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Advanced Control of Wind Turbines

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1. Introduction

Wind energy technology has experienced huge progress during the last decade. This was encouraged by the need to develop ambient friendly clean and renewable forms of energy and the continuously rise of oil price. Sophisticated designs of wind turbines were performed. Large-size wind turbine farms are nowadays producing electricity at great scale throughout the world. Wind energy represents actually the most growing renewable energy; the rate of growth reaches actually 30% in Europe.

The cost of wind energy was not always cheaper than that of the other energy resources if the impact on environment and the risk linked to the classical forms of energy is not considered. The cost has however experienced a regular drop since the early 1970s. Cost reduction continues to constitute a main concern in the field of wind energy and research and development programs are considering it as a top priority. The objective is to extract optimal electric energy from wind with high quality specifications and with reduced installation and servicing expenses (Ackermann & Söder, 2002; Gardner et al., 2003; Sahin, 2004; AWEA, 2005).

Among the most important issues that allow to deal with cost reduction and its stabilisation in the field of wind turbines, one finds controller design for these installations. The objective is to deserve better use of the available energy in wind by providing through intelligent control its optimal extraction. Three main goals are generally pursued during designing of wind turbine controllers. The first one is to optimize use of the wind turbine capacity (optimal extraction of electric energy from the kinetic energy contained in the incident wind). The second is to alleviate mechanical loads in order to increase life of wind turbine components (fatigue loads should be reduced during operation). The third one is to improve power quality to approach the habitual performances met in the classical forms of energy, this is to assess compatibility of wind energy with the common standards about consumption of electricity (Ackermann, 2005).

Control must take into account variability of wind resource and should also cope with the intermittent nature of wind energy. The idea is to exploit optimally the wind resource when it is available and to limit overloading at risky high wind speeds. For this raison modern wind turbines are variable speed. They function by seeking optimal orientation of the wind turbine rotor and by pitching the blades to limit the captured energy from wind when wind speed exceeds the cut-off limit.

Knowing that if the electric generator is directly connected to the grid, then only one rotational speed can be used in order to synchronize with the grid frequency, modern wind

turbines have incorporated electronic converters as an interface between the generator and the grid. This enables to decouple the rotational speed of the electric generator from that of the grid. The electric generator speed can in this way be varied in order to track the optimum tip-speed-ratio which is function of the instantaneous wind speed. Many configurations of active controllers were developed for this purpose (Burton et al., 2001; Hansen et al., 2005; Thiringer & Petersson, 2005; AWEA, 2005). But in practice, pitch-controlled wind turbines are the most performant ones, especially in the mid to high power range. Flexibility is the main advantage of pitching wind turbine blades. This arrangement has enabled to deal with the various concerns intervening in control of wind turbines and was recognized to recompense for the investments cost needed during the research and development operations or those associated to their realization and servicing.

Classical controls have used gain scheduling techniques. These consist in selecting a set of operating points and designing linear controllers for each linearized system near a given operating point. A set of linear time-invariant plants is then considered. The gain-scheduled controller is constructed from this family of linear controllers by operating a switching strategy by means of interpolations (Rugh & Shamma, 2000).

Gain scheduling techniques using roughly interpolation suffer however from lack to guarantee stability and robustness. For this raison, control based on linear parameter varying systems was introduced (Shamma & Athans, 1991; Leith & Leithead, 1996; Ekelund, 1997). This control consists first in describing the wind turbine dynamics by reformulating the nonlinear system as a linear system whose dynamics depend on a vector of time-varying exogenous parameters, the scheduling parameters. The advantage is that the controller design can be achieved through solution of a convex optimisation problem with linear matrix inequalities (Packard, 1994; Becker & Packard, 1994; Apkarian & Gahinet, 1995; Apkarian & Adams, 1998). The existence of efficient numerical methods that enable to solve this optimisation problem has enabled designing high performant controllers based on linear parameter varying and gain scheduling techniques.

Robustness appears to be a main feature in the controller design of wind turbine systems since they are so complex and work in the presence of many uncertainties affecting system parameters and inputs. For instance, the system is elastic in reality and vibrates according to complex patterns. The aerodynamic forces generated by the wind passing through the rotor plane are highly nonlinear. Wind speed varies stochastically and can not be measured through the whole rotor plane to use this information in control. These nonlinearities lead to huge variations in the dynamics of the wind turbine through the whole operating range of useful wind speeds.

To deal with control purposes, a simplified dynamic model for the wind turbine is usually considered. To represent reasonably wind turbine behavior, this model is obtained through an identification process. Identification can be performed conventionally without specifying the order of the model and without making assumptions regarding the wind turbine dynamics. Another more enhanced identification procedure relies on lumped representation of the mechanical system. This last is assumed to be a multi-body system consisting of rigid bodies linked together by flexible joints. The components of the model are adjusted by identification so as the parameters match as close as possible the real dynamic behaviour. In both approaches, the model is subject to parameter uncertainties and lack in general to be valid at high frequencies.

A large number of wind turbine control systems have been developed without taking into account modelling errors in the design process. Few contributions were dedicated to this

crucial features of controllers and robust gain scheduling techniques existing nowadays are far from being robust and optimal (Bongers et al., 1993; Bianchi et al., 2004; Bianchi et al., 2005).

