emerged and attracted interest from the research community and industry. These topics were not covered in a drive book.

The purpose of writing this book is to integrate the state-of-the-art wind energy grid integration research into education. The book can serve as a textbook for a graduate-level course on AC machine modeling with applications in wind energy integration. The book can also be read by researchers and practitioners in the field of wind energy integration.

1.3 STRUCTURE OF THE BOOK

The book is organized as follows.

Chapter 2 discusses AC machine modeling. Class notes from the authors' course on "AC Machines and Drives" at University of South Florida will be used to develop AC machine modeling using space vectors and complex vectors. Following induction machine modeling, DFIG machine modeling will be discussed. Simulation and analysis examples will be provided.

Chapter 3 presents modeling of DFIG converter control. In this chapter, converter control of DFIG will be thoroughly explained. Differences between drive control and grid integration control will be discussed. In this chapter, a simulation example in PSCAD with power electronic switching details will be given. The purpose of the demonstration is to show that converter voltage outputs after filters are sinusoidal. Readers can then build visual connections between control of *abc* sinusoidal waveforms versus vector control or control of *dq*-variables. Modeling of converter controls of DFIG will then be explained based on *dq*-reference frame. The mathematical models will be derived and a simulation example will be demonstrated.

Chapter 4 discusses unbalanced DFIG analysis and control. In this chapter, steady-state analysis and transient analysis of DFIG rotor voltage/current due to unbalanced stator voltage drop will be presented. Following the analysis, mitigation of unbalance effect using converter control is presented. Simulation case studies are presented to verify the mitigation strategies.

Chapter 5 presents state-space-based DFIG wind energy system modeling. The state-space-based DFIG model in the *dq*-reference frame will be presented. Integrated system model of a DFIG with a series-compensated transmission line is presented next. The developed model will be used for SSR analysis. In this chapter, our research on DFIG-related SSR [6, 11, 12] will be elaborated in both modeling and applications of the dynamic models for small-signal analysis as well as dynamic simulation.

Chapter 6 presents frequency-domain-based DFIG wind energy systems modeling. DFIG's frequency-domain models at phase domain (positive and negative sequences) will be derived and explained.

Three examples will be used to explain the usage of frequency-domain-based DFIG models. The first example examines SSR detection and considers only balanced operating conditions. The second example considers unbalanced operation conditions and the effect on SSR. The third example uses torque-speed transfer function to explain DFIG's influence on torsional interactions. Our research work in [13–15] will be elaborated in this chapter.

Chapter 7 presents multimachine modeling and inter-area oscillation damping. In this chapter, steady-state calculating of DFIG is first presented. Then interfacing a DFIG dynamic model in the *dq* reference frame with a multi-machine power system is explained. A design example on inter-area oscillation damping is given to demonstrate the use of such a model.

The flow of information of this book can be visually seen from Fig. 1.2. Chapters 2 and 3 deal with AC machine and converter control, respectively. With both machine and power converter interface modeled, a DFIG wind energy system model is possible. Chapter 4 can be considered as an application of the system model in unbalanced analysis and control. Note that up to Chapter 4, we only consider a simple system where a wind energy system is directly connected to a grid. The transmission line modeled as an resistor-inductor or RL circuit can be considered as the additional stator resistance and leakage inductance. The dynamic model will have a given stator voltage to start with.

Following Chapter 4, we now deal with more complicated transmission systems, first a series-compensated transmission line where the dynamics of the resistor-inductor-capacitor (RLC) line should not be ignored (Chapters 5 and 6), and then a multi-machine power system (Chapter 7). The interfacing techniques between wind generation and grid are detailedly explained in Chapter 5 and Chapter 7. Chapter 6 can be considered as parallel to Chapter 5. In addition to state-space modeling, we also look for another type of modeling: impedance modeling. This frequency-domain modeling approach shows its advantage in modularized modeling and its easiness in handling unbalanced conditions.

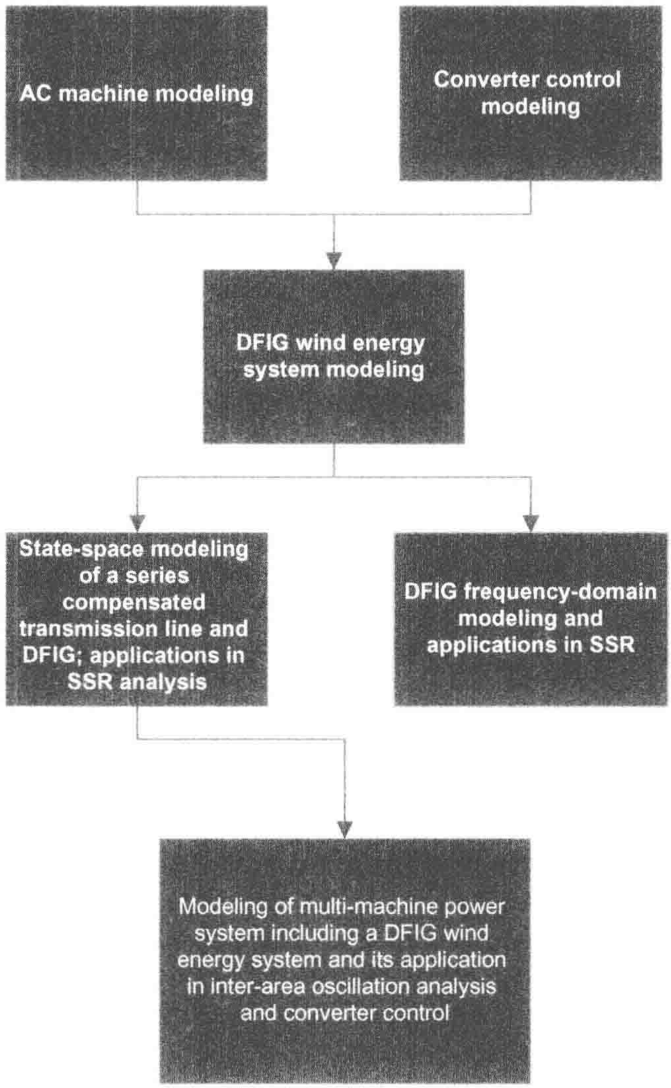

Figure 1.2 Information flow of this book.

