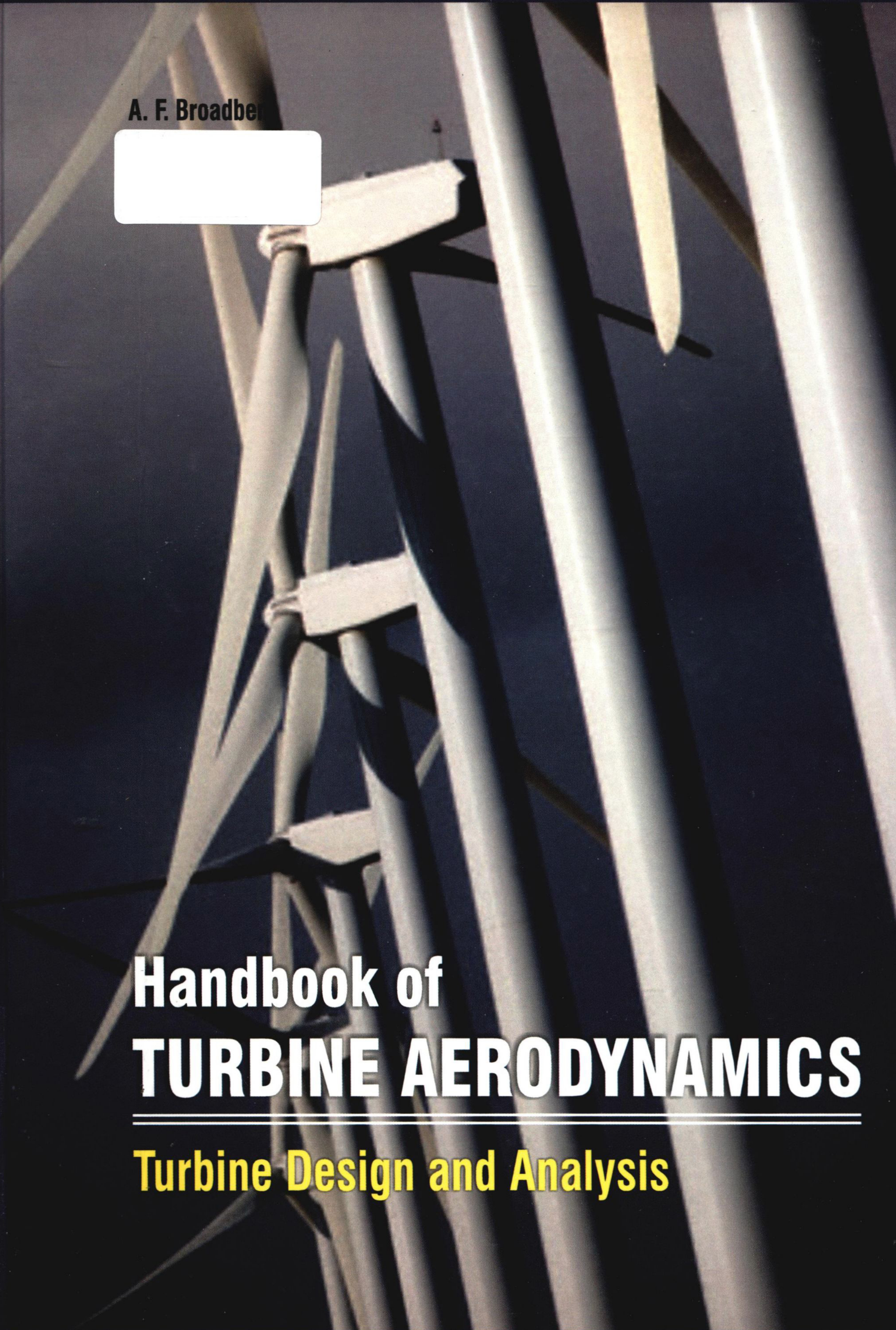

A. F. Broadbe

Handbook of TURBINE AERODYNAMICS

Turbine Design and Analysis

Handbook of
TURBINE AERODYNAMICS
Turbine Design and Analysis

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Handbook of
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PREFACE

It has become almost a ritual to preface a book. But this preface is much more than a ritual. It is a direct interaction with the readers of this book.

