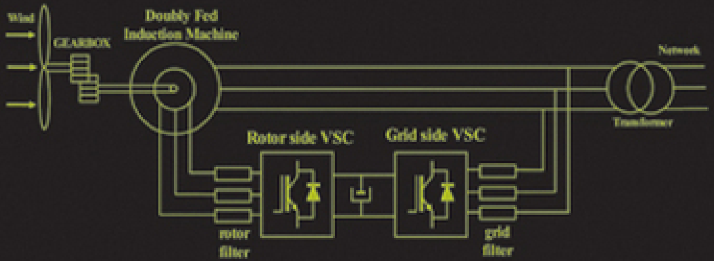
Doubly Fed Induction Machine

Modeling and Control for Wind Energy Generation



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PREFACE

Over the last years, there has been a strong penetration of renewal energy resources into the power supply network. Wind energy generation has played and will continue to play a very important role in this area for the coming years.

Doubly fed induction machine (DFIM) based wind turbines have undoubtedly arisen as one of the leading technologies for wind turbine manufacturers, demonstrating that it is a cost effective, efficient, and reliable solution. This machine, a key element of the wind turbine, is also known in the literature as the wound rotor induction machine (WRIM). It presents many similarities with the widely used and popular squirrel cage induction machine (SCIM). However, despite the parallelism of both machines, the DFIM requires its own specific study for an adequate understanding.

Although there have been a significant number of excellent textbooks on the subject of induction machine modeling and control, books containing a significant portion of material related to the DFIM are less common. Therefore, today this book seems to be the unique and comprehensive reference, exclusively dedicated to the DFIM modeling and control and applied to wind energy generation.

This book provides the reader with basic and advanced knowledge about DFIM based wind turbines, including market overview and tendencies, discussing realistic and practical problems with numerical and graphical illustrative examples, as well as providing guidance to help understand the new concepts.

The technical level of the book increases progressively along the chapters, covering first basic background knowledge, and later addressing advanced study of the DFIM. The book can be adopted as a textbook by nonexpert readers, undergraduate or postgraduate students, to whom the first chapters will help lay the groundwork for further reading. In addition, a more experienced audience, such as researchers or professionals involved in covered topics, would also benefit from the reading of this book, allowing them to obtain a high level of understanding and expertise, of DFIM based wind turbines.

It must be mentioned that, by means of this book, the reader not only will be able to learn from wind turbine technology or from the DFIM itself, but also enhance his/her knowledge on AC drives in general, since many aspects of this book present universal character and may be applied to different AC machines that operate on different applications.

On the other hand, it is the belief of the authors that what makes this DFIM based wind turbine technology cost effective (i.e., its reduced size converter requirement due to the double supply nature of the machine), makes its study challenging for new readers. The combination and coordination of the converter supply and grid supply, compared to single supplied machines such as asynchronous or synchronous machines, lead us to a more enriching environment in terms of conceptual understanding.

In addition, the direct grid supply can be a disadvantage, when the machine must operate under a faulty or distorted grid voltage scenario; especially if its disconnection must be avoided, fulfilling the generation grid code requirements. This mainly occurs because the stator windings of the machine are directly affected by those perturbations. In order to move forward with these problematic but realistic and unavoidable situations, additional active hardware protections or increased size of supplying converter are commonly adopted, accompanied by special control adaptations. Because of this, the work focuses on voltage disturbance analysis for DFIM throughout the book.

It is clear that this work is not intended to be a defense of DFIM based wind turbines, as the best technological solution to the existing alternative ones. Instead, the objective of this book is to serve as a detailed and complete reference, of the well established wind turbine concept.

No matter what the future holds, DFIM based wind turbines have gained an undoubtedly distinguished place that will always be recognized in the history of wind energy generation.

Finally, we would like to first express our sincere gratitude to Professor M. P. Kazmierkowski, for encouraging us to write this book. We wish to also thank everyone who has contributed to the writing of this book. During the last ten years, there have been a significant number of students, researchers, industry, and university colleagues who have influenced us, simply with technical discussions, or with direct and more concise contributions. Thanks to your daily and continuous support, this project has become a reality.

To conclude, we would like also to acknowledge IEEE Press and John Wiley & Sons, for their patience and allowance of the edition of the book.

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CHAPTER 1

Introduction to A Wind Energy Generation System

1.1 INTRODUCTION

The aim of this chapter is to provide the basic concepts to understand a wind energy generation system and the way it must be operated to be connected to the utility grid.

It covers general background on wind turbine knowledge, not only related to the electrical system, but also to the mechanical and aerodynamics characteristics of wind turbines.

In Section 1.2 the components and basic concepts of a fixed speed wind turbine (FSWT) are explained, as an introduction to a modern wind turbine concept; also, energy extraction from the wind and power–torque coefficients are also introduced.

In Section 1.3 a simple model for the aerodynamic, mechanical, and pitch systems is developed together with a control system for a variable speed wind turbine (VSWT). This section explains the different configurations for the gearbox, generator, and power electronics converter, used in a VSWT.

Section 1.4 describes the main components of a wind energy generation system (WEGS), starting with a VSWT based on a doubly fed induction motor (DFIM); then a wind farm electrical layout is described and finally the overall control strategy for the wind farm and the wind turbine.

