Renewable Energy 40 (2012) 1–12

Contents lists available at SciVerse ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Power curve tracking in the presence of a tip speed constraint

C.L. Bottasso [a,*], A. Croce [a], Y. Nam [b], C.E.D. Riboldi [a]

[a] *Dipartimento di Ingegneria Aerospaziale, Politecnico di Milano, Via La Masa 34, 20156 Milano, Italy*
[b] *Department of Mechanical and Mechatronics Engineering, Kangwon National University, Hyoja 2-dong, Chunchon, Kangwon, 200-701, Republic of Korea*

ARTICLE INFO

Article history:
Received 30 July 2009
Accepted 28 July 2011
Available online 17 September 2011

Keywords:
Wind energy
Variable speed wind turbine
Power curve
Noise
Control laws

ABSTRACT

This paper considers the problem of power regulation for a variable speed wind turbine in the presence of a blade tip speed constraint, for example to limit noise emissions. The main contribution of the paper is the formulation of a policy for the regulation of the machine in the transition region between the classical regions *II* and *III* that accommodates the tip speed constraint, and the derivation of associated wind schedules for the rotor speed, blade pitch and aerodynamic torque. To exemplify the possible use of such wind schedules in the design of control laws, model-based controllers are formulated in this paper that are capable of performing power curve tracking throughout all wind speeds, in contrast with commonly adopted approaches that use switching controllers to cover the various operating regimes of the machine. The proposed regulation policies and control laws are demonstrated in a high fidelity simulation environment for a representative 3 MW machine.

1. Introduction

Variable speed wind turbines are regulated according to different policies, depending on the intensity of the mean wind speed. Typically, one may distinguish two main power production regimes (see e.g [8]).

In the first, called region *II*, the machine operates at maximum power coefficient, which means that the wind turbine is governed so as to maintain a constant tip-speed-ratio (TSR) for varying wind speeds; as the wind increases, the rotor angular speed also increases. This regulation policy is obtained by keeping the blade pitch setting fixed at the value of maximum power coefficient, and by modulating the electrical torque so as to trim the machine at the desired rotor speed. In region *II*, the generated power increases according to a cubic law with increasing wind speed.

A second power production regime is called region *III*, which begins for a wind intensity, called rated wind, such that the machine reaches rated power. For winds higher than rated, the machine is kept operating at constant rotor speed and constant torque, and hence at constant power. This regulation policy is obtained by pitching the blades so as to adjust the aerodynamic torque at each mean wind speed value.

Power curve tracking in the two regions imply different regulation policies: constant pitch – variable torque for region *II*, and variable pitch – constant torque in region *III*. Because of this reason, it is a rather common practice to use switching control laws: two different regulators operate in the two different regions, and switching between the two is performed according to the current wind speed. This means that one has to develop two different controllers; furthermore, there is often the need to devise some kind of blending scheme to avoid too sudden a switching between the two operating regimes, which may cause load peaks or vibrations.

Things become even more complicated for large wind turbines with noise constraints. In fact, since wind turbine generated noise is very well correlated with blade tip speed [3,15,18], one of the most effective ways to design relatively quiet wind turbines is to simply place a limit on the blade tip speed (although, clearly, further benefits can be achieved by other means, such as the choice of appropriate airfoils, planform and tip shapes, etc.). For a given rotor radius, a limit on the blade tip speed implies a limit on the rotor speed; for large wind turbines, such a limit is often smaller than the rotor speed necessary to achieve rated power at the end of region *II*. Consequently, the introduction of an upper limit on rotor speed alters the situation described above of regulation with sole two policies, as one now necessitates of a third transition region in between regions *II* and *III* [8].

Therefore, in the presence of a blade tip constraint, it is necessary: a) to define a regulation policy in the transition region, and b) to design control laws capable of effective power curve tracking in

---

* Corresponding author. Tel.: +39 02 2399 8315; fax: +39 02 2399 8334.
E-mail address: carlo.bottasso@polimi.it (C.L. Bottasso).
URL: http://www.aero.polimi.it/~bottasso

0960-1481/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.renene.2011.07.045

all these operating regimes. Clearly, the use of switching regulators in this case becomes a little more problematic. In fact, one has now to design three different control laws, and to devise suitable blending schemes at all transition points from one region to the next.

These problems have been considered in the recent literature. Particularly relevant to the present discussion are developments in the area of control scheduling, which is used for ensuring appropriate performance across the entire operating range of the machine, by accounting for its regime-dependent dynamics. Among the many possible sources, we mention here Ref. [17] that presents a comprehensive review of gain scheduling techniques, and Ref. [16] which addresses the specific case of scheduling for wind turbine control. Recently, Linear Parameter Varying (LPV) control has received considerable attention, because it provides for a theoretical formulation of the problem of gain scheduling and because it can lead to precise statements regarding the stability properties of the controller. LPV control of wind turbines is described in Ref. [6] and references therein, as well as in Refs. [24,7] among others.