The readers of this book will have comprehensive knowledge on design and analyses of wind turbines and various aspects of aerodynamics related to wing turbines and gas turbines. Wind turbines use the same aerodynamics principals as aircrafts. Basic design principles and mechanical aspects of wind turbines are covered on Chapters 1 to 24. Aerodynamics principles of gas turbines have been covered in 4 chapters (No. 25-28).

Chapters 1 and 2 : Covers general consideration of aerodynamics related to wind turbines.

Chapter 3 : Cover aspects related to wind turbine blade aerodynamics.

Chapters 4, 5, 6, 7, 8 and 9 : Cover mechanical aspects related to wind turbines and wind power.

Chapters 10 and 11 : Cover electrical power generation system from a wind turbine.

Chapters 12 to 18 : Covers control methods on wind energy conversion system.

Chapters 19 to 25 : Cover basic principles of aerodynamics and various theories related to wind turbines.

Chapters 26 to 28 : Cover basic concepts of gas turbines and aerodynamics consideration.

I finally believe that there is always scope for improvement. Suggestion and comment from readers would be gratefully received and duly acknowledged.

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CONTENTS

Chapter 15

A Complete Control Scheme for Variable Speed Stall Regulated Wind Turbines

15.1 INTRODUCTION

Wind turbine generators comprise the most efficient renewable energy source. Nowadays, in order to meet the increasing demand for electrical power produced by the wind, wind turbines with gradually increasing power rating are preferred.

The variable speed pitch regulated wind turbine is the most dominant wind turbine technology so far, since it achieves high aerodynamic efficiency for a wide range of wind speeds and at the same time good power control to meet the variable utility grid power requirements. In particular, the power control is performed by altering the pitch angle of the rotor blades and consequently the aerodynamic efficiency of the rotor, through closed loop control, in order to keep the power at the specified level.

Although the above technology has been proved to be quite effective, limitations and challenges appear in the construction of Mega Watt scale wind turbines where larger rotor diameters are required. Specifically, as the rotor diameter increases, the challenges and the cost associated with the pitch mechanism increase too, since this mechanism now has to cope with very large and heavy rotor blades. In addition, due to the increasing height of the tower and the associated increase of the cost, lighter constructions are preferred, which are also more flexible and entail lightly damped tower vibration modes. These vibration modes can be easily excited by the action of the pitch controller (Bossanyi, 2003). Consequently, the stable operation of the whole system poses additional challenges on the design of effective pitch controllers and actuators, while at the same time the cost should be kept as low as possible.

The variable speed stall regulated wind turbine comprises a technology that has several advantages over pitch regulated wind turbines and has been of particular interest in the literature (Biachi et al, 2007). In particular, this type of wind turbine uses a rotor of fixed blade angle and therefore has a simpler and more robust construction and can have lower requirements for maintenance than the existing pitch regulated wind turbines. Due to these features, these wind turbines can have reduced cost, which is a crucial parameter especially for large scale wind turbines. In addition, they can be more economically efficient for offshore applications, where the maintenance is a major consideration. However, this type of wind turbine is not yet commercially available due to existing challenges in its control. Specifically, a variable speed stall regulated wind turbine is not an unconditionally stable system and has a dynamic behaviour which depends on the operating conditions (Biachi et al, 2007). Due to this feature, the control and the consequent construction of variable speed stall regulated wind turbines has not been feasible so far, since more sophisticated control methods than the existing ones are required.

In this chapter a novel control system for variable speed stall regulated wind turbines is presented. The presentation starts with background issues in wind turbines and control, including a brief review of existing attempts to solve the aforementioned control problem and continues with the detailed description of the design and operation of the proposed system. Next, simulation results obtained using a hardware-in-loop simulator are presented and analyzed and useful conclusions are drawn. Finally, recommendations and future work are presented in the last section.

15.2 GENERAL BACKGROUND IN THE CONTROL OF VARIABLE SPEED STALL REGULATED WIND TURBINES

The main components of a variable speed wind turbine are the turbine rotor, usually three bladed, the drivetrain, the generator and the power electronics. Fig. 15.1(a) gives a simple schematic of a wind turbine.