In Section 1.5, the grid integration concepts are presented since the rising integration of wind power in the utility grid demands more constraining connection requirements.

Since the low voltage ride through (LVRT) is the most demanding in terms of control strategy, Section 1.6 deals with the LVRT operation description. The origin, classification, and description of voltage dips are given in order to understand specifications for the LVRT. The section finishes by describing a grid model suitable to validate the LVRT response of wind turbines.

Section 1.7 provides a survey of solutions given by different wind turbine manufacturers. And finally a 2.4 MW VSWT is numerically analyzed.

To conclude, the next chapters are overviewed in Section 1.8.

Doubly Fed Induction Machine: Modeling and Control for Wind Energy Generation,
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1.2 BASIC CONCEPTS OF A FIXED SPEED WIND TURBINE (FSWT)

1.2.1 Basic Wind Turbine Description

The basic components of a wind turbine are described by means of a fixed speed wind turbine, based on a squirrel cage (asynchronous machine) and stall–pitch power control. This technology, developed in the late 1970s by pioneers in Denmark, was widely used during the 1980s and 1990s, and was the base of wind energy expansion in countries like Spain, Denmark, and Germany during the 1990s.

The main manufacturers developing this technology have been Vestas, Bonus (Siemens), Neg-Micon and Nordtank, in Denmark, Nordex and Repower in Germany, Ecotècnia (Alstom), Izar-Bonus and Made in Spain, and Zond (Enron-GE) in the United States. At present, many other small manufacturers and new players such as Sulzon in India or GoldWind in China are in the market.

The first fixed speed wind turbines were designed and constructed under the concept of reusing many electrical and mechanical components existing in the market (electrical generators, gearboxes, transformers) looking for lower prices and robustness (as the pioneers did when they manufactured the first 25 kW turbines in their garages in Denmark). Those models were very simple and robust (most of them are still working, and there is a very active secondhand market).

To achieve the utility scale of 600,750, and 1000 kW, development of wind turbines took only ten years, and around two-thirds of the world's wind turbines installed in the 1980s and 1990s were fixed speed models.

Before we describe the FSWT, let's have a look at the main concepts related to this technology:

- The fixed speed is related to the fact that an asynchronous machine coupled to a fixed frequency electrical network rotates at a quasifixed mechanical speed independent of the wind speed.
- The stall and pitch control will be explained later in the chapter, but is related to the way the wind turbine limits or controls the power extracted from the wind.

Figure 1.1 shows the main components of a fixed speed wind turbine.

The nacelle contains the key components of the wind turbine, including the gearbox and the electrical generator. Service personnel may enter the nacelle from the tower of the turbine.

To the left of the nacelle we have the wind turbine rotor, that is, the rotor blades and the hub. The rotor blades capture the wind and transfer its power to the rotor hub. On a 600 kW wind turbine, each rotor blade measures about 20 meters in length and is designed much like the wing of an aeroplane.

The movable blade tips on the outer 2–3 meters of the blades function as air brakes, usually called tip brakes. The blade tip is fixed on a carbon fiber shaft, mounted on a bearing inside the main body of the blade. On the end of the shaft inside the main blade, a construction is fixed, which rotates the blade tip when subjected to an outward movement. The shaft also has a fixture for a steel wire, running the length of the blade from the shaft to the hub, enclosed inside a hollow tube.

