DESIGN OF WIND TURBINE CONTROLLERS

W.E. Leithead, M.C.M. Rogers, D.J. Leith, B. Connor

Department of Electronic and Electrical Engineering,
Universityof Strathclyde,
50 George Street,
Glasgow, G1 1QE,
UK

Abstract

Owing to concern over the environment, there is much interest in renewable sources of energy, one of the most promising of which is wind power. Wind power is not yet a mature technology and one of the issues to be resolved is the most effective manner in which to regulate the wind turbines are posed by the different wind turbine configurations. A variety of control design tasks with differing objectives. The plant may be SISO or MIMO; it may be unstable and/or non-minimum phase; it may be essentially linear or strongly nonlinear depending on the machine's configuration. The purpose of this paper is to discuss controller design for horizontal axis, grid-connected, medium to large scale wind turbines. The design is invariably nonlinear in order to accomodate the full operating range and the nonlinearities in the plant, actuation system, and control objectives. Both constant speed and variable speed machines are discussed.

Keywords : Wind turbines, Constant speed, Variable speed, Nonlinear control, Controller Implementation

1. Introduction

Owing to concern over the environment, there is much interest in renewable sources of electrical power generation of which one of the most promising is wind power. In both North America and Europe, large scale projects to exploit wind power have been undertaken during the last decade, and others are projected to be completed by the end of the century. However, it is not yet a mature technology and many issues have yet to be resolved. One such issue is the most effective manner in which to regulate the wind turbines.

The wind turbines discussed in this paper are horizontal axis, grid-connected medium to large scale wind turbines (see Figure 1). The generator may be connected directly to the grid thereby locking the speed of rotation of the rotor to the frequency of the grid, which is of course fixed. No speed regulation is required. For this reason, this type of machine is referred to as a constant speed wind turbine. Alternatively, the generator may be connected indirectly to the grid *e.g.* via a rectifier and inverter thereby decoupling the speed of rotation of the rotor from the frequency of the grid. The speed of the rotor is regulated by varying the reaction torque from the generator in response to a measurement of the rotor speed itself and/or the generated power. This type of machine is referred to as a variable speed wind turbine.

As the wind speed increases, the energy available for capture increases as roughly the cube of the wind speed. High wind speed is not encountered frequently enough to make it economic to extract the total energy available. Aerodynamic power limiting is preferred. At a predetermined wind speed (rated wind speed) the power input to the wind turbine will have reached the limit for continuous operation (rated power). When the wind speed exceeds rated the excess power in the wind must be discarded by the rotor to prevent the turbine overloading. The power is maintained at its rated value until a maximum wind speed is reached when the wind turbine is shut-down (cut-out wind speed). A typical power curve is shown in Figure 2.

There are two common methods of aerodynamic power limiting. The first is passive regulation. The rotor blades are designed to stall near rated wind speed preventing the generated power from rising further with wind speed. The rotor speed of a variable speed wind turbine may be adjusted to deliberately induce stall. The second is active regulation. The torque induced on the rotor by the wind depends on the pitch angle of the blades. Hence, the torque may be reduced by feathering the blades and vice versa. During active regulation, above rated wind speed, the pitch of the blades are continuously set to the angle of pitch at which rated power is generated. The whole of the blades may be pitched - full-span pitch regulation - or only the tips may be pitched - part-span pitch (or tip) regulation. For pitch regulated wind turbines, the adjustment of pitch is made in response to power measurement alone or in combination with rotor speed when the machine is variable speed.

Except for stall regulated constant speed wind turbines, a control system is necessary to achieve power limiting regulation and/or speed regulation. However, a control system is only as good as the criterion to which it is designed and without a clear statement of intent it is not possible to evaluate properly the performance. A thorough exposition of the role and objectives of the control of wind turbines has been presented by Leithead et al [1].

The blades of the turbine sweep through a complex time varying three-dimensional wind-field. The structure of the wind-field is a combination of wind speed turbulence (local variations of wind speed), wind sheer (increase in wind speed with height as the boundary effects decrease) and tower shadow (reduction in wind speed at the tower). The wind turbine is subject to induced torques and loads which depend not only on the local variations in the wind-field but also on variations which occur upstream and downstream from the machine by as much as ten rotor diameters. Hence, the wind speed as experienced by a wind turbine is very different from that which is measured by an anemometer; the latter is referred to as "point wind speed". In fact there is really no such thing as "the wind speed" and wind turbine control schemes which propose to employ a wind speed measurement are unrealistic. The fluctuating loads, induced by the wind speed, vary both in time and spatially over the structure. Above rated wind speed, these loads need to be smoothed to avoid excessive rating of components. The fluctuating loads can manifest themselves as very rapid and large fluctuations in generated power. The control system may be used to smooth the power generated by the wind turbine when operating above rated wind speed. However, this is not an adequate criterion on its own.

Since, no fuel costs are entailed in the generation of power from the wind, the only costs are the initial capital costs and maintenance costs and it is important for the cost-effectiveness of wind power to maximise the working life of the wind turbine whilst minimising the over-engineering. It follows that the real purpose of the control system should not be to smooth the power but to alleviate the load transients throughout the wind turbine. Smooth power will be achieved by alleviating these loads but the converse does not necessarily hold.

There are two further goals for the control system. Firstly, it should ensure that there is sufficient damping of the wind turbine power-train (the drive-train and power generation unit) dynamics. Wind turbines are inclined to be lightly damped. If this were not so, energy which has been captured by the wind turbine would be wastefully dissipated. Secondly, the energy capture should maximised.