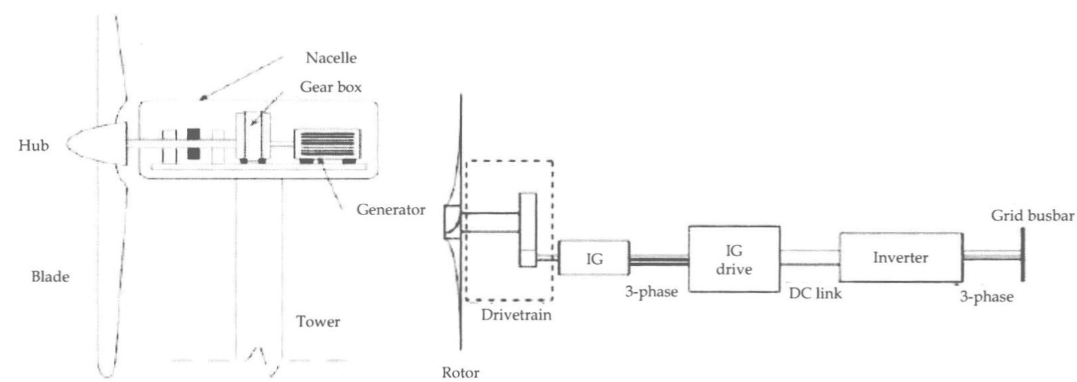

Fig. 15.1(a) Wind turbine schematic mechanical (Biachi et al, 2007) and (b) with electrical subsystem simple schematics, (utilizing an Induction Generator-IG)

The rotor blades can either be rigidly mounted on the rotor hub at a fixed "pitch angle" or through a variable pitch mechanism, for power limitation purposes. The interaction of the rotor blades with the oncoming wind results in the development of an aerodynamic torque T_a which rotates the rotor. For the transmission of this torque from the rotor to the generator, either a direct coupling or a step-up gearbox may be used, depending on the type and the number of pole pairs of the generator (induction, synchronous, synchronous with permanent magnets). In the case of a gearbox, the drivetrain also contains a Low Speed Shaft and a High Speed Shaft, at the rotor and generator side respectively. The power electronics of a variable speed wind turbine are comprised of a generator-side converter and a grid-side converter, both connected back-to-back via a DC link, as can be seen by the diagram in Fig. 15.1(b). The first converter, which can also work as a variable speed drive for the generator, acts as a rectifier, converting the variable frequency/variable amplitude AC voltage of the generator to DC voltage of variable level, while the second acts as an inverter, converting the DC voltage into AC of a frequency and amplitude, matching that of the grid.

15.2.1 Stall Regulation

Stall regulation refers to the controlled intentional enforcement of the rotor blades to stall and it can be achieved at constant speed, constant torque or constant power (Connor & Leithead, 1994; Goodfellow et al, 1988; Leithead & Connor, 2000).

Fig. 15.2 gives a schematic of a wind turbine rotor blade element, which helps to understand how stall works. In the figure 15.6 is the angle between the plane of rotation and the blade chord (pitch angle), where the chord is the line connecting the two ends of the blade. If the undisturbed wind velocity towards the blade is $\vec{V}_w$ and the blade tip velocity is $\vec{V}_b$, then the wind velocity seen by the rotating blade is $\overrightarrow{W} = \vec{V}_w - \vec{V}_b$, which creates with the blade chord an angle *a*, the "angle of attack". Due to the impinging wind $\overrightarrow{W}$, two forces are developed on the blade element, one perpendicular and one parallel to it, the Lift force, *L* and the Drag force *D* respectively.

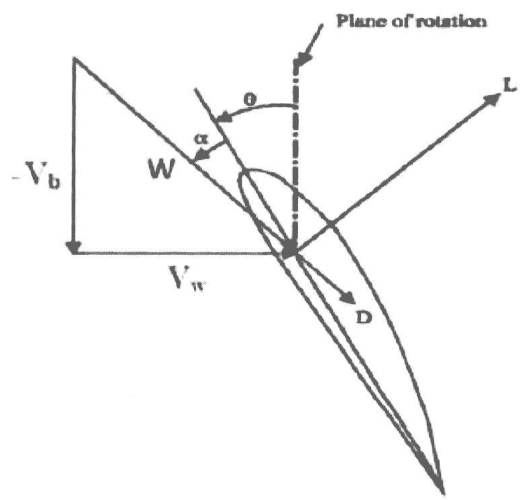

Fig. 15.2 Wind and rotor blade element velocities and forces acting on it (Kurtulmus et al, 2007)

In a wind turbine when the wind speed $|\vec{V}_w|$ increases relative to the blade tip speed $|\vec{V}_b|$, the angle ***a*** increases too, which results in an increase of *L* and consequently an increase of T_a. However, if the wind further increases and ***a*** exceeds a certain value, the air flow detaches from the upper side of the blade and turbulence is created. This results to a drop of the lift force and in turn to drops of T_a and the aerodynamic power P_a, while at the same time, the drag force increases.