In order to optimize conversion efficiency of kinetic energy contained in wind to electric power, advanced strategies of control were introduced without using wind speed measurement. This was performed at first in the context of linearized wind turbine models (Boukhezzar et al., 2006; Boukhezzar et al., 2007). More advanced controllers were presented later (Vivas et al., 2008; Khamlichi et al., 2008; Khamlichi et al., 2009; Bezzazi et al., 2010). While not using wind speed measurement, these last are based on nonlinear observers that are built by using the extended Kalman filter. They were found to provide reliable information about wind speed, enabling to design control in continuous time without the need to make linearization of the system dynamics. These observers were implemented in well known controllers such as aerodynamic feed forward torque control (Vihriälä et al., 2001) and indirect speed control (Leithead & Connor, 2000).

A study regarding performance evaluation of the extended Kalman filter based controllers has been carried out in the below-rated power zone. This was performed through comparison between these controllers and some of the classical ones, chosen as reference. Comparison has focused on the accuracy of tracking the optimal rotor speed, the aerodynamic capture efficiency, control signal characteristics and the generated mechanical forces. The obtained results have shown that the advanced controls are quite pertinent. They are robust; they yield satisfactory results and give better enhancement of power conversion efficiency.

2. Control strategy statement of wind turbines

The details of the control systems used in wind turbines may vary largely from one installation to another, but they all have common elements that are considered in any controller design. This will be illustrated in the following through using a simple wind turbine model which permits to display the intervening turbine components and to review the ordinary basic functional elements that are used to build the controllers.

A wind turbine can be typically modelled, in first approximation, as a rigid mass-less shaft linked to rotor inertia at one side and to the drive train inertia at the other side, figure 1. The captured aerodynamic torque acts on the rotor and the generator electrical torque acts on the drive train.

The aerodynamic torque results from the local action of wind on blades. It is given by the sum of all elementary contributions related to the local wind speed that apply to a given element of a blade and which depend on the rotor speed, the actual blade pitch, the yaw error, the drag error, and any other motion due to elasticity of the wind turbine structure. Except from wind speed and aeroelastic effects, each of the other contribution inputs to aerodynamic torque (rotor speed, pitch, yaw and drag) may be monitored by specific control systems.

All wind turbines are equipped with yaw drives that monitor yaw error and with supplementary devices that are used to modify rotor drag. In the particular case of variable speed wind turbines, these installations can operate at different speeds or equivalently variable tip-speed ratios. Pitch-regulated wind turbines are controlled by modifying the blade orientation with respect to the direction of incident wind.
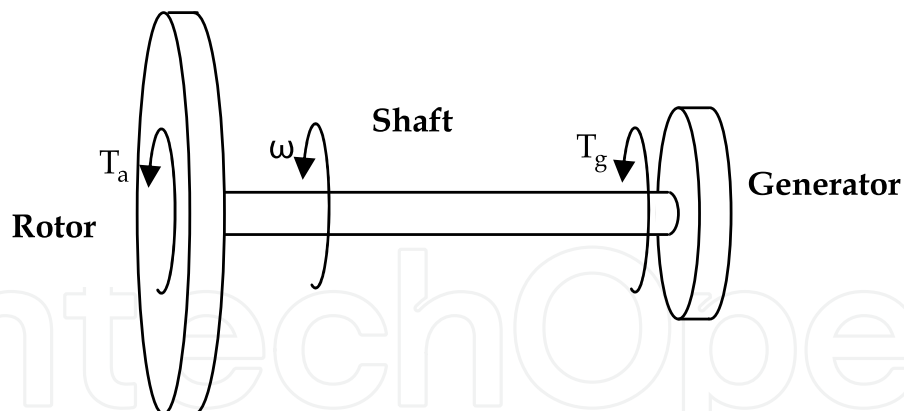
Fig. 1. Simplified model of a wind turbine

Neglecting elastic and aeroelastic effects, dynamics of the wind turbine rotor can be described by a one degree-of-freedom rigid body model (Wilkie et al., 1990) as

$$J\dot{\omega} + D\omega = T_a - T_g \qquad (1)$$

where ω is the rotor speed, J the equivalent inertia of power train, D the equivalent damping coefficient, T_g the applied generator torque as seen from the rotor and T_a the aerodynamic torque.

Denoting $C_p(\lambda, \beta)$ the wind turbine power coefficient which is function of the pitch angle β and the tip-speed ratio λ, the aerodynamic torque acting on the rotor writes

$$T_a = \frac{1}{2}\rho\pi R^3 v^2 \frac{C_p(\lambda, \beta)}{\lambda} \qquad (2)$$

where ρ is the air density, R the rotor radius and v the effective wind speed.

The tip-speed ratio is defined as $\lambda = \omega R / v$. Because of the speed multiplication resulting from the gear box, the high-speed shaft rotates with the rate $\omega_g = n\omega$, where n is the gear box multiplication factor.

It should be noted here that the effective wind speed appearing in equation (2) is not the average wind speed that acts at large on the rotor plane, but some hypothetical wind speed that have to be identified. This can be performed for instance if one fixes the pitch angle and the rotor speed, then measures the aerodynamic torque and solves after that the nonlinear equation (2) to compute the effective wind speed v. Using a reference wind speed in equation (2) instead of the unknown effective wind speed will result in wind speed error and consequently aerodynamic torque error. These two errors are however not perfectly correlated since in case of the aerodynamic torque, air density and rotor blades aerodynamic coefficients may also vary as function of the ambient conditions or because of wear affecting the blades.