The role of the control system is summarised by the following general goals [1]

a) alleviating the load transients throughout the wind turbine;
b) regulating and smoothing the power generated;

c) ensuring that the power-train has the appropriate dynamics; particularly damping of the power-train.
d) maximising the energy capture.

To clarify goal a), a distinction must be made in the loads to which the turbine is subjected. The load transients experienced by the wind turbine are of two types. Firstly, there are variations in the net aerodynamic driving torque induced in the rotor. These drive-train loads propagate down the power-train and affect components such as the gearbox. Secondly, there are variations in the structural loads. If the control system operates perfectly, reducing the variations in the net aerodynamic driving torque to zero, the turbine structural states will track their steady state values as the wind speed changes. The loads the turbine experiences under these conditions are the on-design structural loads. Of course, the control system does not perform perfectly and the wind turbine experiences additional transient structural loads - the so-called off-design loads.

The low-frequency component of the various load transients is induced by stochastic fluctuations in the wind speed and by steady increases or decreases in the wind speed, *i.e.* gusts. The high frequency component is concentrated in spectral peaks. The rotation of the rotor induces spectral peaks, at integer multiples of the rotor speed, Ω, that are caused by the blades periodically sweeping through the wind-field which changes relatively slowly as compared to the speed of rotation of the rotor. The spectral peaks induced by rotational sampling of the wind-field have a deterministic part due to the wind sheer and tower shadow and a stochastic part due mainly to the wind speed turbulence. In addition, the structural dynamics induce peaks at the frequencies of their normal modes. The most important spectral peaks for the drive-train loads of an n-bladed machine are the n-Ω and 1-Ω peaks with the former much more pronounced than the latter. The most important for the structural loads are the 1-Ω peak and those due to the structural modes, specifically at the flap and edge frequencies of the rotor.

The control system should attempt to reduce the low frequency component of the transient loads to a minimum without unduly aggravating the high frequency component.

There is a great variety of wind turbine configurations. The turbine might be constant speed or variable speed; full span pitch regulated, tip regulated or stall regulated; three-bladed, two-bladed or even one-bladed. In addition, the drive-train dynamics and the structural dynamics can vary considerably; when the frequency of the dominant normal modes of the drive train or structure is less than 1-Ω then the dynamics are termed soft. The goals for the control system are strongly dependent on the wind turbine configuration and only a subset will apply to any particular machine.

The precise manner of the control design task depends on the configuration of the wind turbine. The plant may be SISO or MIMO; it may be unstable and/or non-minimum-phase. It may be essentially linear or strongly nonlinear. The range of design tasks exhibited by wind turbines is broad, almost comprehensive. The purpose of this paper id describe this range with the emphasis on the control system design, *i.e.* the choice of the control strategy, the structure required to cater for the full operating range, the accommodation of transients, nonlinearities and actuator restrictions etc., rather than on the synthesis of the control algorithm to be embedded within it. The resulting design is invariably nonlinear. The method of synthesis is immaterial and, provided the precise design task and the given methodology are sufficiently familiar, is straightforward. The paper draws on results from several recent projects [2]-[8] and to some extent constitutes a report of progress in the control of both constant speed and variable speed wind turbines. Earlier investigations were reviewed previously [9].

2. Constant Speed Wind Turbines : Control Design Task

For a constant speed wind turbine, goals c) and d) of the four performance goals are not applicable. The generator, typically an induction generator with a slip of 1% - 2%, provides the drive-train with adequate damping. Also, the energy capture does not directly depend on the control system since, above rated wind speed, the average value of generated power is ensured to be rated power by regulating with that as the set-point. The control system is not active below rated wind speed. With regard to goal a) and so inherently goal b), the control system should minimise the low frequency drive-train loads without unnecessarily aggravating the structural loads, *i.e.* reduce the low frequency off-design structural loads related to the drive-train loads without enhancing the high frequency loads particularly the 1-Ω and n-Ω peaks. The control system can do little about the on-design loads. Connecting the generator directly to the grid has the disadvantage of creating a strong feedback loop. Consequently, wind speed turbulence induces very large drive-train loads and power transients which frequently exceed twice rated. Reducing these markedly enable a reduction in the rating of components or a reduction in the generator slip which increases the turbine efficiency.

For medium scale wind turbines, about 300 kW in rating, the plant is a stable, essentially minimum phase SISO system. The pitch of the blades is varied in response to a measurement of the difference between generated power and rated power. The low frequency range of the load transients is 0 rad/s to approximately 2 rad/s and the actuator has a bandwidth typically 12.5 rad/s to 25 rad/s. Because of the large inertia of the blades and the strong high frequency component of the loads, particularly the peaks at integer multiples of Ω, there are actuator constraints which restrict the control system performance. When the actuator is electro-mechanical the restriction is on actuator torque and so acceleration; when the actuator is hydraulic the restriction is on the actuator speed.

The design challenge is to achieve as much as possible within the actuator constraints. The salient features of the control design are the following.

It must reject slow external disturbances such as changes in mean wind speed or steady increases or decreases in wind speed by reducing the steady state errors. To cope with these the open-loop transfer function must behave as $k/(s(s + a))$ at low frequency with a small. The $1/s$ factor causes the steady state errors in response to changes in mean wind speed to be zero thereby ensuring that the pitch angle changes with wind speed such that the mean error in power is zero. Wind gusts act like ramp disturbances which displace the mean generated power from the set-point of rated power by as much as 100 kW. To reduce the displacement a is small. The low frequency asymptote for the open-loop Bode plot intercepts the 0 dB axis at high frequency and ensures the velocity error constant is large. Hence, the steady state errors in response to steady increases or decreases in the wind speed are small.

