Comparison of Variable Speed Wind Turbine Control Strategies

S. Arnaltes

Department of Electrical Engineering
Escuela Politécnica Superior, Universidad Carlos III de Madrid
Avda. Universidad 30, 28911 Leganés (Spain)
phone:+34 916 249911, fax:+34 916 249430, e-mail: arnalte@ing.uc3m.es

Abstract. Variable speed operation of wind turbines presents certain advantages over constant speed operation. Basically, variable speed wind turbines use the high inertia of the rotating mechanical parts of the system as a flywheel; this helps to smooth power fluctuations and reduces the drive train mechanical stress. Also, variable speed systems could lead to maximise the capture of energy during partial load operation. In this paper alternative control strategies for variable speed operation are considered and compared from the point of view of energy yield and power quality. Control aim is always maximum power generation. Maximum power tracking and power fluctuation will be analysed when exciting the different configurations with a particular wind profile. Also fixed speed wind turbine are considered for the comparison.

Key words

wind energy, power quality, flicker, wind turbine control.

1. Introduction

Early wind energy conversion systems were based on generators directly connected to the grid, hence the speed of these systems was constant (with synchronous generators) or quasi-constant (with asynchronous generators). The evolution of power semiconductors has contributed enormously to variable speed wind energy conversion systems by interfacing the constant frequency of the grid to the variable frequency of the generator.

Variable speed operation of wind turbines demands the application of variable speed generators operating on the constant frequency of the grid. Different types of generators can be used, usually induction generators (with cage or wound rotor) or synchronous generators (with field winding or permanent magnets); all of them require the use of a suitable electronic power converter.

Different control strategies have been proposed in the literature for variable speed operation, but a possible classification could lead to the so-called speed-mode control and torque-mode control [1]. Torque-mode control consists of obtaining an electrical torque reference from the shaft speed measurement that leads to the optimal tip speed ratio [2]. Of course, instead of a torque reference, a power reference can also be obtained [3, 4]. Speed-mode control is based on obtaining a rotational speed reference that leads to the optimal tip speed ratio, thus a speed control loop is required. There are different approaches to obtaining this speed reference. A wind speed measurement can be used to derive the rotational speed reference [5]. The disadvantage of this method is that an anemometer is required, which measures only the wind velocity at one point of the rotor, and also this measurement is affected by the rotor wake. An estimation of the wind velocity can be used instead [6]. Another speed-mode control alternative consists of obtaining the rotational speed reference from a power (or torque) - speed characteristic that leads to the optimal tip speed ratio. This method has the disadvantage of requiring a wind turbine torque observer [7], although generator torque (or power) can also be used, but rotational speed reference will be the optimal only at steady state. Finally, the speed reference that maximize the turbine power can be obtained through a fuzzy logic based search as in [8].

For wind velocities higher than rated, the capture of energy by the turbine must be limited by stall or pitch control. For the following only wind velocities bellow rated are considered, as only in that range of velocities maximum power can be achieved.

2. Variable speed control strategies

The aerodynamic power of a wind turbine is given by the equation:

$$P = \frac{1}{2} \rho \pi R^2 v^3 c_p \tag{1}$$

where ρ is the air density, R the turbine radius, v the wind speed and c_p the power coefficient.

The power coefficient is defined as the ratio of turbine power to wind power, and it is a function of the tip speed ratio (λ) as well as the blade pitch angle (β). For the following β is considered constant, as it changes only when full load is achieved through a feedback control loop that regulates power output. λ is defined as the ratio of turbine speed at the tip of a blade to wind velocity, and given by:

$$\lambda = \frac{R \cdot \Omega}{v} \quad (2)$$

where Ω is the turbine speed. In a typical wind turbine with a fixed β, function $c_p(\lambda)$ shows (figure 1) that there is an optimum value of tip speed ratio (λ_{opt}) that makes power coefficient maximum ($c_{p,max}$). Figure 2 shows the turbine power-speed characteristics for various wind velocity values.