Surface defining $C_p(\lambda, \beta)$ depends on the geometric configuration of the wind turbine blades and the aerofoils composing them. This surface admits a unique maximum denoted $C_{p,opt}$ which is obtained for $\beta = \beta_{opt}$ and $\lambda = \lambda_{opt}$. As the extracted power is given by $p_a = \rho\pi R^2 v^3 C_p(\lambda, \beta) / 2$, energy extraction from the kinetic energy of wind is optimal for $C_p(\lambda, \beta) = C_{p,opt}$.

Control strategy is usually defined by indicating the desired variations of wind turbine velocity and torque in the (ω, T_a) plane. Among the common strategies used in practice one finds that one depicted in figure 2.
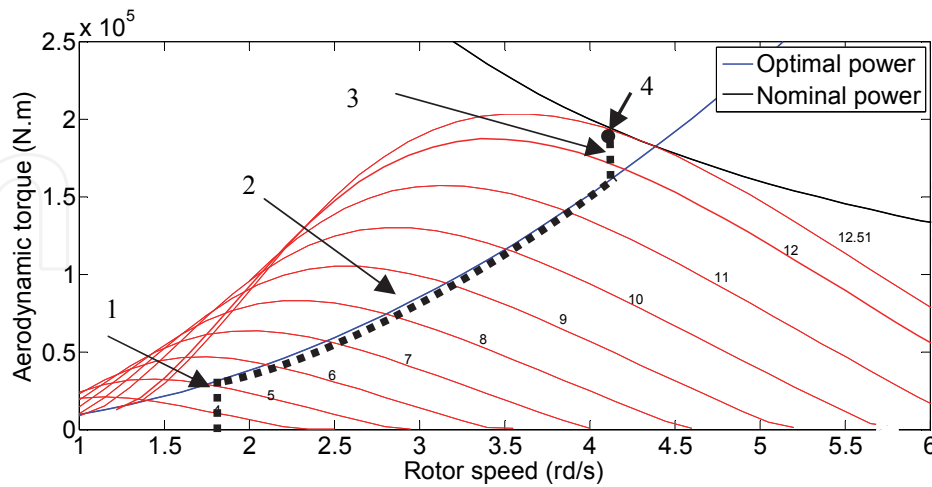

Fig. 2. Strategy of control illustrated in the (ω, T_a) plane as the dashed curve

In the (ω, T_a) plane, the red curves are obtained for different wind speeds by imposing the constant pitch angle $\beta = \beta_{opt}$.

Zone 1 corresponds to the segment between the starting wind speed v_{start} and the optimum lower wind speed $v_{\min,opt} = \omega_{\min} R / \lambda_{opt}$. In zone 1 the rotor speed is maintained constant at the value $\omega_{\min}$. This zone serves to reach at constant pitch angle $\beta = \beta_{opt}$ and constant rotor speed $\omega_{\min}$ the operating point located on the maximum efficiency curve, blue curve. In zone 1, the tip-speed ratio varies from $\lambda = \omega_{\min} R / v_{start}$ to λ_{opt}. The starting aerodynamic torque and the starting extracted power are given respectively as $T_{start} = \rho \pi R^2 v_{start}^3 C_p(\omega_{\min} R / v_{start}, \beta_{opt}) / (2\omega_{\min})$ and $p_{start} = T_{start}\omega_{\min}$. The last point situated in the branch associated to zone 1 and located on the maximum efficiency curve has the following coordinates $\left(\omega_{\min}, T_{\min,opt} = \rho \pi R^5 C_{p,opt} \omega_{\min}^2 / (2\lambda_{opt}^3)\right)$ in the (ω, T_a) plane. The extracted power varies in this zone in the interval $\left[p_{start}, p_{\min,opt} \rho \pi R^5 C_{p,opt} \omega_{\min}^3 / (2\lambda_{opt}^3)\right]$.

Zone 2 corresponds to tracking the maximum efficiency curve where the objective is to adjust the rotor speed to wind speed such that the captured aerodynamic torque is always optimal, the pitch angle as well as the tip-speed ratio are kept constant at their optimal values β_{opt} and λ_{opt}. For a given wind speed v, the optimal rotor speed is defined by $\omega_{opt} = \lambda_{opt} v / R$. The maximum rotor speed is fixed at the value $\omega_{\max}$ which is slightly below the rated rotor speed corresponding to the intersection between the rated (nominal) power curve, black curve, and the optimum efficiency curve, blue curve. The rated rotor speed is given by

$$\omega_{rated} = \lambda_{opt} \left(\frac{2p_{rated}}{\rho \pi R^5 C_{p,opt}} \right)^{\frac{1}{3}} \tag{3}$$

where p_{rated} is the rated generator power.

The maximum wind speed corresponding to zone 2 is given by $v_{\max,opt} = \omega_{\max} R / \lambda_{opt}$. The last point located on the maximum efficiency curve for zone 2 has the following coordinates

$\left(\omega_{\max}, T_{\max,opt} = \rho \pi R^5 C_{p,opt} \omega_{\max}^2 / (2\lambda_{opt}^3) \right)$ in the (ω, T_a) plane. The extracted power varies in the interval $\left[p_{\min,opt} = \rho \pi R^5 C_{p,opt} \omega_{\min}^3 / (2\lambda_{opt}^3), p_{\max,opt} = \rho \pi R^5 C_{p,opt} \omega_{\max}^3 / (2\lambda_{opt}^3) \right]$.