When the wind speed rises rapidly from below to above rated wind speed, the control system must start to operate in a smooth manner with no initial overshoot. Unfortunately, there is a low frequency pole in the controller transfer function, namely the pole at $-a$ which was introduced to induce the correct steady state error behaviour. On starting control action, this low frequency pole causes large torque transients which are relatively slow to decay. This is not acceptable since the wind speed frequently transverses from below to above rated and vice versa. The remedy is to introduce a minor feedback loop as shown in Figure 3 which switches in and permits the controller to continue operating below rated wind speed. It has the further role of preventing integral wind-up in below rated wind speed.

The rotor aerodynamics exhibit strongly nonlinear behaviour. The sensitivity of the aerodynamic torque to changes in the pitch angle of the blades increases with wind speed, which is reflected in a corresponding increase in the gain of the plant transfer function. If not catered for, the cross-over frequency of the open-loop system would increase, and the accompanying changes in phase would seriously reduce the stability margins. However, the dynamics of the plant, as far as the aerodynamics are concerned, can be made essentially linear by the inclusion , as discussed in Section 3 below, of a compensating nonlinear gain in the controller. By positioning the nonlinear gain after all the controller dynamics except for the 1/*s* term, which comes last, the system is essentially linearised.

Naturally, the control design for the wind turbine must be robust to plant uncertainty. Of all the dynamics of the system, the most accurately known are the power-train dynamics. However, a large amount of uncertainty is associated with the aerodynamics. To cater for this uncertainty, reasonable gain and phase margins are necessary, although the phase margin may be chosen to be less than usual, to enable the velocity error constant to be increased, since the greater extent of uncertainty is in the gain.

The structure of the controller which meets the above criteria is depicted in Figure 3.

3. Compensating for the Nonlinear Aerodynamics

As mentioned in section 2, the aerodynamics exhibit strongly nonlinear behaviour. The dynamic relationship of the aerodynamic torque to pitch demand is represented by Figure 4a. The aerodynamic torque, T, depends nonlinearly on both the pitch angle, p, and the wind speed, V, *i.e.*

$$T = T(p,V) \quad (1)$$

Consequently, the continuously changing speed of the wind induces time variations in the dynamics. For each wind speed, V, (above rated wind speed) the rated value of aerodynamic torque, T_o, is attained at a unique pitch angle, p_V. These pitch angles together with their corresponding wind speeds define the locus of equilibrium operating points, (p_V, V) of the system. Of course, the wind turbine controller attempts to ensure that the pitch angle is appropriately set at each wind speed.

Locally to a specific operating point, the system may be linearised as depicted in Figure 5, where δ indicates perturbations about the nominal values at the operating point. The nonlinearity is approximated by a fixed gain, corresponding to the rate of change of the aerodynamic torque with respect to changes in pitch angle. If the operating point changes relatively slowly, then a gain-scheduling approach to compensation of the aerodynamic nonlinearity is to incorporate the reciprocal of the aerodynamic gain within the controller and schedule this gain with the operating point. The dynamics can then be considered to be the same locally at every operating point and a fixed linear controller may be designed. However, scheduling on a direct measurement of wind speed is not possible. Simple scheduling is, therefore, not appropriate and the wind speed must instead be inferred from the plant dynamics via the pitch angle. If the controller is operating correctly, then the pitch angle is a good indicator of wind speed since the state of the turbine would be close to the locus of operating points. Consequently, the scheduling gain is enacted as a continuous nonlinear function of pitch angle. It is known [2], [10] that the positioning of this nonlinear scheduling gain relative to the pure integrator term is important. An obvious choice for its position is after the controller (including the pure integrator term), as in Figure 6a. Alternatively, it might be positioned after the main controller dynamics but immediately before the integrator as in Figure 6b. The performance, as indicated by generated power, is depicted in Figure 7 with the gain positioned both after the integrator and before. The improvement in performance with the nonlinear gain positioned before the integrator is clear. However, it may be accompanied by a reduction in the stability margins and further analysis is required.

Wind speed fluctuations are highly stochastic and the operating point of the wind turbine varies rapidly and continously over the whole operational envelope. Whilst the bandwidth of the closed-loop system is typically around 3 rad/s, the operating point might cover its full range in a few seconds, corresponding to an order of magnitude or greater change in the aerodynamic gain. (The extent of the difference in performance in Figure 7 between positioning it before or after the integrator indicates the strength of the nonlinear gain). Consquently, the emphasis must be on the nonlinear behaviour and performance of the controlled system. It is necessary to confirm that the realisation of Figure 6b is, indeed, the most appropriate.

Since the aerodynamic torque is constant along the locus of operating points, the partial derivatives of T, when evaluated at a point on the locus, are related by

$$\frac{\partial T}{\partial V}(p_V,V) = -\frac{dp(V)}{dV}\frac{\partial T}{\partial p}(p_V,V) \qquad (2)$$

where dp(V)/dV is the rate of change, with respect to wind speed, of pitch angle along the locus. It follows that (f(p)-g(V)) is constant on the locus of operating point provided f and g satisfy the conditions

$$\frac{df}{dp}(p_V,V) = \frac{\partial T}{\partial p}(p_V,V); \frac{dg}{dV}(p_V,V) = -\frac{\partial T}{\partial V}(p_V,V) \qquad (3)$$

for all (p_V,V). Of course, (3) defines, within a constant, f(•) for all pitch angles and g(•) for all above rated wind speeds. Without loss of generality, (f(p)-g(V)) can be chosen to be zero on the locus. Hence, locally to the locus of operating points,

$$T(p,V) \equiv \tau(\varepsilon);\ \varepsilon = f(p) - g(V) \qquad (4)$$

for some function τ such that,

$$\tau(0) = T_o; \qquad d\tau/d\varepsilon(0) = 1 \qquad (5)$$

since, locally to any point (p_V,V) on the locus,

$$\tau(f(p_V+\delta p) - g(V+\delta V)) \approx T_o + \frac{\partial T}{\partial p}(p_V,V)\,\delta p + \frac{\partial T}{\partial V}(p_V,V)\,\delta V \qquad (6a)$$

$$\approx T(p_V+\delta p, V+\delta V) \qquad (6b)$$

The dynamic relationship of the aerodynamic torque to pitch demand can, therefore, be represented locally to the locus of operating points by Figure 4b in which f(•) separately depicts the time varying nonlinear dependence on operating point wind and τ(•) depicts the nonlinear dependence on displacement from the locus of operating points.