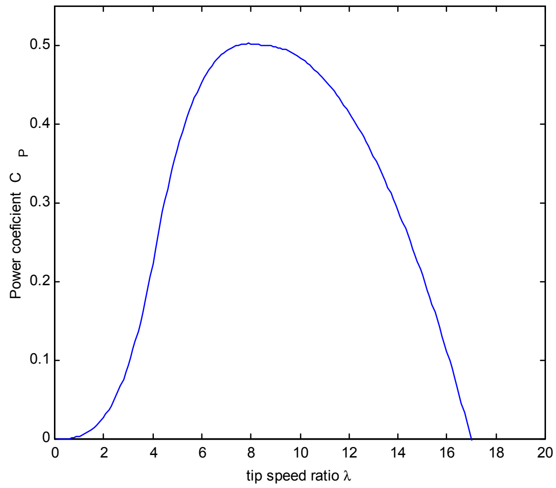

Fig. 1. Function cp(λ)

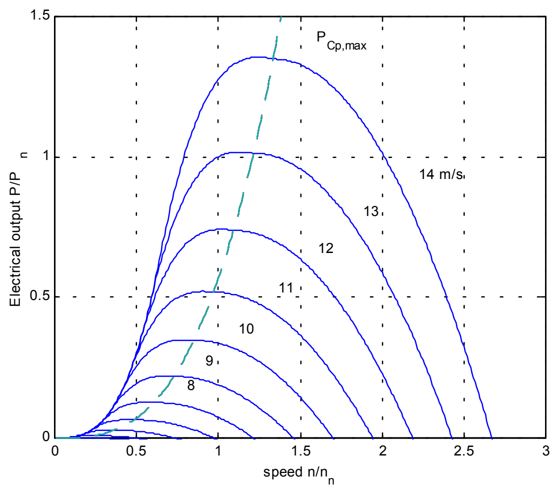

Fig. 2. Power-speed characteristics

By eliminating wind speed from (1) y (2), when power coefficient is maximum:

$$P_{max} = \frac{1}{2} \rho \pi R^2 \left(\frac{R \cdot \Omega_{opt}}{\lambda_{opt}} \right)^3 c_{p,max} \quad (3)$$

where Ω_{opt} is a function of wind speed:

$$\Omega_{opt} = \frac{\lambda_{opt} \cdot v}{R} \quad (4)$$

then

$$P_{max} = K \cdot \Omega_{opt}^3 \quad (5)$$

or, by dividing both terms of (5) by Ω_{opt}

$$T_{opt} = K \cdot \Omega_{opt}^2 \quad (6)$$

where

$$K = \frac{1}{2} \rho \pi R^5 \frac{c_{p,max}}{\lambda_{opt}} \quad (7)$$

Expression (5) shows that maximum power a particular turbine can extract from wind is a cubic function of the turbine optimum speed (figure 2). Expression 6 shows the relationship between torque and speed at the maximum power point of operation.

Two control strategies for capturing the maximum power from a particular wind are going to be considered: speed-mode control and torque-mode control.

A. Speed-mode control

Expression (2) shows that for extracting maximum power from a particular wind, control has to adjust turbine speed so that optimum tip speed ratio (λ_{opt}) is always obtained.

Speed reference that achieves maximum power can be obtained in different ways. First, it can be obtained from the measurement of wind velocity by using (4), but an anemometer is required, which measures only the wind velocity at one point of the rotor, and also this measurement is affected by the rotor wake.

An estimation of wind velocity as seen by the whole turbine rotor can be used. At the maximum power point rotational speed and wind velocity are related by expression (4). Then optimal speed can be obtained directly from (6) as:

$$\Omega_{opt} = \sqrt{\frac{\hat{T}_t}{K}} \quad (8)$$

where $\hat{T}_t$ is an estimation of the turbine torque. This method presents the disadvantage of requiring a turbine torque observer.