Zone 3 constitutes a transition phase between zone 2 and the rated power zone, zone 4 corresponding to the circle point on the black curve. In zone 3 rotor speed is maintained constant at the value $\omega_{\max}$. The wind speed varies in this zone form $v_{\max,opt}$ to $v_{\max,rated}$ which is obtained as solution of the following nonlinear equation

$$v^3 C_p(\omega_{\max} R / v, \beta_{opt}) = \frac{2p_{rated}}{\rho \pi R^2} \tag{4}$$

The maximum aerodynamic torque in zone 3 is $T_{rated} = p_{rated} / \omega_{\max}$. The extracted power varies in this zone in the interval $\left[p_{\max,opt} = \rho \pi R^5 C_{p,opt} \omega_{\max}^3 / (2\lambda_{opt}^3), p_{rated} \right]$.

The first three zones are termed below-rated power region as the extracted power is always smaller than the rated power p_{rated}.

Finally, zone 4 corresponds to the maximum load zone (above-rated power region). In this zone pitch angle is permanently adjusted in order to reduce the captured aerodynamic torque, assuring continuous rated power generation. Giving a wind speed $v \geq v_{\max,rated}$, the pitch angle in zone 4 is obtained as solution of the following nonlinear equation

$$v^3 C_p(\omega_{\max} R / v, \beta) = \frac{2p_{rated}}{\rho \pi R^2} \tag{5}$$

The extracted power is constant in zone 4 and is equal to p_{rated}.

Table 1 recalls the wind speed limits corresponding to each zone and the associated extracted power limits.

Zone	Minimum wind speed limit	Maximum wind speed limit	Minimum extracted power	Maximum extracted power	Pitch angle
1	v_{start}	$v_{\min,opt}$	p_{start}	$p_{\min,opt}$	fixe
2	$v_{\min,opt}$	$v_{\max,opt}$	$p_{\min,opt}$	$p_{\max,opt}$	fixe
3	$v_{\max,opt}$	$v_{\max,rated}$	$p_{\max,opt}$	p_{rated}	fixe
4	$v_{\max,rated}$	v_{end}	p_{rated}	p_{rated}	variable

Table 1. Limits of the different control zones in terms of wind speed and extracted power

For control purposes power can be used as control variable in the transition zones 1 and 3 as well as in the above-rated power zone 4. In these zones rotor speed is maintained constant, while in addition for zone 4 pitch is controlled to maintain the power constant.

In the below-rated zone 2, the rotor speed is varied as function of the actual wind speed to optimize permanently power extraction. The optimal power that can be extracted varies then as function of the wind speed. For a given wind speed the pursued reference in terms of extracted power, aerodynamic torque and rotor speed writes

$$p_{opt} = \frac{1}{2} \rho \pi R^2 C_{p,opt} v^3$$

$$T_{opt} = \frac{1}{2} \rho \pi R^3 v^2 \frac{C_{p,opt}}{\lambda_{opt}} \qquad\qquad (6)$$

$$\omega_{opt} = \lambda_{opt} v / R$$

The optimal extracted power can be used as reference for control, but because it is proportional to v^3, error on the effective wind speed will have an important effect on the reference power to be tracked and hence on control efficiency. This error is proportional to v^2. The aerodynamic torque can not be used as control input because this quantity is not easy to measure in practice. So, the control variable that is usually used is the rotor speed. Control should track the reference $\omega_{opt} = \lambda_{opt} v / R$ by changing the generator torque in order to change the rotor speed. The effective wind speed v which can not be measured may be estimated by using power and rotor speed measurements, p_{mes} and ω_{mes}, and solving the following non linear equation

$$C_p\left(\frac{R\omega_{mes}}{v}, \beta_{opt}\right) v^3 - \frac{2p_{mes}}{\rho \pi R^2} = 0 \qquad\qquad (7)$$

Using equation (7) to extract the estimated effective wind speed is however numerically costly. Moreover, the process of solving this equation is not robust because of noise that could affect the measurements p_{mes} and ω_{mes}, and the delays that are inherent to any measurement system and which yield always late information on the actual wind speed. Variations could result also from ambient conditions such as for example air density ρ which is temperature dependent or the power coefficient which is sensitive to gusts, wear and debris impacting the blades. Since these perturbations affecting the ideal model are not straightforward to take into account, control operates inefficiently and loss of extracted power occurs systematically. In order to emphasize the requisite for developing intelligent controls that can handle more effectively wind turbine system uncertainties, a review is performed in the next section about the standard methods of control that have so far been proposed for these installations.

3. Review of classical controllers for wind turbines

3.1 Standard proportional integral control
Since it is simple to design and easy to implement, the classical proportional integral (PI) control is widely used in industry applications. This controller which requires little feedback information can be employed over most plants for which a dynamical model can be derived. PI controller can be used alone or in conjunction with other control and modelling techniques such as linearization or gain scheduling.

For fixed pitch wind turbines operating in the below-rated power zone 2, capture of maximum energy that is available in the wind can be achieved if the turbine rotor operates such that the tip-speed ratio is made equal to the optimal value λ_{opt}. This regime can be obtained by tracking the optimal rotor speed. Useful details about PI controlling of wind turbines are given in (Bossanyi, 2000; Muljadi et al., 2000; Burton et al., 2001). One can find

three kinds of control loops for tracking the optimal rotor speed. In all of them the target rotor speed is given by $\omega_{opt} = \lambda_{opt} v / R$ where the wind speed v is assumed to be known from measurements and the generator torque is synthesized as

$$T_g = K\omega^2 \tag{8}$$

with

$$K = \frac{1}{2}\rho\pi R^5 \frac{C_{p,opt}}{\lambda_{opt}^3} \tag{9}$$

Based on the rotor speed measurement and a generator torque control loop, a control loop on λ is built. The PI controller zeroes the difference between the target and the measured rotor speed and imposes the generator torque reference. This control is known as the Indirect Speed Control (ISC). One can expect large torque variations, as the torque demand varies rapidly in this configuration.