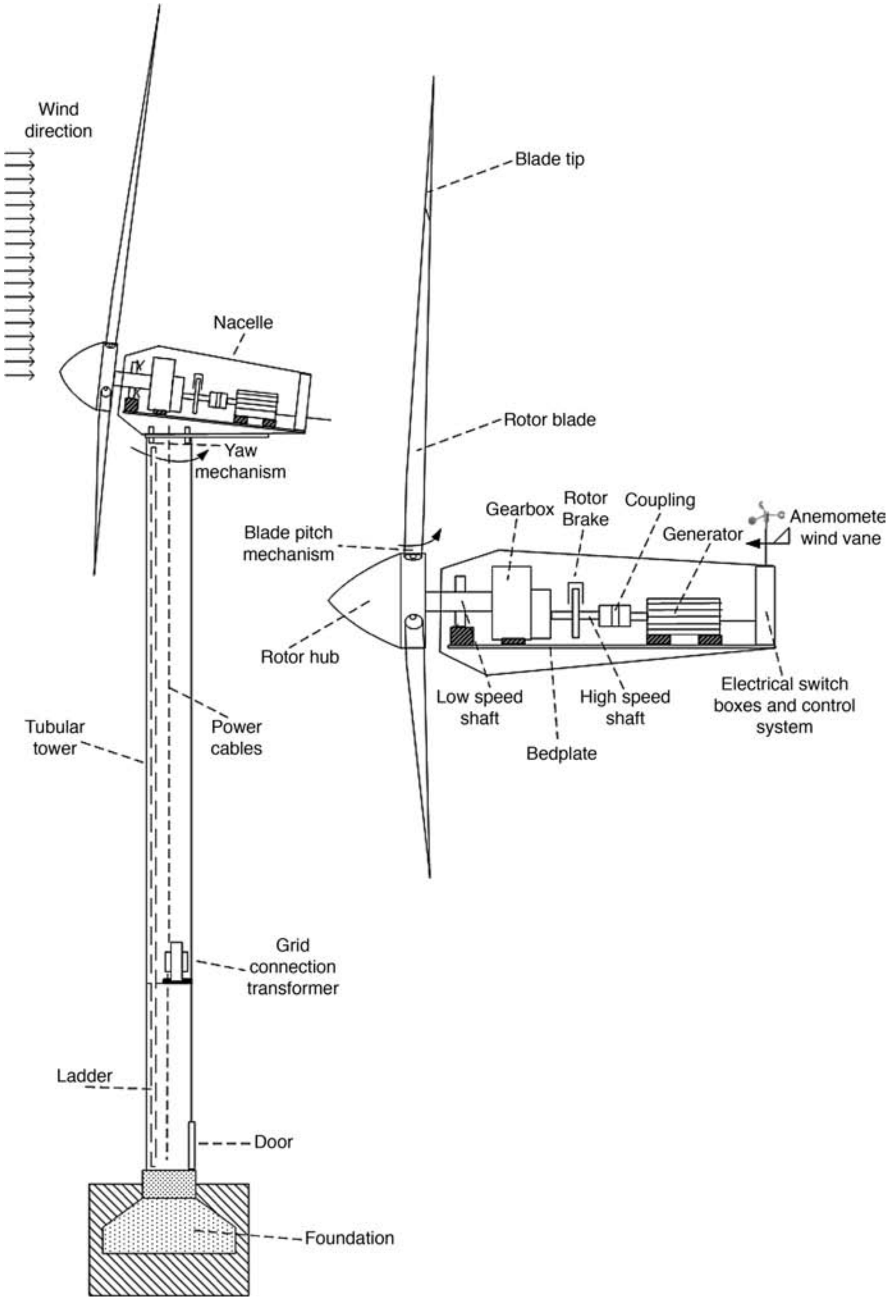

Figure 1.1 Main components of a fixed speed wind turbine.

During operation, the tip is held fast against the main blade by a hydraulic cylinder inside the hub, pulling with a force of about 1 ton on the steel wire running from the hub to the blade tip shaft.

When it becomes necessary to stop the wind turbine, the restraining power is cut off by the release of oil from the hydraulic cylinder, thereby permitting centrifugal force to pull the blade tip outwards. The mechanism on the tip shaft then rotates the blade tip through 90 degrees, into the braking position. The hydraulic oil outflow from the hydraulic cylinder escapes through a rather small hole, thus allowing the blade tip to turn slowly for a couple of seconds before it is fully in position. This thereby avoids excessive shock loads during braking.

The tip brakes effectively stop the driving force of the blades. They cannot, however, normally completely stop blade rotation, and therefore for every wind speed there is a corresponding freewheeling rotational speed. The freewheeling rotational speed is much lower than the normal operational rotational speed, so the wind turbine is in a secure condition, even if the mechanical brake should possibly fail.

The hub of the rotor is attached to the low speed shaft of the wind turbine. The low speed shaft of the wind turbine connects the rotor hub to the gearbox. On a 600 kW wind turbine, the rotor rotates relatively slowly, about 19–30 revolutions per minute (rpm).

The gearbox has a low speed shaft to the left. It makes the high speed shaft to the right turn approximately 50 times faster than the low speed shaft.

The high speed shaft rotates with approximately 1500 revolutions per minute (rpm) and drives the electrical generator. It is equipped with an emergency mechanical disk brake. The mechanical brake is used in case of failure of the aerodynamic brake (movable blade tips), or when the turbine is being serviced.

The electrical generator is usually a so-called induction generator or asynchronous generator. On a modern wind turbine, the maximum electric power is usually between 500 and 1500 kilowatts (kW).

The shaft contains pipes for the hydraulics system to enable the aerodynamic brakes to operate. The hydraulics system is used to reset the aerodynamic brakes of the wind turbine.

The electronic controller contains a computer that continuously monitors the condition of the wind turbine and controls the yaw mechanism. In case of any malfunction (e.g., overheating of the gearbox or the generator), it automatically stops the wind turbine and calls the turbine operator's computer via a telephone modem link.

The cooling unit contains an electric fan, which is used to cool the electrical generator. In addition, it contains an oil cooling unit, which is used to cool the oil in the gearbox. Some turbines have water-cooled generators.

The tower of the wind turbine carries the nacelle and the rotor. Generally, it is an advantage to have a high tower, since wind speeds increase farther away from the ground.

Towers may be either tubular towers (such as the one in Figure 1.1) or lattice towers. Tubular towers are safer for the personnel who have to maintain the turbines, as they may use an inside ladder to get to the top of the turbine. The advantage of lattice towers is primarily that they are cheaper. A typical 600 kW turbine will have a tower of 40–60 meters (the height of a 13–20 story building).

Wind turbines, by their nature, are very tall slender structures. The foundation is a conventional engineering structure that is designed mainly to transfer the vertical load (dead weight). However, in the case of wind turbines, due to the high wind and environmental loads experienced, there is a significant horizontal load that needs to be accounted for.