In steady state, turbine torque is equal to generator torque, so if maximum power tracking is only an objective in steady state, then optimal speed can be obtained from (5) using generator power output as input:

$$\Omega_{opt} = \sqrt[3]{\frac{P_g}{K}} \tag{9}$$

This method has the advantage of using generator power as input, which is a variable that can be easily measured (in fact it is measured for other control functions).

Figure 3 shows the system block diagram. Here for a particular wind velocity (lower than rated), a speed reference that achieves maximum power is given to a speed control loop. The speed controller will set a torque reference to the electrical generator. Balance between turbine torque and generator torque will result in an accelerating (or decelerating) torque until desired speed is achieved. A subordinated torque control loop will control generator torque by acting on the proper variable, depending on the generator type.

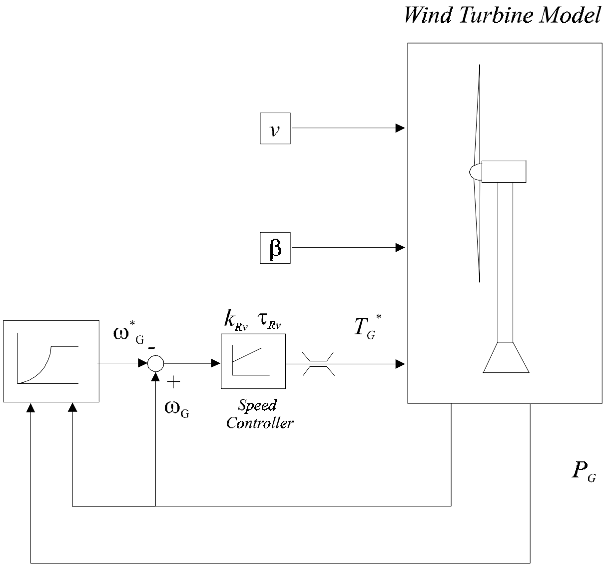

Fig. 3. Speed mode control block diagram

Speed-mode control assures a fast tracking of maximum power if a high bandwidth speed control loop is used, but as it will be shown later, although energy capture is maximised the results are not so good from the power quality point of view.

B. Torque- mode control

Expression (6) shows the relationship between torque and speed at the maximum power point. Then, in order to obtain the turbine optimal torque, control has to adjust the generator torque reference so that maximum power is obtained. In steady state turbine torque is equal to generator torque. Then, maximum power can be achieved by demanding an electrical torque from the generator as:

$$T_g = K \cdot \Omega^2 \tag{10}$$

Figure 4 shows the system block diagram, here for a particular wind velocity (lower than rated), an electromagnetic torque reference that achieves maximum power is given to the inner torque control loop. If wind velocity increases suddenly there will be an increase of turbine torque, and because turbine speed can not change instantaneously, from the above expression generator torque will remain the same, resulting in an accelerating torque until the new optimal point of operation is achieved.

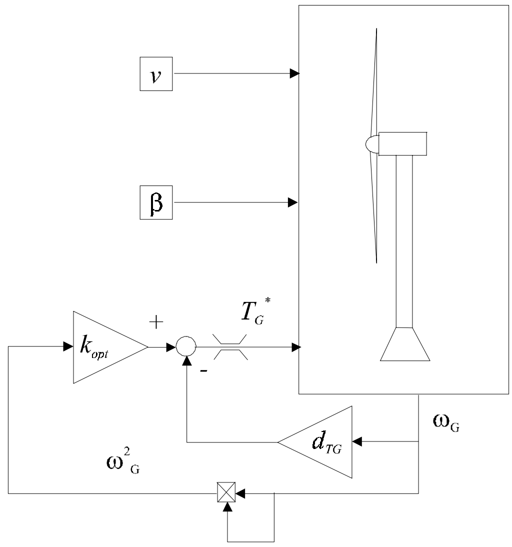

Fig. 4. Torque mode control block diagram

3. Simulation Results

A comparative analysis of the aforementioned control strategies is going to be carried out by using simulation results. To compare simulation results the following characteristics are used: maximum power tracking and power quality. These characteristics are quantified as follows:

- Maximum power tracking is evaluated as the energy yield during simulation time.
- Power quality is evaluated as generator power output standard deviation.