REFERENCES

[1] J. Garcia-Gonzalez, R.R. de la Muela, L.M. Santos, A.M. González, Stochastic joint optimization of wind generation and pumped-storage units in an electricity market, IEEE Trans. Power Syst. 23(2) (2008) 460-468.

[2] J. Hetzer, D.C. Yu, K. Bhattarai, An economic dispatch model incorporating wind power, IEEE Trans. Energy Convers. 23(2) (2008) 603-611.

[3] F. Bouffard, F.D. Galiana, Stochastic security for operations planning with significant wind power generation, in: 2008 IEEE Power and Energy Society General Meeting—Conversion and Delivery of Electrical Energy in the 21st Century, IEEE, 2008, pp. 1-11.

[4] J. Lopez, P. Sanchis, X. Roboam, L. Marroyo, Dynamic behavior of the doubly fed induction generator during three-phase voltage dips, IEEE Trans. Energy Convers. 22(3) (2007) 709-717.

[5] J. Lopez, E. Gubia, P. Sanchis, X. Roboam, L. Marroyo, Wind turbines based on doubly fed induction generator under asymmetrical voltage dips, IEEE Trans. Energy Convers. 23(1) (2008) 321-330.

[6] L. Fan, R. Kavasseri, Z.L. Miao, C. Zhu, Modeling of DFIG-based wind farms for SSR analysis, IEEE Trans. Power Delivery 25(4) (2010) 2073-2082.

[7] J. Morren, S.W. De Haan, W.L. Kling, J. Ferreira, Wind turbines emulating inertia and supporting primary frequency control, IEEE Trans. Power Syst. 21(1) (2006) 433-434.

[8] H. Yin, L. Fan, Z. Miao, Fast power routing through HVDC, IEEE Trans. Power Delivery 27(3) (2012) 1432-1441.

[9] Z. Chen, J.M. Guerrero, F. Blaabjerg, A review of the state of the art of power electronics for wind turbines, IEEE Trans. Power Electron. 24(8) (2009) 1859-1875.

[10] R. Wiser, 2012 wind Technologies Market Report, 2014. http://www1.eere.energy.gov/wind/pdfs/2012_wind_technologies_market_report.pdf.

[11] L. Fan, C. Zhu, Z. Miao, M. Hu, Modal analysis of a DFIG-based wind farm interfaced with a series compensated network, IEEE Trans. Energy Convers. 26(4) (2011) 1010-1020.

[12] L. Fan, Z. Miao, Mitigating SSR using DFIG-based wind generation, IEEE Trans. Sustainable Energy 3(3) (2012) 349-358.

[13] L. Fan, Z. Miao, Nyquist-stability-criterion-based SSR explanation for type-3 wind generators, IEEE Trans. Energy Convers. 27(3) (2012) 807-809.

[14] Z. Miao, Impedance-model-based SSR analysis for type 3 wind generator and series-compensated network, IEEE Trans. Energy Convers. 27(4) (2012) 984-991.

[15] Z. Miao, Impact of unbalance on electrical and torsional resonances in power electronic interfaced wind energy systems, IEEE Trans. Power Syst. 28(3) (2013) 3105-3113.

CHAPTER 2

AC Machine Modeling

2.1 SPACE VECTOR AND COMPLEX VECTOR EXPLANATION 8
2.1.1 Examples of Space Vector 12
2.2 DERIVATION OF AN INDUCTION MACHINE MODELING IN SPACE VECTOR AND COMPLEX VECTOR 13
2.2.1 Induction Machine Modeling in Space Vector 13
2.2.1.1 Per Unit System 15
2.2.2 Induction Machine Modeling in Complex Vector 16
2.2.2.1 Model in Per-Unit System 18
2.2.3 Swing Equation 18
2.3 DFIG MODELING 21
2.3.1 Wind Turbine Aerodynamics Model 21
2.4 EXAMPLES 23
2.4.1 Example 1: Free Acceleration 23
2.4.1.1 Induction Machine Simulink Model 25
2.4.2 Example 2: DFIG Stator Voltage Drop 27
REFERENCES 33

In this chapter, analytical models of induction machines are first described. Analytical models of DFIG are then presented. The models are related to electric machine only. Converter controls will be discussed in Chapter 3. Two examples are given to demonstrate the usage of the analytical models to simulate free acceleration of an induction machine or analyze the consequences of DFIG stator voltage dip.

2.1 SPACE VECTOR AND COMPLEX VECTOR EXPLANATION

The type of induction machines to be discussed is three-phase induction machines where both the stator and the rotor have *abc* windings. The key dynamics of the magnetic field can be described by Faraday's law that the change of flux field induces electromagnetomotive force (EMF). To model a

Modeling and Analysis of Doubly Fed Induction Generator Wind Energy Systems.
http://dx.doi.org/10.1016/B978-0-12-802969-5.00002-0