The actuator dynamics may be adequately approximated as a first order system such that

$$\dot{p} + a\,p = a\,y \qquad (7)$$

where y is the input signal applied to the actuator. Let u denote the output of the fixed linear controller design. The objective is to determine a realisable relationship of y to u such that the nonlinear dependence of φ, in Figure 4b, on y and so on u is counteracted; that is, φ is linearly related to u by,

$$\dot{\varphi} + a\varphi = a\,b\,u \tag{8}$$

The gain b is chosen to match the aerodynamic gain at the operating point selected when designing the fixed linear controller. This objective can be achieved by treating the actuator dynamics, (7), in combination with the relationship of φ to p as a nonlinear system which can be reformulated in a manner suitable for the application of feedback linearisation [11]. However, realisable relationships with both the nonlinear gain before the integrator and after the integrator can be derived more directly. (Extension of the analysis that follows to higher-order approximations of the actuator is straightforward, if required).

From Figure 4b, it may be observed that,

$$\varphi = f(p) \tag{9}$$

and so

$$\dot{\varphi} = \frac{df}{dp}\dot{p}; \qquad \ddot{\varphi} = \frac{d^2f}{dp^2}(\dot{p})^2 + \frac{df}{dp}\ddot{p} \tag{10}$$

It follows that

$$(\dot{\varphi} + a\varphi) - \frac{df}{dp}(\dot{p} + ap) = a\left(f(p) - p\frac{df}{dp}\right) \tag{11}$$

and, using (7) and (8),

$$a\,b\,u - \frac{df}{dp}a\,y = a\left(f(p) - p\frac{df}{dp}\right) \tag{12}$$

Hence, a realisable choice for y is defined by

$$y = \frac{b\,u - (f(p) - p\,df/dp)}{df/dp} \tag{13}$$

resulting in the controller structure of Figure 8a. It corresponds to Figure 6a with the nonlinear gain after the integrator. Alternatively, from (9) and (10), it follows that

$$\frac{d}{dt}(\dot{\varphi} + a\varphi) - \frac{df}{dp}\frac{d}{dt}(\dot{p} + ap) = \frac{d^2f}{dp^2}\dot{p}^2 \tag{14}$$

and, using (7) and (8),

$$a b \dot{u} - \frac{df}{dp} a \dot{y} = \frac{d^2 f}{dp^2} \dot{p}^2 \qquad (15)$$

Hence, a realisable choice for y is defined by,

$$y = \int_0^t \frac{b\dot{u} - 1/a \; d^2f/dp^2 \; (\dot{p})^2}{df/dp} \, dt \qquad (16)$$

resulting in the controller structure of Figure 8b. It corresponds to Figure 6b with the nonlinear gain before the integrator.

The above analysis, apparently, supports the positioning of the nonlinear gain both before and after the integrator but with additional nonlinear feedback. Both df/dp and d^2f/dp^2 are straightforward to obtain as, respectively, $\partial T/\partial p$ and $\partial^2 T/\partial p^2$ along the locus of operating points. Also, p and dp/dt are usually available from measurements internal to the actuator, as in the controller structures of Figure 8a, b. Alternatively, they may be estimated from a model of the actuator dynamics, resulting in the controller structures of 8c,d. Nevertheless, positioning the nonlinear gain before the integrator is preferred. The nonlinear feedback in the realisation in Figure 8a is generally weaker than in Figure 8b and so the dynamic sensitivity to the inevitable discepancies between the models used when deriving the realisations and the real plant is less.

Observation (4) is essential to the preceeding analysis which is quite general. It enables a global analysis of the compensation of the nonlinear aerodynamics to be undertaken provided the control system maintains the state of the system within a neighbourhood of the locus of operating points sufficiently small that (4) is valid and τ is weakly nonlinear. For a 300 kW wind turbine, the neighbourhood of the locus of operating points for which (4) is an adequate representation of the aerodynamic torque is substantial. From Figure 9, it can be seen that the control system performs sufficiently well if it ensures that the aerodynamic torque, and so power, is kept below 2½ times its rated value. There is no difficulty in meeting this requirement; see, for example, Figure 7. This result is not unexpected because there are underlying physical reasons why the representation (4) should hold for a wide neighbourhood for all wind turbines. The aerodynamic torque largely stems from the outer third of the rotor but, in this region, the velocity of the blade is much greater than the wind velocity. It follows that the direction of the wind velocity, relative to the blades, changes almost linearly as the wind speed varies but its magnitude changes little. Hence, the aerodynamic torque is largely a function of the angle of attack of the wind on the outer third of the blades, which is simply the difference in the direction of the relative velocity of the wind and the pitch angle.

For a 300 kW wind turbine, the nonlinear feedback in Figure 8a is generally sufficiently weak that it can be omitted. In addition, the bandwidth of the actuator is sufficiently large that the gain can be adjusted on the demanded pitch rather than the actual pitch. Hence, the gain scheduling of Figure 6b is appropriate.