For the comparative analysis four cases are considered:

- Case 1: fixed speed wind turbine.
- Case 2: torque mode control strategy.
- Case 3, a and b: speed mode control strategy.

As it has already been said, a speed controller is needed when the wind turbine is being operated in the speed mode control. This controller is going to affect greatly the dynamic behaviour of the whole system. So, special attention is going to be paid to the design of the speed controller. A PI controller has been chosen for the speed control loop. For the comparative analysis two controllers have been designed (cases a and b), both have been designed to provide the same phase margin, but they differ in the resulting speed control loop bandwidth. The parameters of both controllers and the resulting characteristics of the control loops are given in Table I.

Table I. Speed control loop parameters and characteristics

PI Controller	Proportional Gain	Integral Gain	Phase Margin	Bandwidth
Case a	10.94	7.76	65º	2 rad/s
Case b	22.04	31.04	65º	4 rad/s

System response will be obtained when exciting the wind turbine with a particular wind profile. This wind profile, given in figure 5, represents the wind velocity on the turbine rotor as measured by an anemometer.

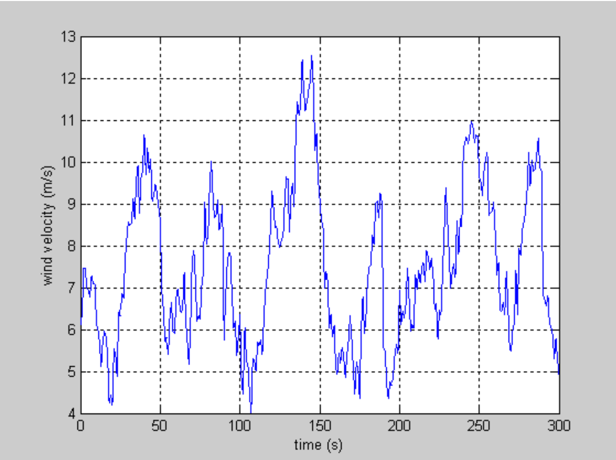

Fig. 5. Wind profile

The parameters of the wind turbine and the wind profile are given in Table II.

Table II. Turbine and wind profile characteristics

Turbine radius	25.85 m
Rated power	1 MW
Rated rotational speed	26.6 rpm
Inertia constant	3.88 s
Rated wind velocity	12 m/s
Mean wind velocity	7.5 m/s
Turbulence intensity	0.244

A. Maximum power tracking analysis

Figures 6, 7, 8 and 9 show system responses in cases 1, 2, 3a y 3b, respectively. In figures, rotational speed response is shown in red, while power output response is shown in magenta. Obviously, speed is nearly constant in case 1, while in cases 2 and 3 rotational speed tends to follow wind velocity variations. Figures show that the dynamic tracking of maximum power is better in speed mode control than in torque mode control, and also that the higher the controller bandwidth the better the tracking. Nevertheless, as a consequence of this, generator torque oscillations, imposed by the speed controller for achieving optimal tip speed ratio, are going to affect power output fluctuations.

From figures, it seems that speed mode control of variable speed wind turbines produces even more power fluctuations than fixed speed wind turbines, and the higher the controller bandwidth the higher the power fluctuations. Obviously, the best power response is obtained in case 2, where torque mode control of a variable speed wind turbine is used. When integrating power output in the studied time interval, energy yield in that period is obtained (see table III). Energy capture is higher in case 3b, when turbine speed follows wind velocity more accurately, and energy capture is obviously lower in case 1, when fixed speed wind turbine is used.