In a variable speed stall regulated wind turbine the objective is to keep the power P equal to the rated P_N, so $P = P_N$ for every wind speed $V > V_N$, where V_N is the rated wind speed and this can be theoretically achieved by reducing the speed of the rotor via control of the reaction torque of the generator. This method comprises an implementation of stall regulation at constant power and it is still an open research area due to the nonlinear dynamics involved.

15.2.2 Aerodynamic Torque

When the rotor of the wind turbine is subjected to an oncoming flow of wind, an aerodynamic torque T_a is developed as a result of the interaction between the wind and the rotor blades, which rotate with angular speed ω. Using simplified aerodynamics, an expression of the aerodynamic power P_a has been derived (Biachi et al., 2007; Manwell, 2002). This is given in Eqn. 1:

$$P_a = \frac{1}{2}\pi\rho R^2 C_p V^3 \tag{1}$$

where ρ is the air density, R the radius of the rotor, C_p is the power coefficient of the rotor and V the effective wind speed seen by the rotor, which is a result of a number of phenomena due to the interaction of the rotor and the oncoming wind (Biachi et al, 2007). In particular, V is a quantity used in the equations that attempts to represent the effect on the produced torque of a 2-dimensional wind field with a 1-dimensional quantity. That way, harmonic components of the aerodynamic torque caused by the rotational sampling of the rotor (due to the wind shear or the small spatial correlation of the wind turbulence as well as to the tower shadow) are assumed to be present in the V timeseries. From the above it is obvious that V is a non-measurable quantity, since an anemometer gives only a point wind speed far from the turbine rotor (Leithead & Connor, 2000).

C_p is defined as ratio of the power extracted from the wind to the power available in the wind (Manwell, 2002; Parker, 2000) and it is a measure of the aerodynamic efficiency of the rotor, which indicates the ability of the rotor to extract power from the wind. It is also a nonlinear function of the tip-speed ratio $\lambda = \omega R/V$ and the pitch angle θ and it is particular for each rotor, with its shape depending on the rotor blade profile. C_p has a theoretical maximum of C_{pmax} = 0.593, known as the Betz limit, which indicates that the maximum ability to extract power from the wind is less than 60% (Biachi et al., 2007; Parker, 2000). In practice this value is lower, usually C_{pmax} = 0.45. In general, for a wind turbine it is desirable to operate at C_{pmax} for every V and so to have maximum aerodynamic efficiency for every V, unless the rated power of the wind turbine P_N is reached. Also, the torque coefficient of the rotor is defined as $C_q=C_p/\lambda$ and expresses the ability of the wind turbine rotor to produce torque. Typical C_p and C_q curves of a rotor with blades at a fixed pitch angle *6* are given in Fig. 15.3.

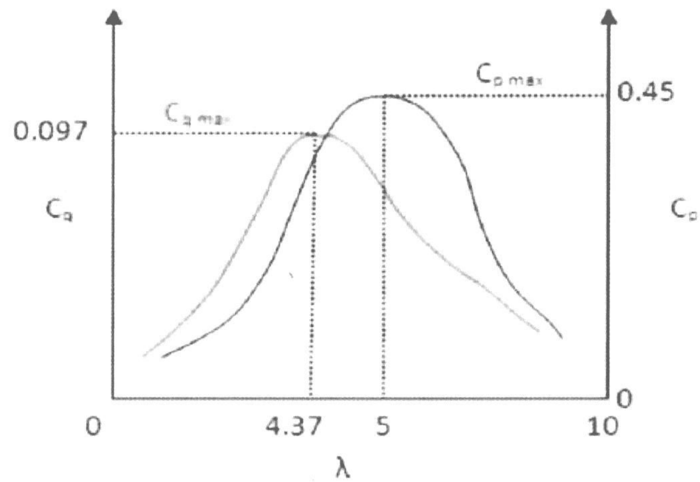

Fig. 15.3 Typical C_p (black) and C_q (red) curves of a stall regulated wind turbine

In Fig. 15.3 it can be observed that the maximum of the torque coefficient (C_{qmax}) is obtained at a lower tip speed ratio than the maximum power point (C_{p-max}), which is the case in general. The value of λ that corresponds to C_{pmax} is the optimum tip speed ratio, λ_o:

$$\lambda_o = \frac{\omega_o R}{V} \tag{2}$$

where ω_o is the optimum rotational speed of the rotor for a given V.