The yaw mechanism uses electrical motors to turn the nacelle with the rotor against the wind. The yaw mechanism is operated by the electronic controller, which senses the wind direction using the wind vane. Normally, the turbine will yaw only a few degrees at a time, when the wind changes its direction. The anemometer and the wind vane are used to measure the speed and the direction of the wind.

The electronic signals from the anemometer are used by the wind turbine's electronic controller to start the wind turbine when the wind speed reaches approximately 5 meters per second (m/s). The computer stops the wind turbine automatically if the wind speed exceeds 25 meters per second in order to protect the turbine and its surroundings.

The wind vane signals are used by the wind turbine's electronic controller to turn the wind turbine against the wind, using the yaw mechanism.

The wind turbine output voltages were in the low voltage range—380, 400, 440 V—for the first wind turbine models (20–500 kW) in order to be connected directly to the low voltage three-phase distribution grid, but the increasing power demand and the integration in wind farms has increased this voltage to 690 V. When the wind turbine must be connected to the medium voltage distribution grid, a transformer is included (inside the tower or in a shelter outside).

1.2.2 Power Control of Wind Turbines

Wind turbines are designed to produce electrical energy as cheaply as possible. Wind turbines are therefore generally designed so that they yield maximum output at wind speeds around 15 meters per second. Its does not pay to design turbines that maximize their output at stronger winds, because such strong winds are rare.

In the case of stronger winds, it is necessary to waste part of the excess energy of the wind in order to avoid damaging the wind turbine. All wind turbines are therefore designed with some sort of power control.

There are two different ways of doing this safely on modern wind turbines—pitch and stall control, and a mix of both active stall.

1.2.2.1 Pitch Controlled Wind Turbines On a pitch controlled wind turbine, the turbine's electronic controller checks the power output of the turbine several times per second. When the power output becomes too high, it sends an order to the blade pitch mechanism, which immediately pitches (turns) the rotor blades slightly out of the wind. Conversely, the blades are turned back into the wind whenever the wind drops again.

The rotor blades thus have to be able to turn around their longitudinal axis (to pitch) as shown in Figure 1.1.

During normal operation, the blades will pitch a fraction of a degree at a time—and the rotor will be turning at the same time.

Designing a pitch controlled wind turbine requires some clever engineering to make sure that the rotor blades pitch exactly the amount required. On a pitch controlled wind turbine, the computer will generally pitch the blades a few degrees every time the wind changes in order to keep the rotor blades at the optimum angle and maximize output for all wind speeds.

The pitch mechanism is usually operated using hydraulics or electrical drives.

1.2.2.2 Stall Controlled Wind Turbines (Passive) stall controlled wind turbines have the rotor blades bolted onto the hub at a fixed angle.

Stalling works by increasing the angle at which the relative wind strikes the blades (angle of attack), and it reduces the induced drag (drag associated with lift). Stalling is simple because it can be made to happen passively (it increases automatically when the winds speed up), but it increases the cross section of the blade face-on to the wind, and thus the ordinary drag. A fully stalled turbine blade, when stopped, has the flat side of the blade facing directly into the wind.

If you look closely at a rotor blade for a stall controlled wind turbine, you will notice that the blade is twisted slightly as you move along its longitudinal axis. This is partly done in order to ensure that the rotor blade stalls gradually rather than abruptly when the wind speed reaches its critical value.

The basic advantage of stall control is that one avoids moving parts in the rotor itself, and a complex control system. On the other hand, stall control represents a very complex aerodynamic design problem, and related design challenges in the structural dynamics of the whole wind turbine, for example, to avoid stall-induced vibrations.

1.2.2.3 Active Stall Controlled Wind Turbines An increasing number of larger wind turbines (1 MW and up) are being developed with an active stall power control mechanism.

Technically, the active stall machines resemble pitch controlled machines, since they have pitchable blades. In order to get a reasonably large torque (turning force) at low wind speeds, the machines will usually be programmed to pitch their blades much like a pitch controlled machine at low wind speeds. (Often they use only a few fixed steps depending on the wind speed.)

When the machine reaches its rated power, however, you will notice an important difference from the pitch controlled machines: If the generator is about to be overloaded, the machine will pitch its blades in the opposite direction from what a pitch controlled machine does. In other words, it will increase the angle of attack of the rotor blades in order to make the blades go into a deeper stall, thus wasting the excess energy in the wind.

One of the advantages of active stall is that one can control the power output more accurately than with passive stall, so as to avoid overshooting the rated power of the machine at the beginning of a gust of wind. Another advantage is that the machine can be run almost exactly at rated power at all high wind speeds. A normal passive stall controlled wind turbine will usually have a drop in the electrical power output for higher wind speeds, as the rotor blades go into deeper stall.

The pitch mechanism is usually operated using hydraulics or electric stepper motors.

As with pitch control, it is largely an economic question whether it is worthwhile to pay for the added complexity of the machine, when the blade pitch mechanism is added.