Based only on the rotor speed feedback, a torque control loop can be built using as reference T_g given by equation (8) (Pierce, 1999). A variant of this control, known as the Aerodynamic Torque Feed forward (ATF) where the aerodynamic torque and the rotor speed are estimated using a Kalman filter was presented in (Vihriälä et al., 2001). An advantage of this control structure is the increased mechanical compliance of the system, but rotor speed variations result in general to be high.

An active power loop can also be built using once more the measured rotor speed, in conjunction with the captured power and the inner torque control loop. The target power is defined by the first equation in (6). By zeroing the power error, the operating point is driven to move to the maximum power point (Burton et al., 2001). The drawback of this control is sensitivity of the reference to error measurement of wind speed.

To show how the first variant of PI control using the λ loop can be derived, let us notice that equations (1), (2), (8) and (9) yield the following ordinary differential equation

$$\left(\dot{v} + \frac{D}{J}v\right)\lambda + v\dot{\lambda} = \frac{\rho\pi R^4}{2J}\left(\frac{C_p(\lambda,\beta)}{\lambda^3} - \frac{C_{p,opt}}{\lambda_{opt}^3}\right)\lambda^2 v^2 \tag{10}$$

To apprehend how this standard control works, let us assume that v is constant. Since in reality damping is small so that $(D/J)\lambda \ll 1$ is satisfied, the sign of $\dot{\lambda}$ depends on the sign of the difference in the right hand side of (10). Taking into account that $C_p(\lambda,\beta) < C_{p,opt}$, it follows from (10) that $\dot{\lambda} < 0$ when $\lambda > \lambda_{opt}$, and the rotor decelerates towards λ_{opt}. When $\lambda < \lambda_{opt}$, $\dot{\lambda} > 0$ happens and the rotor accelerates towards λ_{opt}. Thus, the control defined by equations (8), (9) and (10) causes the rotor speed, for a well definite wind turbine, to approach the optimal tip speed ratio enabling to track always the optimal extraction power curve. This control is easier to understand under constant wind conditions, but this behavior occurs only in an averaged sense under time-varying wind conditions.

It was assumed so far that the wind speed is measured and that this value is equal to the effective wind speed appearing in equation (2). It was assumed also that turbine properties used to calculate the gain K in equation (9) are accurate. These conditions are rarely met in

practice, because air density varies as function of temperature and, over time, debris build up and blade erosion change the $C_p(\lambda,\beta)$ surface and thus $C_{p,opt}$. Consequently an inaccurate gain K is used in control. Knowing that a small error on the tip-speed ratio of about 5%, causes a significant energy loss of about 2% (Johnson et al., 2006), the potential improvement for energy capture and cost savings has motivated investigation on adaptive control approaches that could enhance control efficiency.

3.2 Adaptive control

The dynamic behavior of a wind turbine is highly dependent on wind speed due to the non-linear relationship between wind speed, turbine torque and pitch angle. System parameter variations can be tackled by designing a controller for minimum sensitivity to changes in these parameters. Adaptive control schemes continuously measure the value of system parameters and then change the control system dynamics in order to make sure that the desired performance criteria are always met. In (Simoes et al., 1997; Bhowmi et al., 1999; Song et al., 2000) use is made of adaptive control to compensate for unknown and time-varying parameters in the below-rated power zone 2. In (Johnson et al., 2006) an adaptive control scheme is developed for this region. The authors have addressed also the question of theoretical stability of the torque controller, showing that the rotor speed is asymptotically stable under the adaptive generator torque control law in the constant wind speed input case and L2 stable with respect to time-varying wind input. Furthermore, the authors have derived a method for selecting the adaptive gain to ensure convergence to its optimal value. In the context of gain-scheduling, adaptive control structures which allow different control goals to be formulated; depending on the considered operating points were also introduced. To decide which controller to apply to the plant varies from simply switching between the controllers associated to the various operating points to quite sophisticated interpolation strategies (Shamma, 1996). In addition to its complexity, the adaptive structure has a major drawback in that the rotor characteristics should be known quite accurately.

3.3 Search algorithms control

Based on measurement of the captured power, heuristic search algorithms have been proposed to perform control of wind turbines. These algorithms change constantly the rotor speed in the objective to maximize the captured power. If a reduction of rotor speed yields a decreased power then the controller would slightly increase the speed. In this manner the rotor speed could be kept permanently near the maximum power coefficient as the wind speed changes. This kind of controller does not need a wind turbine model to be implemented; it is thus insensitive to changes in operation conditions due to dirty blades, mispitched blades or ambient temperature variations.

This approach supposes that the wind turbine reacts sufficiently fast to variation of the low frequency components of wind speed; this happens in practice in case of low power wind turbines. For ensuring the optimal energy extraction, it is thus sufficient to feed the electrical generator with the torque control value corresponding to the steady state operating point placed on the optimal power extraction curve. To this end, an on-off-controller-based structure can be used in order to zeroing the difference on λ. The choice of such a structure (Munteanu et al., 2006) is characterized by its robustness to the parametric uncertainties inherent to any wind turbine.

The control law associated to the on-off-controller-based structure provides a steady state torque reference by adding two components. The first component is an equivalent control, corresponding to the optimal operating point, and depends proportionally on the low frequency wind speed squared. The second component is a high-frequency component, which switches between two values, depending on the sign of the actual error on λ. The first component is intended to drive the system to the optimal operating point, whereas the second one has the role of stabilising the system behaviour around this point.