4. Dependence on Configuration

Control systems for a variety of wind turbines have been designed to meet the criteria discussed in section 2. The performance is strongly dependent on the wind turbine configuration.

A parametric study [6] has investigated the influence of the wind turbine configuration - the number of blades, whether the power is full-span pitch or tip regulated and the drive-train dynamics - on the controller performance of medium scale wind turbines as measured by the extent of fluctuations in generated power and the extent of actuator activity. Figure 10 shows the relationship of the controller capability, as measured by the crossover frequency of the open-loop system, to the power fluctuations for two- and three-bladed machines with a first drive-train mode frequency of 6 rad/s (typical of commercial medium scale wind turbines). Figure 10(a) is for a high wind speed site and Figure 10(b) is for a low wind speed site at which wind speed rarely exceeding 20 m/s. There is an order of magnitude difference in performance between the best, that of the three-bladed tip regulated machine, and the worst, that of the two-bladed full-span pitch regulated machine. The performance of these two machines is illustrated in Figure 11 for mean wind speeds of 12, 16 and 23 m/s. Whereas the performance of the three-bladed machine increases strongly with controller crossover frequency, the performance of the two-bladed machine in low wind speeds does not. It can be seen in Figure 11(a) that the most testing conditions for the tip regulated turbine are low wind speeds. Such conditions are encounted frequently. Hence, the controller should be designed for such conditions and the crossover frequency should be as high as possible. In contrast, it may be observed from Figure 11(b) that the most testing conditions for the full-span regulated turbine are in high wind speed conditions. These are encountered rather infrequently. Except at high wind speed, the standard deviation of power is only weakly related to the controller crossover frequency. Hence, there is little benefit to be gained by increasing the controller crossover frequency when such a wind turbine is placed on a low wind speed site. Also shown in Figure 11 are the controller crossover frequencies at which the standard deviation of pitch acceleration is 6, 18, and 57 $°/s^2$ when the mean wind speed is 12 m/s (the most demanding wind speed for the actuator). The actuator acceleration required by the tip regulated wind turbine to achieve the same control system capability as the full-span regulated wind turbine is significantly lower. The performance of the three-bladed tip regulated wind turbine is much better than the two-bladed full-span regulated wind turbine when the actuators have the same rating.

In addition to the above factors, the performance is also dependent on the size of the wind turbine. For large scale wind turbines, about 1 MW in rating, there are several modifications of the control design task as compared to medium scale machines. The modifications are unavoidable as they arise from scaling effects since the inertias increase as the fifth power of the rotor diameter whereas the forces are related to area and increase as the square of the rotor diameter. These modifications are discussed below.

Firstly, as the size of the machine increases the tower dynamics normally become soft. The tower dynamics cause the drive-train dynamics and so the plant to become non-minimum phase. There is significant loss of phase at low frequency. Therefore, the non-minimum phase dynamics, related to the tower, significantly restrict the performance which can be achieved by a controller. Secondly, undesirable nonlinear dynamic effects due to the large inertia of the rotor are noticeable in full-span regulated machines. The strength of these effects is related to the blade edgewise and flapwise frequencies and are particularly strong in wind speeds close to rated when the pitch velocity is large. They restrict the rate at which the pitch of the blades can be changed, typically to a maximum 5 rad/s -10 rad/s. Thirdly, the bandwidth of the actuator is much reduced to approximately 2 rad/s - 3 rad/s. The actuator is, therefore, much more liable to saturate than in the medium scale case. The minor feedback loop in Figure 3 no longer provides adequate protection against integrator wind-up and additional protection is necessary. In addition, significant dynamics are now present between the controller and pitch angle of the blades. The treatment of the nonlinear gain in Figure 3 may no longer be adequate and the nonlinear feedback in Figure 8b may need to be retained.

The structure of the controller in Figure 3 needs to be adapted to meet these additional requirements.

5. Nonlinear Control

The nonlinear aerodynamic behaviour has been catered for by the inclusion of the nonlinear gain in Figure 6. Nevertheless, the application of nonlinear control to wind turbines is still indicated by the requirement to exploit the actuators to their maximum potential.

The actuator characteristics, especially the limits on torque, are one of the main restrictions on the performance that can be achieved by a controller. As the wind speed rises, a linear controller places less demand on the actuator since the sensitivity of the aerodynamic torque to pitch changes increases faster than the sensitivity to wind speed changes. Hence, for a controller with fixed open-loop cross-over frequency, while the actuator may be worked to its full level at low wind speed, it may not be used as fully at higher wind speeds. However, it is at these higher wind speeds that loads are greatest and therefore controller performance is most critical. Parametric studies [6], [12], [13] indicate that there is an advantage in using this spare actuator capacity as the wind speed rises and that there exists an optimum level of activity for the controller at each wind speed. Whether, at any particular wind speed, the resulting optimum cross-over frequency can be achieved in practice depends on the capabilities of the actuator.

The requirement is to design a controller which works the actuator as near as possible to its optimal level of activity in all wind speeds, subject to actuator constraints. Simple scheduling is not appropriate and the wind speed must be inferred from the plant dynamics via the pitch demand. However, employing an internal state of the system, such as the pitch demand, to implicitly change the controller as wind speed varies must be treated with some caution, however, since it introduces additional nonlinear feedback loops, thereby changing the dynamic behaviour of the system. The design task is to develop a continuously varying controller which induces the appropriate closed-loop dynamics at any wind speed, despite the presence of these feedback loops. The resulting controller is nonlinear.

