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Tomasz Barszcz

Vibration-Based Condition Monitoring of Wind Turbines

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To my wife, Katarzyna

Preface

Wind turbines have become very popular in the landscape in recent years. Their appearance triggered a number of discussions concerning their impact on the environment, their efficiency, potential threat to animals, and plethora of other subjects. For a mechanical engineer, however, wind turbines are complex machines operating in very challenging conditions. Cost structure of operating a wind farm is very different from a thermal plant. In a wind farm, a majority of costs must be paid before turbines start to generate income. In other words, capital expenditures (CAPEX) are very high and operating expenditures (OPEX) can be low, as the energy source is free of charge. In such a situation, an uninterrupted readiness to generate electricity is a key requirement. An engineer will say that we require high availability. For machines with gearboxes (which make up a majority of all wind turbines), the most vulnerable part of a wind turbine is its drivetrain, i.e., a main bearing, a gearbox, and a generator. A single unplanned exchange of a gearbox can cost several hundred thousand euros, and methods which can tell us whether the gearbox is in a good shape are very important to the users.

This book explains how the technical state of a wind turbine drivetrain can be assessed, based on the vibration analysis of its mechanical vibration. After the introduction, Chap. 1 starts with the description of vibration signals used for monitoring drivetrains and presents its key features. The signal processing methods, including the advanced ones, like signal resampling and signal envelope, are described in Chap. 2. This chapter puts great importance to the fact that turbines generate electricity in response to the wind. It is a fundamental cause why they work in highly varying operational conditions.

Vibration-based condition monitoring has become an important branch of the market. There are several monitoring devices available to potential users. They vary greatly in features and applications. Chapter 3 describes types of devices used for condition monitoring purposes, ranging from vibration sensors, through supervisory control and data acquisition (SCADA), to portable data analyzers and online condition monitoring systems.

Vibration analysis is a vibrant research field, in which new methods are introduced to help to process vibration data more accurately. Chapters 4 and 5 constitute the main part of this book and are dedicated to such new methods. It is accompanied by real case studies, in which advanced signal processing methods were used to detect failures of gearboxes and bearings of wind turbines.

This book is intended for researchers in the field of vibration signal analysis interested in wind turbines. It will provide them with an in-depth understanding of the most recent research achievements in this domain. It can also be useful for practitioners active in the field of wind turbine condition monitoring, help them in extending their knowledge in the field, and give examples of equipment available on the market. Finally, it will be interesting to graduate students who would like to extend their knowledge into the field of vibration analysis. The information contained in this book will also be valuable to those interested in condition monitoring of other machines working in varying operational conditions, like airplanes, helicopters, vehicles, mining equipment.

Kraków, Poland Tomasz Barszcz

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During writing this book, I had a privilege of working with wonderful people, who contributed to the formation of this work. First of all, I'd like to thank Adam Jablonski and Jacek Urbanek, who completed their Ph.D. under my supervision. They both combined curiosity and imagination with hard work. The journey with them into the land of vibration signal processing was a very productive and fortunate period of my life. I also would like to thank my mentors and colleagues who accompanied me on my scientific trip. I have special thanks to Prof. J. Antoni, Prof. W. Bartelmus, Dr. N. Martin, Prof. B. Randall, Prof. T. Uhl, Prof. A. Wylomanska, and Prof. R. Zimroz. We had so many stimulating discussions, often resulting in innovative ideas and common work. My research in the field of wind power generation was in large part initiated by real problems of real machines. I would like to say thanks to my colleagues and friends from companies I was privileged to work with: PGE, ENEA, Energa, RP Global, GE, Alstom, Siemens, SEACOM, EC Systems, and AMC VIBRO.

Writing of this book took a long time and was often delayed to many other duties. I would like to give a very special thanks to my wife, Katarzyna. She motivated and encouraged me in this effort. Moreover, many daily chores were taken out of my head so I had enough time to finish this volume.