1.2.3 Wind Turbine Aerodynamics

The actuator disk theory explains in a very simply way the process of extracting the kinetic energy in the wind, based on energy balances and the application of Bernoulli's equation. The rotor wind capturing energy is viewed as a porous disk, which causes a decrease in momentum of the airflow, resulting in a pressure jump in the faces of the disk and a deflection of downstream flows (Figure 1.2).

The theory of momentum is used to study the behavior of the wind turbine and to make certain assumptions. The assumptions are that the air is incompressible, the fluid motion is steady, and the studied variables have the same value on a given section of the stream tube of air.

The power contained in the form of kinetic energy in the wind crossing at a speed V_v, surface A_1, is expressed by

$$P_v = \tfrac{1}{2}\rho A_1 V_v^3 \tag{1.1}$$

where ρ is the air density.

The wind turbine can recover only a part of that power:

$$P_t = \tfrac{1}{2}\rho\pi R^2 V_v^3 C_p \tag{1.2}$$

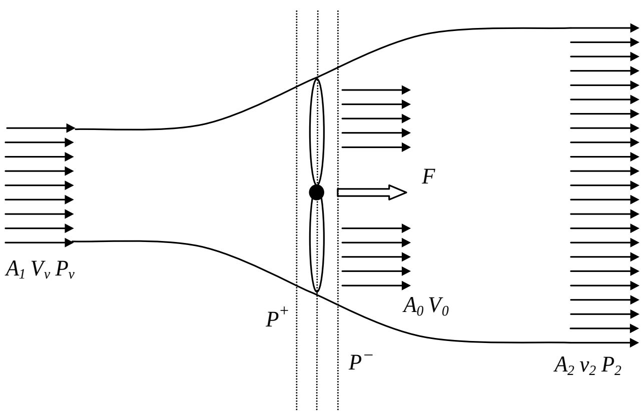

Figure 1.2 Schematic of fluid flow through a disk-shaped actuator.

where R is the radius of the wind turbine and C_p is the power coefficient, a dimensionless parameter that expresses the effectiveness of the wind turbine in the transformation of kinetic energy of the wind into mechanical energy.

For a given wind turbine, this coefficient is a function of wind speed, the speed of rotation of the wind turbine, and the pitch angle.

C_p is often given as a function of the tip speed ratio, λ, defined by

$$\lambda = \frac{R\Omega_t}{V_v} \tag{1.3}$$

where R is the length of the blades (radius of the turbine rotor) and Ω_t is the angular speed of the rotor.

The theoretical maximum value of C_p is given by the Betz limit:

$$C_{p\_theo\_max} = 0.593 = 59.3\%$$

The rotor torque is obtained from the power received and the speed of rotation of the turbine:

$$T_t = \frac{P_t}{\Omega_t} = \frac{\rho\pi R^2 V_v^3}{2\Omega_t} C_p = \frac{\rho\pi R^3 V_v^2}{2\lambda} C_p = \frac{\rho\pi R^3 V_v^2}{2} C_t \tag{1.4}$$

where C_t is the coefficient of torque. The coefficients of power and torque are related by the equation

$$C_p(\lambda) = \lambda \cdot C_t(\lambda) \tag{1.5}$$

Using the resulting model of the theory of momentum requires knowledge of the expressions for $C_p(\lambda)$ and $C_t(\lambda)$. These expressions depend mainly on the geometric characteristics of the blades. These are tailored to the particular site characteristics, the desired nominal power and control type (pitch or stall), and operation (variable or fixed speed) of the windmill.

The calculus of these curves can only be done by means of aeroelastic software such as Bladed or by experimental measurements.

From these curves, it is interesting to derive an analytical expression. This task is much easier than obtaining the curves themselves. Without analytical expression, it would save in table form a number of points on the curves and calculate the coefficient corresponding to a given λ (pitch angle) by means of a double interpolation.

The analytical expression for $C_p(\lambda)$ or $C_t(\lambda)$ may be obtained, for example, by polynomial regression. One typical expression that models these coefficients will be described in the next section.

Figure 1.3 shows an example of $C_p(\lambda)$ and $C_t(\lambda)$ curves for a 200 kW pitch regulated wind turbine.

The power and torque of the turbine are shown in Figure 1.4.

The wind speed V_v of precedent equations is not real; it is a fictitious homogeneous wind. It's a wind, expressed as a point of the area swept by the wind turbine, but the wind must be traceable torque T_t near the field that produced the true wind speed incident on the entire area swept by the rotor.

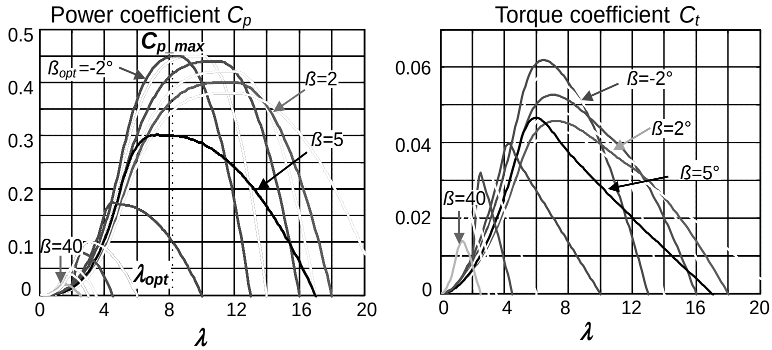

Figure 1.3 Curves of coefficients of power and torque of a 200 kW pitch regulated wind turbine, for different pitch angles β.