This type of nonlinear control strategy is illustrated in some detail for a typical two bladed constant speed configuration of wind turbine [8], [16]. A family of linearised controllers is designed for various wind speeds using classical loop-shaping design techniques. Some care was taken to minimise the differences between these controllers so that interpolation between them could be carried out as smoothly as possible. The continuous family of controllers thereby generated is :

$$g \frac{(s^2+7.59s+68.06)}{(s^2+as+b)} \frac{(s+1.7)(s+1.8)(s^2+3s+416.16)}{s(s+0.3)(s+3.7)(s^2+8s+416.16)}$$

$$x \frac{(s^2+2s+104.04)(s^2+7.243s+38.637)2209}{(s^2+11s+104.04)(s+100)(s+30)(s^2+65.8s+2209)}$$

where

$a=-0.033047p^2 + 0.75064p + 3.3749$

$b= 2.6002p + 58.040$

$g = (0.13779p + 0.29784)$

and p is the pitch angle demanded by the controller, in degrees. The Bode plot of the open-loop transfer function of the system with the member of this family of controllers for 12 m/s wind speed is shown in Figure 12. The family of controllers has the following features :

- Low frequency shaping to improve disturbance rejection.
- Notches at 2P and 4P to reduce actuator activity and reduce the enhancement of the loads induced by these spectral peaks.
- High frequency roll-off to reduce actuator activity.

Upper and lower bounds are placed on a, b and g,. When p is less than 3.84 degrees (corresponding to 12 m/s wind speed), a, b and g are held at their 3.84 degree values. Similarly, when p is greater than 20.59 degrees (24 m/s wind speed), a, b and g are held at their 20.59 degree values. It can be seen that these controller transfer functions are the same except for a varying gain and a pair of varying poles. The gain and phase margins of the transfer functions for a range of values of p are given in the following table :

p (deg)	gain margin (dB)	phase margin (deg)	cross-over freq. (rad/s)
3.84 (12 m/s)	13.74	55.23	1.36
11.14 (16 m/s)	10.03	55.89	2.51
16.21 (20 m/s)	10.00	55.62	2.85
20.59 (24 m/s)	10.79	55.64	3.25

The controller is split into two main blocks as shown in Figure 3 to cater for the situation when the wind speed has fallen below rated [2], [14]. The controller partitioning in the present case is as follows:

Inner Block

$$g\ 4.5\ K_{nl} \frac{(s+1.7)(s+1.8)(s^2+7.59s+68.06)}{s(s+0.3)(s+3.7)(s^2+as+b)}$$

Outer Block

$$0.222 \frac{(s^2+7.243s+38.637)(s^2+2s+104.04)}{(s+100)(s+30)(s^2+11s+104.04)(s^2+65.8s+2209)}$$

$$\times \frac{(s^2+3s+416.16)}{(s^2+8s+416.16)}$$

where K_{nl} is the previously discussed (section 3) nonlinear gain required to compensate for the nonlinear variation with wind speed in the aerodynamic torque sensitivity to pitch change.

Because of their global mutual compensation [14], these two nonlinearities are ignored in the remainder of this section.

A nonlinear controller is obtained by interpolating continuously between the members of the family of linear controllers as pitch demand varies. The realisation of the nonlinear controller must be chosen with care since the dynamic behaviour of the nonlinear controller clearly depends on the positioning of the nonlinear elements relative to the integrations. (For example, while $\int k\, x(t)dt$ is equivalent to $k \int x(t)dt$ for fixed k, this is no longer the case when the value of k is varying). The nonlinear elements of the present controller are confined to the inner block. Clearly, a necessary condition for the appropriate controller to be attained at every wind speed is that the linearisation of the nonlinear controller is identical to the linear controller obtained by setting p in the nonlinear controller to the value of pitch angle corresponding to the wind speed. This condition is satisfied by the manner in which the inner block is realised. The realisation adopted [8], [16] is shown in Figure 13. The position of the pure integrator is chosen to be after the other elements so that, with the exception of the output pitch demand, the signals x_1, x_2, x_3, x_4 of the nonlinear dynamics (Figure 13) are zero when at an equilibrium point. In conjunction with the realisation, it follows that the linearisation of the inner block about any operating point results in the same transfer function as when p is frozen at the appropriate value, and the previous linear analysis is locally valid. The performance of the nonlinear controller, in response to small fluctuations in the wind speed about some mean value, can therefore be expected to be in good agreement with that of the corresponding linear controller. However, satisfaction of the local control requirements alone is not sufficient in the wind turbine application. The wind turbulence does not consist solely of small wind speed fluctuations. Large, rapid fluctuations in wind speed and power output are common, in particular gusts; that is, steady increases or decreases in the wind speed which persist for ten seconds or more. In addition to exhibiting local linear equivalence about equilibrium operating points, the realisation adopted displays local linear equivalence under unsteady conditions.

The non-local stability and robustness properties of the nonlinear controller must be similar to the linear controllers. The nonlinear control strategy involves implicit scheduling on a state which is not slowly varying *prima facie*. The stability and robustness of such a controller can be studied using a variety of methods, although the analytical tools available give results which in general are more conservative than in the linear case. Three approaches to stability and robustness analysis have been considered, namely:

(i) Simulation.
(ii) Small Gain theorem.
(iii) Rate of controller variation.

While none of the stability analysis are conclusive, they appear to be consistent with one another and with the linear analysis.

Significant improvement in performance is achieved over conventional linear controllers. Some typical results are the probability distributions in Figure 14a.