Contents

Abbreviations

ADC	Analog Digital Converter
AE	Acoustic Emission
AI	Artificial Intelligence
AM	Amplitude Modulation
AZT	Allianz Zentrum fuer Technik
BPFI	Ball Pass Frequency of the Inner Ring
BPFO	Ball Pass Frequency of the Outer Ring
BSF	Ball Spin Frequency
BW	Bandwidth
CAPEX	Capital Expenditures
CF	Crest Factor
CF	Center Frequency
CM	Condition Monitoring
CMMNO	Condition Monitoring of Machinery in Non-stationary Operations
CMS	Condition Monitoring System
CMS	Cyclic Modulation Spectrum
CPU	Central Processing Unit
DFT	Discrete Fourier Transform
EK	Excess Kurtosis
ESK	Envelope Spectrum Kurtosis
FEM	Finite Element Model
FFT	Fast Fourier Transform
FIR	Finite Impulse Response
FM	Frequency Modulation
FRF	Frequency Response Function
FTF	Fundamental Train Frequency
GL	Germanisher Lloyd
GMF	Gear Mesh Frequency

HFRT	High Frequency Resonance Technique
HP	High Pass
HT	Hunting Tooth
IAS	Instantaneous Angular Speed
ICPCP	Instantaneous Circular Pitch Cyclic Power
IEPE	Integrated Electronics Piezo-Electric
IMD	Integrated MID
IPS	Instantaneous Power Spectrum
ISO	International Standardization Organization
LP	Low Pass
LSCh	Load Susceptibility
MCSA	Motor Current Signature Analysis
MEMS	Micro Electro Mechanical Systems
MID	Modulation Intensity Distribution
MIF	Modulation Intensity Factor
MIMO	Multi Input Multi Output
NEA	Narrowband Envelope Analysis
NREL	National Renewable Energy Laboratory
OFB	Optimum Frequency Band
OPEX	Operational Expenditures
PC	Personal Computer
PDF	Probability Distribution Function
PP	Peak–Peak
PSC	Product of two Spectral Correlations
PSCoh	Product of two Spectral Coherences
PSD	Power Spectrum Density
REB	Rolling Element Bearing
RMS, rms	Root Mean Square
RPM, rpm	Rotations Per Minute
RUL	Remaining Useful Life
SCADA	Supervisory Control and Data Acquisition
SCD	Spectral Correlation Density
SCoh	Spectral Coherence
SCohD	Spectral Coherence Density
SK	Spectral Kurtosis
SNR	Signal-to-Noise Ratio
SOI	Signal of Interest
SP	Spectrogram
STFT	Short Time Fourier Transform
SVM	Support Vector Machine
TC	Technical Committee
TSA	Time Synchronous Averaging

VDI	Verein Deutscher Ingenieure
VOC	Varying Operational Conditions
WT	Wind Turbine
WTAS	Wind Turbine Analysis System
ZP	Zero–Peak

Symbols

N, L	Integer number
t	Continuous time
k	Discrete time
τ	Time lag
f	Frequency
α	Cyclic frequency
T	Period
TH	Threshold value
$x, y, \ldots$	Time signals
$X, Y, \ldots$	Fourier transforms of signals
df	Frequency resolution
ω	Cyclic frequency
φ	Angle
h	Impulse response function
H	Frequency response function
$1X, 2X, \ldots$	1, 2, … harmonics
M	Amplitude
c	Complex coefficient
$hann$	Profile of the window function
$E(), \langle\cdot\rangle$	Averaging operators
$p()$	Probability density
μ	Mean value
σ	Standard deviation
sup	Supremum
K	Kurtosis
R	Autocorrelation
$\mathcal{P}_0$	Averaging operator
$x_{\Delta f}(t;f)$	$x(t)$ filtered through the frequency band with center frequency f of width Δf
$\mathcal{P}_\alpha\{\cdot\}$	Operator extracting the periodic component at a frequency α
$\mathcal{P}\{\cdot\}$	Operator extracting all cyclic frequencies