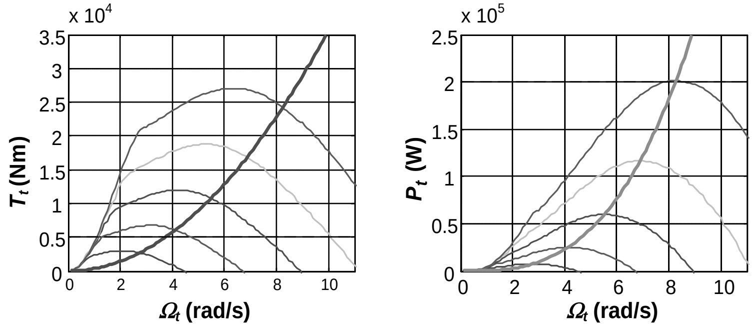

Figure 1.4 Curves of power and torque of a 200 kW pitch regulated wind turbine.

The generation of this fictitious wind can be really complicated depending on the phenomenon to be analyzed, for example, for flicker studies.

1.2.4 Example of a Commercial Wind Turbine

The Nordex N60 (1.3 MW nominal power) is a typical example of a fixed speed wind turbine based on the concepts explained previously. The main characteristics of the turbine are:

- The diameter of the turbine is 60 meters and has a stall power regulation.
- The rotor rotates at 12.8 and 19.2 fixed speeds.
- The gearbox is a three-stage design with a ratio of 78.3 for a 50 Hz wind turbine, with the first stage as a high torque planetary stage and the second and third stages as spur stages.
- The generator is a water-cooled squirrel cage asynchronous type. It is connected to the gearbox by a flexible coupling and it can turn at two speeds

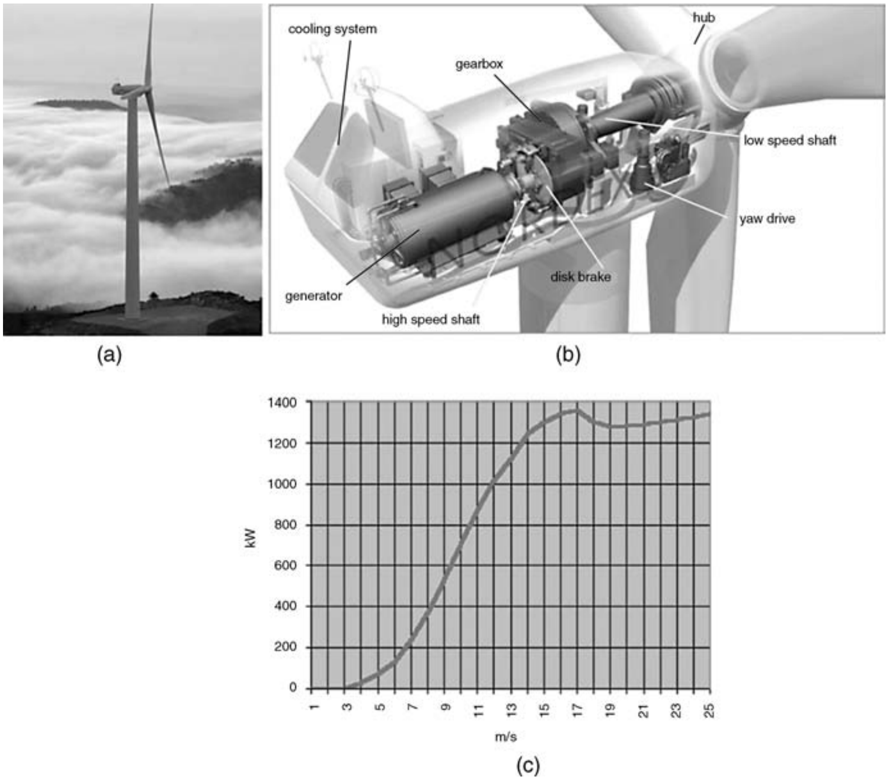

Figure 1.5 Nordex N60 fixed speed wind turbine: (a) picture of the complete wind turbine, (b) nacelle components, and (c) Power curve. (*Source:* Nordex).

(1000 and 1500 rpm), changing the number of pairs of poles of the machine (3 and 2).

- The generator is provided with a thyristor based soft-starter.
- The primary brake system is the aerodynamic blade tip brake. The secondary mechanical brake is a disk brake.

Figure 1.5 shows a picture of the Nordex N60, the main components located in the nacelle, and their power curve.

1.3 VARIABLE SPEED WIND TURBINES (VSWTs)

Figure 1.6 shows the nacelle layout of a Nordex N80 (2.5 MW nominal power), 2.5 MW variable speed wind turbine.