Nonlinear control strategies are also possible which exploit the soft nature of constraints on the actuator average rate of work. While the average rate is subject to limits, it is possible to intermittently demand a high level of activity for short periods, taking the actuator up to its hard velocity and/or torque constraints. One control strategy is to cause the actuator to work temporarily at or near its maximum level when the start of an unacceptably high peak in the power output is detected in order to respond as rapidly as possible to the disturbance. Such a strategy is of particular interest since it is the occasional extreme loads experienced by a wind turbine during its life which contribute most to fatigue damage. Moreover, this strategy may be combined with the previously described nonlinear control approach in order to exploit the capabilities of the actuator more fully.

There are a variety of design issues to be considered when implementing this control strategy. It is unlikely that the actuator can be worked at its maximum level for the full duration of a power excursion without a loss of stability. The design of suitable switching rules is therefore necessary, which trade-off performance against robustness. This type of control strategy also affects the skew of the probability distribution of the power, and it may depress the mean power output which is extremely undesirable from an economic standpoint. The switching rules should be designed to take this into account. Finally, performance may be significantly improved if a predictor is used to permit an earlier reaction to a peak in the power. Measurement noise and the auto-correlation characteristics of the power output introduce well-understood fundamental limits on prediction accuracy as a function of the distance prediction horizon. However, in the present application the predictor is incorporated into the controller and the predictor output influences the power output which in turn is fed back to the predictor. An analysis of the behaviour of a predictor within the loop is not straightforward for a nonlinear system, and estimation of the performance requires nonlinear simulation. An example of the performance improvement that may be obtained is indicated by Figure 14b, where the probability distribution of the power output for a linear controller is shown together with the distribution obtained when the controller is augmented to reduce extreme loads.

For the control system to maximise effectiveness, it should be augmented by a combination of both the above nonlinear strategies.

6. Variable Speed Wind Turbines

Variable speed operation of wind turbines is perceived to have several potential advantages of which two frequently mentioned ones are

(i) additional energy capture below rated wind speed
(ii) additional power-train compliance and associated load alleviation above rated wind speed.

In addition, the noise emitted by the wind turbine can be reduced in low wind speeds by reducing the rotor speed.

The variable speed capability of the turbine enables the rotor speed to be varied with wind speed and there are a multiplicity of choices of strategy defining precisely that relationship. However, it is more appropriate to define the strategy by a curve in the torque/rotor speed plane [16] rather than the rotor speed/wind speed plane because of the nonlinear nature of the aerodynamics and the non-uniqueness of the relationship between the wind speed and the operating state of the wind turbine, *i.e.* there may be more than one wind speed for a given operating point and more than one operating point for a given wind speed. Each possible strategy can be represented by a curve on the torque/speed plane which the control system must cause the wind turbine operating point to track as closely as possible, *i.e.* curves on the torque/speed plane represent possible choices of control strategy for a variable speed wind turbine. Which control strategy is most appropriate depends on the configuration of the wind turbine, in particular, the aerodynamic characteristics of the rotor.

All four performance goals are relevant to variable speed wind turbines. First, both the drive-train loads and the structural loads, on-design and off-design, are dependent on the choice of control strategy. In addition, the control system should attempt to minimise the low frequency drive-train loads and the related off-design structural loads without aggravating the high frequency loads. Second, power smoothing is again achieved by alleviating the transient drive-train loads. Third, a consequence of the generator not being directly coupled to the grid is that the drive-train has very little natural damping. Indeed, it may resonate. Consequently, the control system is required to provide damping [5]. Fourth, the energy capture is a function of both the choice of control strategy and the performance of the control system.

Below rated wind speed, the wind turbine is regulated by varying the generator reaction torque. The rectifier firing angle or an equivalent variable is altered in response to the tracking error with respect to the selected control strategy. The plant is a stable and minimum phase SISO system but the disturbance may be non-minimum phase.

Above rated wind speed, the wind turbine may be stall regulated or pitch regulated. When stall regulated, the rectifier firing angle is again altered in response to the tracking error. The plant is an unstable and/or non-minimum phase SISO system. The separation between the frequencies of the right half-plane poles and zeros may be small. When pitch regulated, the rectifier firing angle or an equivalent variable is altered in response to a measurement of power to maintain power at its rated value and the pitch angle of the blades is altered in response to a measurement of rotor speed to maintain constant speed. The pitch capability is similar to that of an equivalent constant speed wind turbine. The plant is a stable minimum phase MIMO system with 2 inputs and 2 outputs.

The design challenge is to select the most appropriate control strategy for a given configuration of wind turbine and design a control system to realise that strategy as effectively as possible. The most appropriate design must be determined both for below rated operation and for above rated operation. In addition, smooth switching between different parts of the control strategy must be achieved. The latter can strongly influence the choice of the former.

An extensive investigation of control strategies has been conducted but, for reasons of space only a subset of the relevant issues can be described in the following.

The aerodynamic characteristics of the rotor influence strongly the control system performance and, thus, the choice of strategy. The rotor characteristics are indicated by the power coefficient C_p which is a function of the ratio of the rotor tip speed to the wind speed, (λ). The aerodynamic efficiency of the rotor increases as C_p increases. Typical C_p-λ curves are shown in Figure 15 for a constant speed rotor and two rotors designed for variable speed operation. Rotor A has a broad flat peak whereas Rotor B has a narrow sharp peak. In general, the sharper the C_p-λ curve the greater the sensitivity of performance to transient displacements from the nominal operating points.

Below rated wind speed, the rectifier firing angle is regulated to cause the wind turbine to operate at maximum aerodynamic efficiency; *i.e.*, the turbine is required to track the curve along which C_p attains its maximum value, the $C_{p\,max}$ curve (curve ac in Figure 16), which can be approximated by the parabola, $T=kV^2$, where T is torque, V is rotor speed and k is a constant.