Search algorithms based controllers do not consider mechanical loads as an objective. Wind turbines are hence vulnerable to induced torque variations which result from the alternate control input and could increase dramatically fatigue loads.

3.4 Optimal control

Optimal control theory formulates the control problem in terms of a performance index. This last is a function of the error between the references and actual system responses. Sophisticated mathematical techniques are then used to solve the constrained optimisation problem in order to determine the optimal values of design parameters. Optimal control algorithms often need a measurement of the various system state variables. If this is not possible a state estimator based on a plant model is used.

The need to consider a performance index in control of wind turbines comes from the fact that tracking the optimal rotor speed induces variations of the generator torque, thus additional cyclic mechanical stresses which reduce the lifetime of the drive train parts. Furthermore, the turbine energetic efficiency is also decreased because of the supplementary maintenance costs and reduced turbine availability time.

The above mentioned control methods have as an exclusive goal that consists in the maximization of the energy efficiency, while ignoring the possible drawbacks related to large control input efforts that could be needed. In (Ekelund, 1997), it is stated that keeping λ_{opt} in turbulent winds is possible only with large generator torque variations, thus significantly high mechanical stress. Therefore, the supplementary mechanical fatigue of the drive train should be reduced by imposing the minimization of the generator torque variations ΔT_g used as control input, around the optimal operating point. In (Ekelund, 1997) this has been expressed through a performance index consisting of the following combined optimization criterion

$$I = E\left\{\alpha\left(\lambda - \lambda_{opt}\right)^2 + \left(\Delta T_g\right)^2\right\} \qquad (11)$$

where E is the statistical expectation symbol.

The first term in equation (11) illustrates the energy efficiency maximisation, whereas the second term expresses the minimisation of the torque control variations. The trade-off between the two terms is adjusted by means of the weighting coefficient α.

Operation around optimality is ensured by minimizing only the first term in the right hand side of equation (11), but allowing important torque variations that are represented by the last term of this equation. The positive coefficient α confers flexibility to the control law in the following sense. If the wind turbulence is low, then the energy efficiency of the wind turbine will be considered as a priority and therefore α may take a large value. If the wind

turbulence is important, then through a small value of α focus will be done on reducing the mechanical stress and increasing the life service of the wind turbine components.

The mechanical loads alleviation is an issue in all the wind turbine operating modes. At high winds, when the system works in full load, an optimal linear quadratic control with Gaussian noise LQG was given in (Boukhezzar et al., 2007). A flexible drive train wind turbine was considered and the equations were linearized around the above-rated power operating point. The optimal controller was designed to determine the pitch variation $\Delta\beta$ such that to minimize the performance index

$$I = E\left\{x^t Q x + \alpha (\Delta\beta)^2\right\} \tag{12}$$

where x is the state vector deviation from desired reference values and Q the penalty matrix.

To derive an optimal controller, linearization of equations is needed around an operating point. The solution proposed to deal with the dependency of the linearized dynamical state system on the average wind speed was a gain-scheduling adaptive structure, together with an observer for state reconstruction, which uses the rotor speed ω as measurable output.

In (Munteanu et al., 2005) the performance index to be minimized is stochastically defined. An optimal control structure was presented in order to optimize the criterion at equation (11) without using adaptive structures. This approach, named the frequency separation principle, relies upon using a low-pass filter to separate the turbulence high frequency and the low frequency wind speed components (Nichita et al., 2002). Since the two components excite the plant dynamics in two distinct spectral ranges, the proposed structure is formed by two loops that are respectively driven by the low-frequency and the turbulence component of wind speed. While this structure desensitizes the closed loop system subject to the steady-state operating point, control cost to deal with the high-frequency components was recognized to be elevated.

4. Advanced control

In order to track the optimal rotor speed, it is required that reliable measurement of the effective wind speed v is available. But, this is impossible in reality because the effective wind speed is a rather averaged value that could only be identified by solution of equation (2) if the torque T_a was measured by means of a torquemeter for example. Therefore, it is smarter designing controls that do not require wind speed measurement. This is performed in the following through using the extended Kalman filter to derive a wind speed observer.

The control problem that states to track optimal power extraction in the below-rated power zone 2 takes the form of single-input single-output system. For a given effective wind speed v, it consists in synthesising the generator torque T_g to adjust the rotor speed ω to its optimal value ω_{opt}. The option of choosing T_g as the control variable is justified by the fact that this last is quite easy to generate through swift and effective electric machine controllers using either vector control (Pena et al., 1996) or direct torque control (Arnalte et al., 2002).

To test performance of the new introduced controllers, the well-known reference controllers ISC (Leithead & Connor, 2000; Wright, 2003) and ATF (Pena et al., 1996; Vihriälä et al., 2001; Johnson, 2004) are considered. ATF and ISC are far from being optimal and lack robustness (Boukhezzar et al., 2006; Boukhezzar et al., 2007). To overcome these deficiencies, feed back

nonlinear controllers using Kalman based wind speed observer were introduced by these authors. This was performed in two steps: estimation of the aerodynamic torque and deduction of the wind speed from it by solving the nonlinear equation (2) where a Newton-Raphson like iterative scheme was used. Based on this technique of observing wind speed, a Nonlinear Static State Feedback control with Estimator (NSSFE) and a Nonlinear Dynamic State Feedback control with Estimator (NDSFE) were derived (Boukhezzar et al., 2006; Boukhezzar et al., 2007). These controllers were shown to be robust in comparison with the classic ISC and ATF. However, the major difficulty resulting from estimating wind speed by using the aerodynamic torque value is linked to the necessity to perform at each time inversion of the nonlinear equation (2). This is numerically costly. On the other hand Kalman filter requires a local linearization of system equations. Considering multiple linearizations performed over the whole below-rated zone 2 results in a conservative condition on stability which limits control performance.