One must appreciate the big differences between the fixed speed and the variable speed wind turbines; it is a technological evolution from the first one. An increase

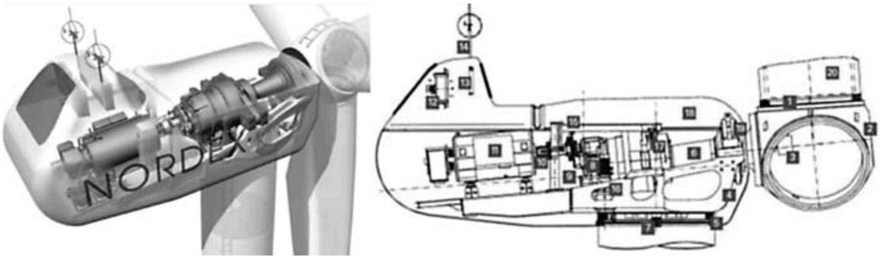

Figure 1.6 Nordex variable speed pitch regulated wind turbine. (*Source:* Nordex).

in size equals an increase in mechanical efforts, and the variable speed and the power control provide the tools to do this without risks. The major differences between them are:

- Power control is by means of pitchable blades.
- Doubly fed induction generator and power converters provide variable speed.

The main components of the nacelle and rotor are: (1) pitch bearing, (2) rotor hub, (3) pitch drive, (4) framework, (5) yaw adjustment bearing, (6) main rotor shaft, (7) yaw brakes, (8) gearbox, (9) holding brake, (10) coupling to generator, (11) generator, (12) cooler for the generator, (13) cooler for the gearbox, (14) wind sensors, (15) on-board crane, (16) yaw drive mechanism, (17) support of the gearbox, (18) nacelle fiberglass housing, (19) rotor bearing, and (20) stem of the rotor blade.

The following subsections will explain the basic models and control for the wind turbine. In Section 1.7 a more detailed description is given of commercial wind turbines.

1.3.1 Modeling of Variable Speed Wind Turbine

The proposed wind turbine model is composed of the following systems:

- Aerodynamic model, evaluates the turbine torque T_t as a function of wind speed V_v and the turbine angular speed Ω_t
- Pitch system, evaluates the pitch angle dynamics as a function of pitch reference β_{ref}
- Mechanical system, evaluates the generator and turbine angular speed (Ω_t and ω_m) as a function of turbine torque and generator torque T_{em}
- Electrical machine and power converters transform the generator torque into a grid current as a function of voltage grid
- Control system, evaluates the generator torque, pith angle and reactive power references as a function of wind speed and grid voltage

Figure 1.7 shows the interaction between the different subsystems.

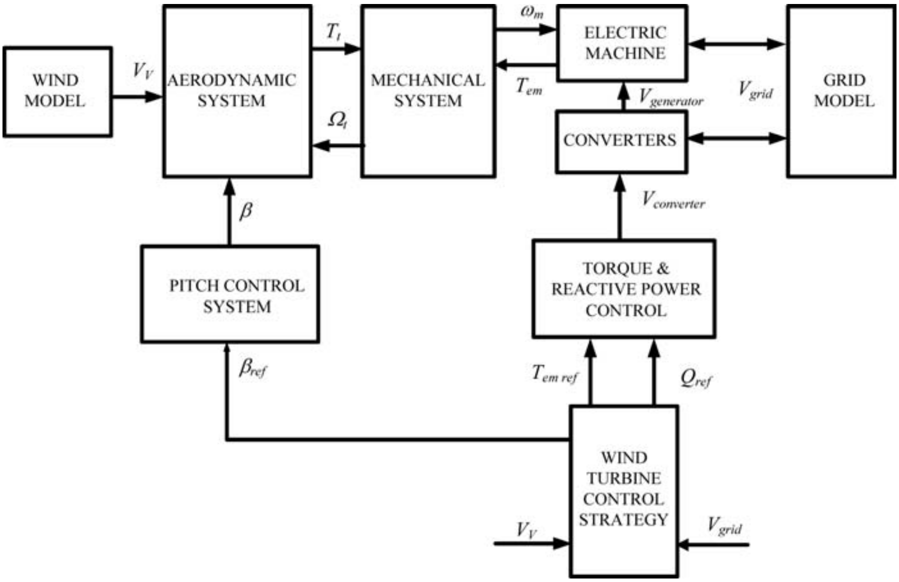

Figure 1.7 Block scheme of a variable speed wind turbine model.

1.3.1.1 Aerodynamic Model The aerodynamic model represents the power extraction of the rotor, calculating the mechanical torque as a function of the air flow on the blades. The wind speed can be considered as the averaged incident wind speed on the swept area by the blades with the aim of evaluating the average torque in the low speed axle.

The torque generated by the rotor has been defined by the following expression:

$$T_t = \tfrac{1}{2}\rho\pi R^3 V_v^2 C_t \tag{1.6}$$

As mentioned in a previous section, the most straightforward way to represent the torque and power coefficient C_p is by means of analytical expressions as a function of tip step ratio (λ) and the pitch angle (β). One expression commonly used, and easy to adapt to different turbines, is

$$C_p = k_1\left(\frac{k_2}{\lambda_i} - k_3\beta - k_4\beta^{k_5} - k_6\right)(e^{k_7/\lambda_i}) \tag{1.7}$$

$$\lambda_i = \frac{1}{\lambda + k_8} \tag{1.8}$$

with the tip step ratio,

$$\lambda = \frac{R\Omega_t}{V_v} \tag{1.9}$$

1.3.1.2 Mechanical System The mechanical representation of the entire wind turbine is complex. The mechanical elements of a wind turbine and the forces suffered or transmitted through its components are very numerous.