$P_x(t, f;\ \Delta f)$	Instantaneous power spectrum
$P_x^{\propto}(f;\ \Delta f)$	Cyclic power spectrum
$SC_x^{\propto}(f)$	Spectral correlation density
$\gamma_x^{\alpha}(f)$	Spectral coherence density
$MID(\cdot)_{\Delta f}(f, \alpha)$	Modulation intensity distribution with modulation intensity factor (.)
$IMD(\cdot)_{f_1}^{f_2}(\alpha, \Delta f)$	Integrated MID in frequency range $f_1 \ldots f_2$

Chapter 1
Introduction

1.1 Who Should Read This Book

My career path comprises sharing my time between academia and industry. I have experienced and appreciated how much both communities are different and how much they can learn from one another. The most important field for me is vibration based condition monitoring of wind turbine drivetrains. This has become my main motivation to write a book on the topic which I hope will be useful for both researchers and practitioners.

During the past 25 years, I have come across many books on vibration signal analysis. They present the subject from many angles, but still I could not find any book devoted to wind turbine drivetrains. There are hundreds of scientific papers being published in this domain and adjacent ones. For most readers, however, it is really time consuming to browse through all the papers and pick up the ones relevant to wind turbine drivetrains. My ambition is to fill this gap by providing basic information about the wind turbines market and design, a comprehensive survey of currently used vibration analysis methods and available condition monitoring systems, finally, presenting recent research in this field.

Important aspects of condition monitoring of wind turbines are varying operational conditions of these machines. Constant wind variability causes variations in all the process parameters, primarily the rotational speed and the generated power. Since the rotational speed governs frequencies generated by all the drivetrain components, the frequency spectrum is very different from this of a constant speed machine. A varying load is another factor changing amplitudes of vibration signals. All of it needs to be included in efficient analysis of a wind turbine technical state.

This book is primarily intended for researchers in the field of vibration signal analysis interested in wind turbines and it will provide them with in-depth understanding of the most recent research achievements in this domain. I have included

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the most recent (as of February 2018) research results in the field. My main interest was detection of gear and rolling bearing faults with vibration signals. The book contains several case studies which provide additional understanding of the presented methods.

It can also be useful for practitioners active in the field of wind turbines condition monitoring and help them in extending their knowledge in the field. The important part of the book is the survey about the equipment available on the market. As this market is mature now, there is a wide variety of off-the-shelf products which can be applied for condition based monitoring. To achieve the best possible return on investment from the condition monitoring the key requirements toward the CM implementation process are stressed.

Last but not least, the book will also be interesting to graduate students who would like to extend their knowledge into the field of vibration analysis. The first chapters include a compendium of vibration signal analysis methods starting from basic broadband features to the advanced ones.

The information contained in this book will also be valuable to those interested in condition monitoring of other machines working in varying operational conditions, like airplanes, helicopters, vehicles, mining equipment and others. Most of the techniques presented in the book can be quickly applied in the domains mentioned above.

1.2 Types of Drivetrains

Wind turbine technology has been developed for centuries. Nevertheless, the wide application of wind power generation to a public grid has gained momentum since the 80s. During this time dozens of different machines converting wind energy into its other forms have been invented, designed and tested. The complete process involves information and experience from many fields of knowledge, e.g. aerodynamics, material science, mechanical and electrical engineering. An interested reader can find facts and data about the historical developments and physical principles in books by Hau [1] or Burton et al. [2]. In these book the most popular design is going to be considered: a horizontal axis upwind turbine. The term “upwind” depicts a turbine in which the main rotor is the part directed towards the wind.

A drivetrain itself consists of the following parts:

- main shaft,
- main bearing,
- gearbox (only in the gear design),
- coupling,
- generator.