As a principal contribution in this work, a direct estimation of wind speed by means of the nonlinear extended Kalman filter is proposed without using aerodynamic torque estimation. The idea consists in using a time dependant Riccati like equation to construct a robust continuous observer of the effective wind speed which is capable of rejecting system perturbations and disturbances that are acting on the generator torque T_g (Gelb, 1984; Reif et al., 1999).

Assuming that the dynamics of wind speed v is driven by a Gaussian white noise such that $\dot{v} = \xi$ and the noise affecting measurement of the rotor speed ω is ζ, denoting the state vector $x = \begin{bmatrix} \omega & v \end{bmatrix}^t$, the observable variable $y = \omega + \zeta$ and the input variable $u = T_g$, the state system equations write

$$\dot{x} = \begin{bmatrix} \dot{\omega} \\ \dot{v} \end{bmatrix} = \underbrace{\begin{bmatrix} -\dfrac{D}{J}\omega + \dfrac{1}{J}T_a(\omega,v) \\ 0 \end{bmatrix}}_{f(x,u)} + \begin{bmatrix} -\dfrac{1}{J} \\ 0 \end{bmatrix} T_g + \begin{bmatrix} 0 \\ \xi \end{bmatrix} \tag{13}$$

$$y = \begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} \omega \\ v \end{bmatrix} + \zeta = Cx + \zeta \tag{14}$$

For a dynamic system governed by equations (13) and (14) an exponential observer which is based on the extended Kalman filter can be constructed (Reif et al., 1999) as

$$\dot{\hat{x}} = f(\hat{x},u) + K(t)\big(y - C\hat{x}\big) \tag{15}$$

with $K(t) = P(t)C^t S^{-1}$ and $\dot{P}(t) = A(t)P(t) + P(t)A^t(t) - P(t)\big(C(t)S^{-1}C - c_1^2 I\big)P(t) + c_2^2 I$ where I is the identity matrix having dimension of x, S the symmetric definite positive matrix defining noise correlations and having also dimension of x, $c_1 > 0$, $c_2 > 0$ are the weights and

$$A(t) = \frac{\partial f}{\partial x}(\hat{x},u) = \begin{bmatrix} -\dfrac{D}{J}\omega + \dfrac{1}{J}\dfrac{\partial T_a}{\partial \omega} & \dfrac{1}{J}\dfrac{\partial T_a}{\partial v} \\ 0 & 0 \end{bmatrix} \tag{16}$$

To find the weighting constants c_1 and c_2, the following bisection algorithm is proposed:

- - step 1: first guess of $c_1 > 0$, $c_2 > 0$ and $S = sI$ with $s > 0$;
- - step 2: decreasing s by replacing it by $s/2$ until matrix P is positive definite;
- - step 3: if it is impossible to find a positive definite matrix P, then $c_2 > 0$ is decreased to its half and $S = sI$ is reinitialized and steps 1 and 2 are repeated.
- The iterations are stopped if $c_2 > 0$ is lesser than a given critical value. In the present case $c_1 = 0.9$, $c_2 = 0.087$ and $s = 0.06$ were found to be the best weights. System of equations (1-2) and (13-16) is solved numerically by using Matlab command ode45.

Based on the extended Kalman filter (EKF) two kinds of robust controllers are built. The first one is a combination between (ISC) and (EKF) where the wind speed and the rotor speed are observed. The second one derives from a combination between (ATF) and (EKF).

To characterize performances of the various controllers, an efficiency ratio is defined over the period of time $\left[t_{ini}, t_{fin} \right]$ as the actual produced electric energy divided by the ideal optimal energy that could be extracted from the kinetic energy contained in the incident wind. This efficiency ratio writes

$$\eta = \frac{\int_{t_{ini}}^{t_{fin}} p_{extracted} dt}{\int_{t_{ini}}^{t_{fin}} p_{optimal} dt} = \frac{\int_{t_{ini}}^{t_{fin}} T_g \omega_g \, dt}{\int_{t_{ini}}^{t_{fin}} T_{a,opt} \omega_{opt} \, dt} \tag{17}$$

where $p_{extracted} = T_g \omega_g$ is the real electric power extracted at time t and $p_{optimal} = T_{a,opt} \omega_{opt}$ the theoretical optimal power that could be extracted.