The shape of the C_p-λ curve and the choice of tracking error, $T-kV^2$, have a significant influence on energy capture below rated wind speed. There are two possible choices of T in the tracking error, namely an estimate of aerodynamic torque or the drive-train torque [7]. The former is most appropriate but the latter is used in practise. When the $C_{p\,max}$ curve is tracked by the aerodynamic torque, the energy capture is maximised but the corresponding drive-train torque transients are relatively large. Also, the ability to track the $C_{p\,max}$ curve is limited by the non-minimum phase nature of the dynamics from the wind speed disturbance to the tracking error which can cause the aerodynamic torque to deviate from the curve. When the $C_{p\,max}$ curve is tracked by the drive-train torque, the drive-train torque transients are smaller but the aerodynamic efficiency may be reduced which is particularly significant for a rotor with a sharp C_p-λ curve.

A compromise is to track a linear combination of the two errors, *i.e.* for the controller to act on $e_c(\varepsilon) = (1-\varepsilon)e_1+\varepsilon e_2$, where e_1 is the error based on drive-train torque, e_2 is the error based on aerodynamic torque and ε is a constant in the range $0 \leq \varepsilon \leq 1$. The $C_{p\ max}$ curve is tracked by aerodynamic torque when $\varepsilon=1$ and by drive-train torque when $\varepsilon=0$. Increasing the value of ε increases the tendency of the dynamics from the wind speed disturbance to the tracking error to be non-minimum phase. When the rotor has a broad flat C_p-λ curve like that of Rotor A in Figure 15, the tracking error $e_c(\varepsilon)$, does not offer any significant advantage over the tracking error e_1. The tracking error, $e_c(\varepsilon)$, is more beneficial for rotors with a sharp C_p-λ curve like that of Rotor B in Figure 15.

A more active controller is required for Rotor B than for Rotor A since, for the former, the penalty for small deviations from maximum C_p is a large reduction in energy capture. Rotor B has good stalling properties but, if the wind turbine inadvertently enters the stall region, the control system becomes sluggish and is slow to bring the operating state of the turbine out of this region, thereby causing a reduction in energy capture. If the wind turbine is operated further away from the stall region then it may be possible to increase the energy capture. This can be achieved by tracking lower efficiency curves instead of the $C_{p\ max}$ curve.

The variation in energy capture for the different control strategies can be as much as 20% in some wind conditions.

Above rated wind speed, the wind turbine may have the capability to pitch the blades. In this case, the pitch angle is varied to regulate the generator speed to within pre-defined limits of a reference speed and the rectifier firing angle is varied to regulate the drive-train torques in response to wind speed disturbances. The usual philosophy is to use fast torque control action and slow speed control action in order to minimise the actuator activity. But, fast torque control action, through the rectifier firing angle, is not always necessary. The rotor speed range can be reduced, and thereby the peak loads, by increasing the activity of the speed controller. However, the actuator activity increases with the crossover frequency of the speed controller. In addition, increasing the crossover frequency may result in oscillations appearing in the rotor speed and the drive-train torque. The usual nonlinear gain of the pitch control system becomes inappropriately set due to the lag associated with the rotor inertia which is inherent to variable speed wind turbines. The risk of oscillations is avoided with a less active pitch control system.

The alternative to pitch control is stall control. The wind turbine is deliberately brought into the stall region by reducing the rotational speed of the rotor. There are several different strategies. The turbine can be regulated to maintain constant rotor speed, constant generated power or constant aerodynamic torque, see Figure 16. Depending on the rotor characteristics, a combination of all three strategies may be required. In each case the plant is SISO.

Control of a variable speed stall regulated wind turbine with a constant speed mode in above rated operation is equivalent to tracking the curve bd in Figure 16. Alternatively, power is kept at its rated value by reducing the rotational speed such that the curve ce is tracked by aerodynamic torque. Or again, rated aerodynamic torque is achieved by tracking the curve cf in Figure 16. The plant dynamics change considerably along these curves with unstable poles and non-minimum phase zeros occurring which restrict the crossover frequency and stability margins. Since the aerodynamics are uncertain in the stall region, a fixed controller is required for robustness. The plant dynamics are such that at the operating points b or c, the transition point from below to above rated operation, the controller crossover frequency is small which can result in overshoots at the transition point. If the control strategy could be modified such that the plant dynamics permit more active control in this region, then better control would be achieved. One possible approach is to track a steeper maximum power curve instead of ce in

Figure 16. The difference in tracking these two curves is not thought to be significant for energy capture.

Both the extent of the transient loads and energy capture depend on the choice of strategy to induce stall but which is most appropriate depends strongly on the rotor characteristics.

7. Summary

The control design task for both constant speed and variable speed wind turbines has been discussed. It is strongly dependent on the configuration of the wind turbine. The plant may be SISO or MIMO, it may be unstable and/or non-minimum phase. It may be essentially linear or strongly nonlinear. The precise role and objectives of the control design task also depend on the configuration. For constant speed wind turbines, the number of blades, the nature of the pitch action, the drive-train dynamics and the size of the machine, all influence the controller performance and design. The design challenge is to achieve as much as possible within the actuator constraints and to this end nonlinear control has been demonstrated to have considerable potential. For variable speed wind turbines, the aerodynamic characteristics of the rotor influence the controller performance and design. The design challenge is to select the most appropriate control strategy for a given configuration of wind turbine and design a control system to realise that strategy as effectively as possible. It has been demonstrated that the most appropriate formulation of the design task, for both pitch regulated and stall regulated turbines, is in terms of tracking a curve in the torque/speed plane.

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