There are also other mechanical components in the nacelle, though they are not part of a drivetrain and will not be considered here. Such mechanical subsystems are a blade pitch, a yaw and a brake. A pitch control mechanism is used in pitch

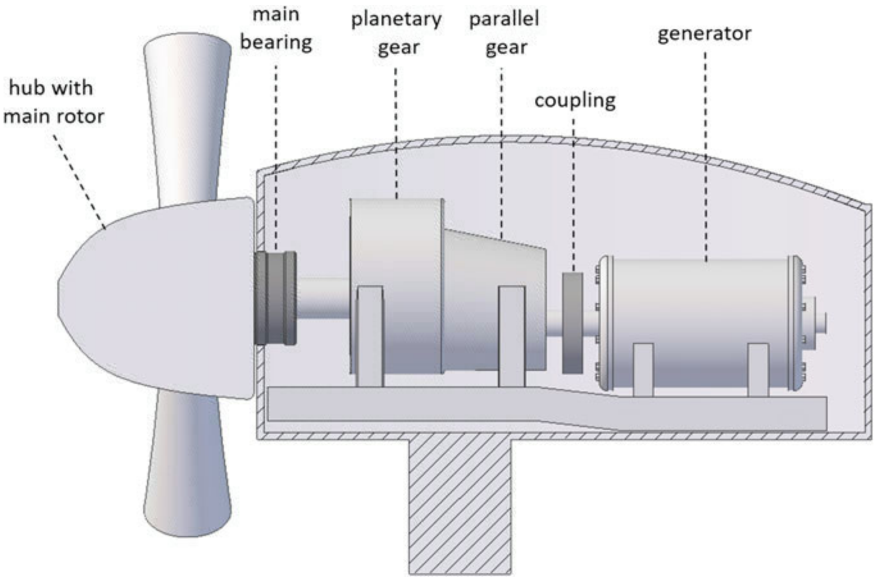

Fig. 1.1 Drivetrain of the horizontal axis wind turbine with gearbox

controlled turbines; it is mounted in a rotor hub and continuously sets the pitch angle of the main rotor blades. A yaw drive can change the azimuth and is used to direct the nacelle towards the wind. A mechanical brake is used to stop a turbine. It is typically mounted between a gearbox and a generator.

The main role of a wind turbine drivetrain is to transmit mechanical power from a main rotor to a generator. There are two fundamental setups of mechanical transmission:

- gearbox between the main rotor and the generator,
- direct drive (gearless).

The most popular design is such in which a gearbox is placed in between a rotor and a generator. The example of the most typical setup is presented in the Fig. 1.1. The main rotor with three blades is supported by the main bearing and transmits torque to the planetary gear. The planetary gear input is a plate to which the main rotor is connected. The planetary gear has three planets, with their shafts attached to the plate. The planets roll over the stationary ring and transmit torque to the sun. The sun shaft is the output of the planetary gear. Further, the sun drives the two-stage parallel gear. The parallel gear has three shafts: the slow shaft connected to the sun shaft, the intermediate shaft and the fast shaft which drives the generator. The intermediate shaft is mounted inside the parallel gear.

A gearbox is used to increase slow rotational speed of a rotor (ca. 18 rpm) to match the speed of a generator (ca. 1500 rpm for 50 Hz grid). Thus, a gearbox ratio is in the range of 80–100. As presented above, the most popular design uses a one