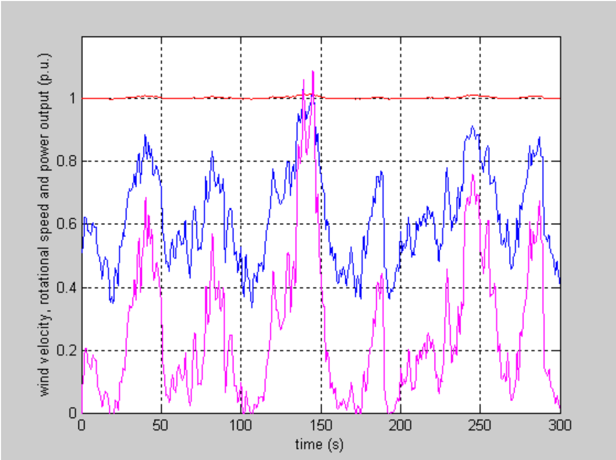

Fig. 6. Simulation results (case 1)

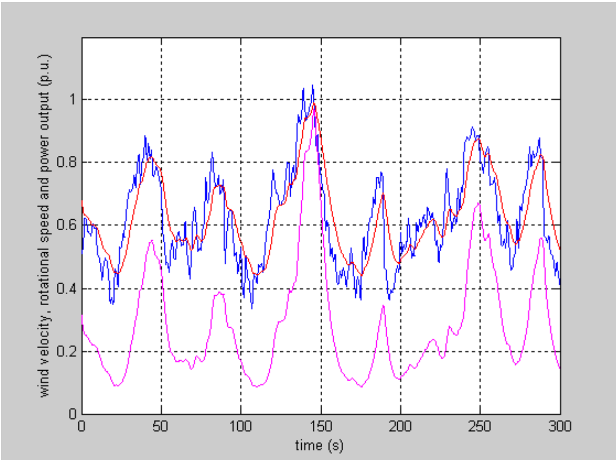

Fig. 7. Simulation results (case 2)

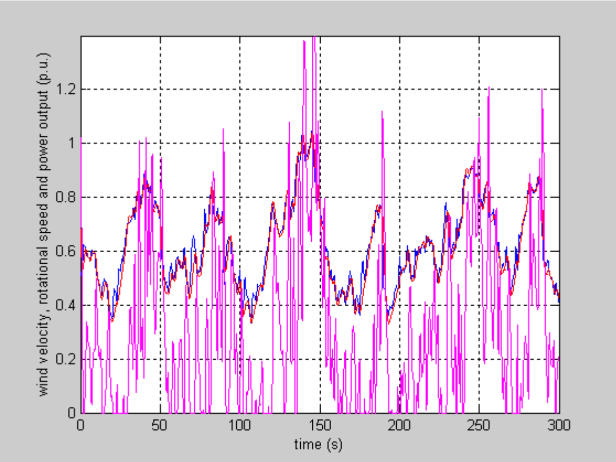

Fig. 8. Simulation results (case 3a)

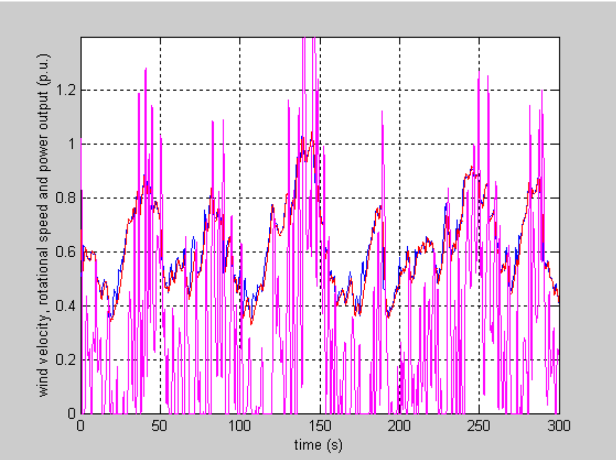

Fig. 9. Simulation results (case 3b)

Nevertheless, energy yield and hence the deviation from maximum power coefficient depends on the shape of the c_p-λ curve. With a sharp characteristic a significant increase in energy capture can be obtained when a good power tracking control method is employed.