The aerodynamic torque of the rotor of the wind turbine is given by:

$$T_a = \frac{P_a}{\omega} = \frac{1}{2\omega}\pi\rho R^2 C_p V^3 = \frac{1}{2}\pi\rho R^3 C_q V^2 \tag{3}$$

The above expression for the aerodynamic torque has been used for the control system design and for wind turbine simulations using a hardware-in-loop simulator as will be seen later. In particular, for the wind turbine simulation, a model of the dynamic inflow has also been included, using a lead lag filter (Parker, 2000). The dynamic inflow relates to dynamic phenomena occurring during the development of T_a under changes of ω or V, which are not represented in Eqn. 3 (Biachi et al, 2007; Parker, 2000).

12.2.3 Control for Below Rated Operation

Due to the different objectives that must be satisfied by the control system of the wind turbine, the operating region of the wind turbine is divided in the below rated area and the above rated area, where the terms below and above rated refer to operation in wind speeds below and above the rated V_N respectively, where V_N is defined as the wind speed where the wind turbine produces rated power P_N. In this paper focus is put on the below rated control, while requirements and issues to be addressed for above rated control are also mentioned throughout the chapter.

The main control objective for a variable speed wind turbine for below rated operation is maximum power production. This control objective can be shown graphically in an a $T_a - \omega$ plane, as the one of Fig. 15.4, where the T_a characteristics of the wind turbine are given as functions of ω, for several values of V and the locus of the maximum power points is shown for every V.

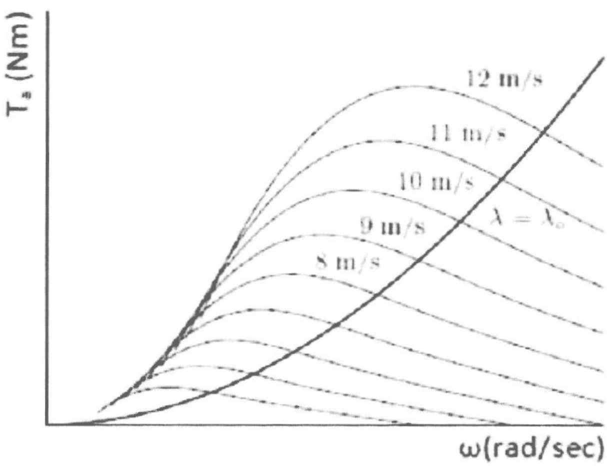

Fig. 15.4 T_a characteristics and maximum power point locus (Biachi et al., 2007)

The maximum power point locus is a quadratic curve described by Eq. 4:

$$T_a = K\omega^2 \tag{4}$$

where

$$K = \frac{1}{2\lambda_o^3}\rho\pi R^5 C_{pmax} \tag{5}$$

The control of the generator of commercial variable speed pitch regulated wind turbines in below rated conditions is currently performed by setting its torque equal to the value given in Eqn. 4 (Biachi et al., 2007; Manwell, 2002; Leithead, 1990; Bossanyi, 2003). Hence, the control law for the generator torque is given as:

$$T_g = K\omega^2 \tag{6}$$

Compensation for the drivetrain losses can be also included:

$$T_g = K\omega^2 - \gamma\omega \tag{7}$$

where γ is the estimated friction loss coefficient and K is given by Eqn. 5. It is mentioned that in general, measurement of the rotor speed ω is not available, therefore, the control of Eqns. 6–7 is realized through the generator speed measurement ω_g, which is nominally equal to ω scaled up with the gearbox ratio, N, in case this is used. Of course, the factor K of Eqn. 5 then takes into consideration the presence of a gearbox.

The control of Eqns. 6-7 is often mentioned as Indirect control, since it does not take into account the dynamics of the wind turbine, due to the large rotor inertia and therefore it has the disadvantage that it can lead to considerable deviations of the operating point from C_{pmax}, during fast wind speed changes (Biachi et al., 2007; Leithead, 1990). It is established in (Leithead, 1990) that this control law performs better, when the C_p curve is broad, as is the case in variable speed