It is therefore necessary to choose the dynamics to represent and the typical values of their characteristic parameters. The first is the resonant frequency of the power train. The power transmission train is constituted by the blades linked to the hub, coupled to the slow shaft, which is linked to the gearbox, which multiplies the rotational speed of the fast shaft connected to the generator.

For the purpose of this simulation model, representing the fundamental resonance frequency of the drive train is sufficient and a two mass model, as illustrated in Figure 1.8, can then model the drive train. The second resonance frequency is much higher and its magnitude is lower.

All the magnitudes are considered in the fast shaft. Inertia J_t concerns the turbine side masses, while J_m concerns those of the electrical machine. These inertias do not always represent exactly the turbine and the electrical machine. If the fundamental resonance frequency comes from the blades, part of the turbine inertia is then considered in J_m.

The stiffness and damping coefficients, K_{tm} and D_{tm}, define the flexible coupling between the two inertias. As for the inertias, these coefficients are not always directly linked to the fast shaft but to the fundamental resonance, which may be located somewhere else.

D_t and D_m are the friction coefficients and they represent the mechanical losses by friction in the rotational movement.

The turbine rotational speed and driving torque are expressed in the fast shaft by

$$\Omega_{t\_ar} = N\Omega_t \tag{1.10}$$

$$T_{t\_ar} = \frac{T_t}{N} \tag{1.11}$$

where N is the gearbox ratio.

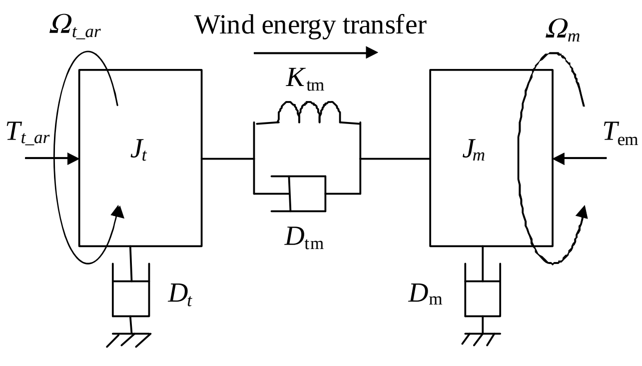

Figure 1.8 Two mass mechanical model.

Next,

$$
\begin{aligned}
J_t \frac{d\Omega_{t\_ar}}{dt} &= T_{t\_ar} - D_t\Omega_{t\_ar} - T_{em} \\
J_m \frac{d\Omega_m}{dt} &= T_{em} - D_m\Omega_m + T_{em} \\
\frac{dT_{em}}{dt} &= K_{tm}(\Omega_{t\_ar} - \Omega_m) + D_{tm}\left(\frac{d\Omega_{t\_ar}}{dt} - \frac{d\Omega_m}{dt}\right)
\end{aligned}
\tag{1.12}
$$

The model can be simplified by neglecting the damping coefficients (D_t, D_m, and D_{tm}), resulting in a model with two inertias (J_t and J_m) and the stiffness (K_{tm}). The resulting transfer function relating the generator torque and speed presents a pole at ω_{01} pulsation and a zero ω_{02} pulsation:

$$\omega_{01} = \sqrt{K_{tm}\frac{J_t + J_m}{J_t J_m}} \tag{1.13}$$

$$\omega_{02} = \sqrt{\frac{K_{tm}}{J_t}} \tag{1.14}$$

The pole has a frequency in the range between 1 and 2 hertz for a multimegawatt wind turbine.

1.3.1.3 Pitch System The controller is designed for rotating all the blades at the same angle or each of them independently. This independent regulation gives more degrees of freedom to the control system. This particular operation would reduce the stresses in the blades. The independent regulation of blades is an important innovation that will bring more intelligence into the control system of wind turbines.

In studying a dynamic control system, a blade pitch involves many torques and forces. The representation of this torques requires modeling the structural dynamics of the blade, the behavior of the air around the blades, or the inclusion of friction in the bearings. Moreover, regulation of the speed of rotation around the longitudinal axis of the blades has a bandwidth much greater than that of the control of the angle itself.

Given these last two observations, the most standard approach is to represent the loop control, the rate of change of pitch angle, and a linear system of first order containing the main dynamics of the actuator (hydraulic or electric).

In fact, when modeling the pitch control, it is very important to model the rate of change of this angle. Indeed, given the effort sustained by the blades, the variation of the pitch must be limited. It is limited to about 10°/s during normal operation and 20°/s for emergencies.

Regulation of the blade angle is modeled as shown in Figure 1.9, by a PI controller that generates a reference rate of change of pitch; this reference is limited and a first-order system gives the dynamic behavior of speed control of pitch variation. The pitch angle itself is then obtained by integrating the variation of the angle.