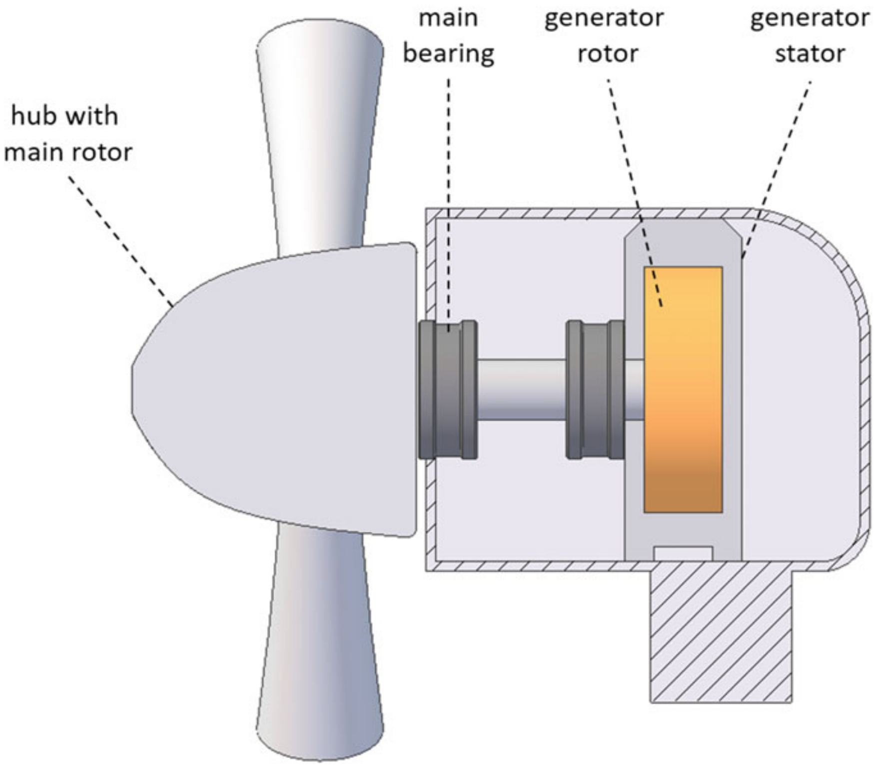

Fig. 1.2 Drivetrain of the direct drive wind turbine

stage planetary gear and a two stage parallel gear. Other gearbox designs are also manufactured, e.g. a two stage planetary gear with a one stage parallel gear. There are also gearbox designs with a three stage parallel gearing.

The main advantage of a standard design is the ability to use conventional gearboxes and generators which are used in other industries and manufactured by many independent companies. Using popular components from the market results in a relatively light and inexpensive system. Another important advantage is easy maintenance, both in terms of access to individual components as well as in availability of spare parts.

The other design, less frequent, is a direct drive (gearless) wind turbine. The main rotor is placed directly on a multi-pole generator shaft. The major problem of a gearless wind turbine is the need of a dedicated, multi-pole generator. Next, a power electronic frequency converter further increases frequency to match the grid. The example of such a design is shown in the Fig. 1.2.

As the generator rotational speed is that of the main rotor, the generator requires a high number of poles. Thus, direct drive generators have large diameters. It helps to distinguish them from the standard design. In general, direct drive machines require a

Table 1.1 Basic operational parameters of the Enercon E82 E2 wind turbine

Parameter	Value	Unit
Tower height	78–138	m
Rotor diameter	82	m
Nominal power	2000	kW
Control type	Pitch	–
Gearbox	None	–
Rotor speed	6–18	rpm
Generator speed	6–18	rpm
Weight (nacelle, rotor and blades)	Approx. 135	Mg

Table 1.2 Basic operational parameters of the Vestas V90-2 wind turbine

Parameter	Value	Unit
Tower height	80–125	m
Rotor diameter	90	m
Nominal power	2000	kW
Control type	Pitch	–
Gearbox	1 planetary + 2 parallel	–
Nominal rotor speed	18	rpm
Nominal generator speed	1500	rpm
Weight (nacelle, rotor and blades)	Approx. 108	Mg

dedicated generator resulting in heavier and more costly turbines. On the other hand, its most important advantage is the increased reliability on account of a simplified drivetrain.

Tables 1.1 and 1.2 present key parameters of two comparable 2 MW wind turbines. Please, note that the parameters given in Table 1.2 are for the 50 Hz market. For the 60 Hz market nominal generator speed for a geared type turbines is 1800 rpm.