Often, scheduling of wind turbine controllers is driven by the wind speed, since this enables the same scheduling logic to be used over the entire operating envelope of the machine. Estimates of the wind for this purpose can be obtained by the use of ad hoc estimators, as described for example in Refs. [12,19,20,23].

Within the area of power regulation across the whole wind speed range, described above, the present work has two main goals.

First, we describe a formulation of the transition region, here named region *II½*, that accounts explicitly for power production, the presence of the tip speed constraint, and torque-rotor speed stability. The resulting regulation policies in regions *II*, *II½* and *III* define smoothly varying wind-dependent regulation set points for the rotor speed, collective blade pitch and rotor torque, throughout the whole range of operating wind speeds. Although regulation policies similar to the one here described are probably used by manufacturers of large (especially on-shore) wind turbines, we are not aware of publications describing in detail how to formulate the transition region.

A second goal of the present work is to develop an example of the use of the proposed regulation policy for the implementation of a scheduled control law. To this end, we consider the case of model-based optimal controllers, which have received considerable attention since almost twenty years for the regulation of wind turbines, as described in Ref. [8] and more recently in Ref. [13]. More specifically, considering the well known case of linear quadratic regulators (LQR) [22,8], it is shown here how the proposed wind-scheduled policy can be used to define a wind-varying reference for feed-forward control [28,29] driven by wind estimates [12,19,20,23]. It should be stressed that by using wind-scheduled LQR control one can not guarantee the stability of the closed-loop system; although stability seldom seems to pose problems in wind turbine control, we notice that a similar wind-scheduling approach could be implemented using LPV control, for which one can indeed prove stability.

Since goal regulation quantities vary with continuity across the wind speed range, there is no need to use different controllers in the different operating regimes, nor there is any need to introduce switching logics or blending schemes to deal with the transitions from one region to the next. In fact, controllers designed on the basis of the proposed wind-scheduled regulation policies are not even aware of the presence of different operating regions: all they deal with are wind scheduled goal regulation states, which vary in a smooth way as the wind speed changes. This comes with a substantial simplification in the formulation, coding, testing and tuning of the control laws.

The paper is organized according to the following plan. At first, we describe wind scheduled regulation strategies, describing policies in region *II*, *II½* and *III*. This part is completed by showing rotor speed, pitch and torque wind schedules for a hypothetical representative 3 MW wind turbine, and by illustrating the effect of the transition region on the torque-rotor speed stability of the machine. Next, we formulate both a collective LQR and an individual blade pitch LQR; the latter uses the azimuthal position of the rotor to introduce individual pitch variations for the rotor blades that help in reducing harmonic load components, with a resulting reduced fatigue damage to the structure. It is not the goal of this paper to thoroughly compare these two different LQR formulations between themselves and with other possible approaches; their goal here is just to show that the proposed approach is readily applicable to various model-based controllers, irrespectively of the details of their formulations. Finally, the two controllers are used for demonstrating power curve tracking in a high fidelity simulation environment using a detailed aero-servo-elastic wind turbine model.

2. Wind scheduled regulation strategies

The different wind speed operating regimes of a variable speed wind turbine are named regions I, *II* and *III*. In region I, the machine is not yet in a power production mode since the wind is not sufficiently high to maintain the machine in operation.

2.1. Region II regulation

Power production begins at the cut in wind speed, which signals the beginning of region *II*. The power P can be expressed in general as

$$P = \frac{1}{2}\rho A V^3 C_P(\lambda, \beta), \tag{1}$$

where ρ is the air density, A the rotor area, V the wind speed, C_P the power coefficient, which depends on the TSR $\lambda = \Omega R/V$, with Ω the rotor angular speed and R the rotor radius, while β is the collective blade pitch setting.

In region *II*, power is maximized by operating for all wind speeds at the maximum value of the power coefficient, which is computed by solving the following optimization problem

$$C_P^{II} = \max_{\lambda,\beta} C_P(\lambda, \beta). \tag{2}$$

The constant (with respect to the wind speed) values of TSR and blade pitch that correspond to the maximum value of the power coefficient C_P^{II} are indicated as λ^{II} and $\beta^{II,}$ respectively:

$$\lambda^{II}, \beta^{II} = \arg\max_{\lambda,\beta} C_P(\lambda, \beta). \tag{3}$$

Fig. 1 shows the behavior of the $C_P - \lambda - \beta$ curves for a hypothetical 3 MW machine, and the values of the optimal parameters C_P^{II}, λ^{II} and $\beta^{II.}$ The tracing of the curves of Fig. 1 using a comprehensive aero-servo-elastic model is explained later on in 3.3.

Since in region *II* the TSR is held constant, $\lambda^{II} = const.$, the rotor angular speed increases linearly with the wind speed V:

$$\Omega(V) = \frac{\lambda^{II} V}{R}. \tag{4}$$

It is readily verified that the power and rotor aerodynamic torque increase with increasing wind speed as