To examine performance of the controllers, the experimental wind turbine called CART (Fingershand & Johnson, 2002) is considered. This two-bladed wind turbine has largely been studied in the literature related to control purposes. The low-speed shaft is coupled by means of a gear box to the high-speed shaft. This last constitutes the rotor of the induction electric generator. The principal characteristics of CART wind turbine are: $R = 21.38\,m$, $n = 43.165$, hub height $H = 36.6\,m$. Here the CART wind turbine is assumed to have the rated power $p_{rated} = 850\,kW$.
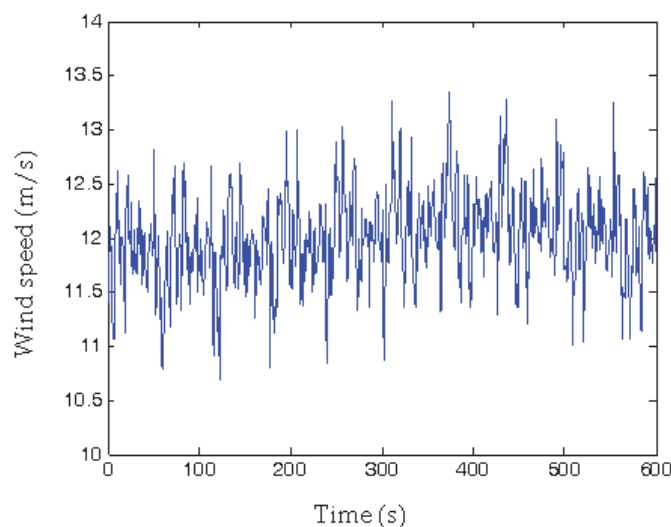

Fig. 2. Instantaneous wind speed

To illustrate results due to the introduced new controllers, a stochastic wind speed, $v(t)$, having a mean value of $12\,m.s^{-1}$, turbulence characteristic length $L = 15\,m$ and standard deviation $\sigma = 0.5$ is assumed to generate the source power of wind during the time interval of simulation $[0, 600s]$, figure 2.

Reference controllers ISC, ATF, and Kalman filter based robust controllers NSSFE and NDSFE are considered in this comparative study. Their performances are evaluated through simulations carried out under Matlab environment where use was made in particular of Kalman and ode45 commands. Newton-Raphson iterations were also implemented when necessary. The obtained results are compared to the new proposed extended Kalman filter based robust controllers ISC_EKF and ATF_EKF with the same conditions of functioning regarding disturbances and measurement noise. Three kinds of results will be focused on: the generator torque which is related to the energetic cost of control, the energetic efficiency of control defined in terms of ratio η, and the torque acting on the low-speed shaft which is related to fatigue loads.

Table 2 summarizes the obtained results in terms of generator torque variations over the time interval $[0, 600s]$. It gives the maximum value, the mean, value, the minimum value and the relative variation. It gives also the extracted power efficiency associated to each controller.

Table 3 gives the obtained results in terms of the mechanical torque T_{ls} variations in the low-speed shaft over the time interval $[0, 600s]$. It gives the maximum value, the mean, value, the minimum value and the relative variation.

From table 2, controllers could be classified into two categories: high fluctuated generator torque (ATF, NSSFE, NDSFE) and low fluctuated generator torque (ISC, ISC_EKF, ATF-EKF).

	Max (T_g) ($10^4\,N.m$)	Mean (T_g) ($10^4\,N.m$)	Min (T_g) ($10^4\,N.m$)	Relative variation %	η (%)
ATF	16.71	13.87	11.13	40.2	80.37
ISC	15.96	13.87	11.96	28.8	80.11
NSSFE	17.12	13.87	10.49	47.8	78.91
NDSFE	17.11	13.87	10.45	48.0	78.76
ATF_EKF	15.56	14.72	13.75	12.3	81.59
ISC_EKF	16.41	14.27	12.25	29.1	80.82

Table 2. Generator torque variations and extracted power efficiency for the different controls

From table 3, it is seen that three classes of controllers are distinguishable: high fluctuated mechanical torque (NSSFE, NDSFE), intermediate fluctuated mechanical torque (ATF, ISC) and low fluctuated mechanical torque (ISC_EKF, ATF-EKF).

The obtained results show that for NSSFE and NDSFE controllers generator torque and low-speed shaft overloads are maximum while power efficiency is minimum. Although some performances of the controllers ISC and ATF are good in comparison with the previous controllers, they must be discarded as they are not robust in real operation conditions. Now comparing only the robust controllers between them shows that the proposed extended

	Max (T_{ls}) (10^5 $N.m$)	Mean (T_{ls}) (10^5 $N.m$)	Min (T_{ls}) (10^5 $N.m$)	Relative variation %
ATF	1.9759	1.6777	1.3900	2.9822
ISC	1.9012	1.6776	1.4666	2.2368
NSSFE	2.000	1.6774	1.3566	3.2318
NDSFE	1.9999	1.6773	1.3543	3.2251
ATF_EKF	1.8550	1.7506	1.6351	1.0433
ISC_EKF	1.8449	1.7129	1.5764	1.3201

Table 3. Mechanical torque variations in the low speed shaft for the different controls

Kalman filter based methods perform better than NSSFE and NDSFE. Comparing finally the two new proposed controllers shows that the ATF_EKF is better than ISC_EKF in terms of power efficiency, generator torque fluctuations and fatigue loads.

3. Conclusion

A review of the principal control methods that are used in the context of wind turbines was performed. Using a one-degree-of freedom mechanical model for wind turbine, focus was done on various controllers in the below-rated power zone and their performances were analyzed. These include two classic controllers that are largely used in practice, the indirect speed control and the aerodynamic torque feed forward control. Two other recent controllers using Kalman filter to make wind speed estimates were also considered. Finally two new non linear controllers were introduced. These last combine judiciously the classic controllers and an exponential continuous wind speed observer based on the extended Kalman filter.

The obtained results are promising. They have shown that the new controllers perform better than all the others since they robustify the indirect speed control and the aerodynamic torque feed forward control. They limit also to large extent generator torque fluctuations and fatigue loads, as compared with Kalman filter based methods, while maximising the extracted electric power energy.

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Fundamental and Advanced Topics in Wind Power

Edited by Dr. Rupp Carriveau

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