B. Power quality analysis

As shown in figures 6, 7, 8 and 9, wind turbines produce a power output that is not constant due to wind variations. Power oscillations produce voltage fluctuations at the point of common coupling (PCC), which increase with the turbulence intensity. Voltage flicker can become a limiting factor for connecting wind turbines at weak networks, and even on relatively strong networks with a high wind power installed capacity.

Variable speed wind turbines can improve many aspects of power quality in distribution grids due to the reduction of short-term power fluctuations that results in a reduction of flicker. Also, reactive power can be controlled in variable speed wind turbines which helps to improve power quality.

Measuring flicker at the PCC has the disadvantage that the measurement include the contribution to the flicker produced by other equipment connected to the same PCC. For this reason, the evaluation of flicker emission by wind turbines is based on current, or power, measurements instead of voltage.

Voltage fluctuations ΔU at PCC are related to power fluctuations according to:

$$\Delta U = \frac{P \cdot R + Q \cdot X}{U} \qquad (10)$$

where P and Q are, respectively, the active and reactive power injected into the grid by the wind turbine generator (figure 10) and R and X are, respectively, the shortcircuit resistance and reactance of the grid.

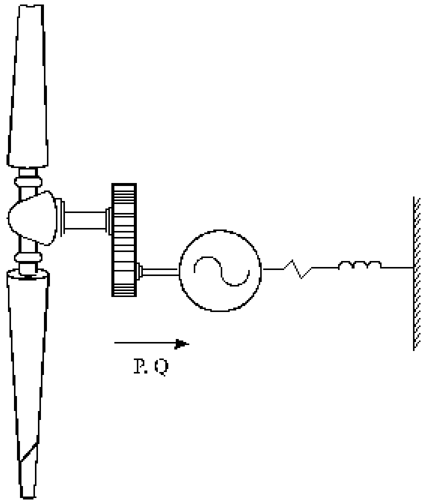

Fig. 10. Grid connected wind turbine generator

Voltage fluctuations at the PCC can be used to calculate short term flicker severity, P_{st}, by using a flickermeter that complies with the IEC 61000-4-15.

In this subsection, P_{st} is not going to be used for the comparative analysis but only power fluctuations, as this is enough for reaching the conclusions of this subsection. Note that generally speaking, for a particular grid, higher power fluctuations will cause higher voltage fluctuations and therefore higher flicker emissions.

Power fluctuations are going to be quantified by calculating the ratio of standard deviation to mean value of power response in the considered cases. Results are given in table III. From these results, it is clear that torque mode control strategy is better than speed mode control strategy, because it results in lower power fluctuations. Also, the higher the controller bandwidth the higher power fluctuations are obtained.

Table III. Energy yield and power fluctuations

	Mean power output	Standard deviation / mean output
Case 1	256.2 kW	0.8975
Case 2	286.1 kW	0.6396
Case 3a	295.1 kW	1.0302
Case 3b	298.6 kW	1.1217

4. Conclusions

Variable speed wind turbines feature higher energy yields and lower power fluctuations than fixed speed wind turbines. The last feature is particularly important as flicker may become a limitation to wind generation on power systems. Also, variable speed wind turbines produce more reduced loads in the mechanical parts than fixed speed wind turbines, but this analysis has not been carried out in this paper.

When comparing torque mode control and speed mode control strategies, simulation results shows that speed mode control strategy follows wind speed, in order to achieve maximum power coefficient, more accurately, i.e., it is more adequate for fast maximum power tracking, and the higher the speed control loop bandwidth is, the better the tracking is. Nevertheless, as a consequence, it produces more power fluctuations, since speed is rigidly imposed to the turbine. So, from power quality point of view, torque mode control strategy presents better behaviour, because speed is not directly imposed to the turbine and this control strategy lets the wind turbine to freely change rotational speed during the transient.

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