1.3 Stall Controlled and Pitch Controlled Turbines

Another important distinction within geared wind turbines is a control type which greatly influences generated vibration signals. The main problem to solve is how to adjust turbine power to changing wind conditions in high winds. There are two main design solutions to this problem: stall control and pitch control.

Stall control takes advantage of the physical phenomenon of separation of air flow from the profile of a blade when the angle of attack is too high. In aerospace it is very dangerous as the lift force decreases suddenly and may lead to a catastrophic failure. In wind turbines, on the other hand, it is used to decrease generated power.

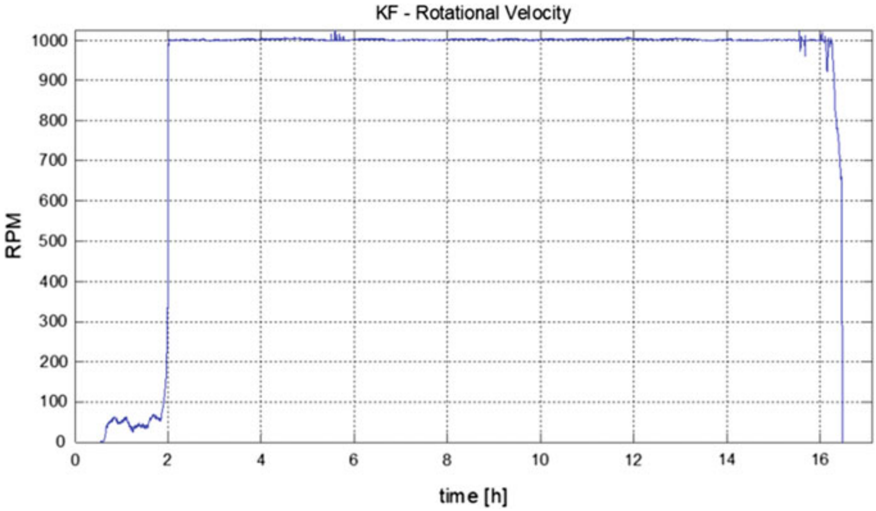

Fig. 1.3 Example of speed profile of a stall controlled wind turbine

Such a design is very simple and does not require a control system of the blades. Since it is not possible to achieve efficient generation in wide range of wind speeds, stall controlled turbines have two nominal generator speeds, most often 1000 and 1500 rpm. As long as the turbine works at a given speed, the load may vary, but the speed is almost ideally constant. It has important consequences for generated vibration signals. Every component (as it will be shown in Sect. 1.4) generates its own vibration pattern bound to so-called characteristic frequency which depends on rotational speed. If the rotational speed is constant, characteristic frequencies are constant and can be determined and analyzed by frequency spectrum. The Fig. 1.3 presents the speed profile of the stall controlled turbine. One can observe that for several hours the turbine maintained almost perfectly constant speed of 1000 rpm.

With the increasing size and power, stall turbines have lost the market to a more efficient pitch controlled design. Stall controlled ones can be found in the field, but this design rarely achieves nominal power above 1 MW. For an illustration, the Table 1.3 presents the main parameters of a stall controlled turbine.

The currently dominant model, namely the pitch control, is a design in which a pitch angle of the main rotor blades is changed depending on wind speed. The goal is to maintain the optimal operating conditions. Rotor blades operate at more efficient conditions than the stall controlled ones. Therefore, pitch control turbines are more efficient though at the cost of a complex pitch control mechanism.

As far as vibration signal analysis is concerned, continuously varying rotational speed is a major obstacle. The characteristic frequencies mentioned above do not represent constant frequency lines if the rotational speed is not constant. The Fig. 1.4 presents the speed profile of a pitch controlled turbine. There are periods when within only 3 min the rotational speed can vary from 820 to 1080 rpm. It is a change of