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PROGRESS IN CONTROL OF WIND TURBINES

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Abstract

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 wind turbines. A variety of control design tasks with differing objectives are posed by the different wind turbine configurations. The plant may be SISO or MIMO; it may be unstable and/or non-minimum phase; it may be essentially linear or strongly non-linear. The purpose of this paper is to discuss the control task for horizontal axis, grid-connected, medium to large scale wind turbines. Both constant speed and variable speed machines are discussed.

1 Introduction

The wind turbines discussed in this paper are horizontal axis, grid-connected medium to large scale wind turbines. 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).

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. 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. 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.

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. The precise nature 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 non-linear. The purpose of this paper is to describe the broad, almost comprehensive, range of design tasks exhibited by wind turbines. The emphasis is 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, non-linearities and actuator restrictions etc., rather than on the synthesis of the control algorithm to be embedded within it. 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.

2 Constant Speed Wind Turbines

2.1 Control Objectives

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. 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.

2.2 Plant Characteristics

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 the rotor speed, Ω, caused by the blades periodically sweeping through the wind-field, 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.

2.3 Control Design Task

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. 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.

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 causes transients which are relatively slow to decay. This is not acceptable since the wind speed frequently traverses from below to above rated and vice versa. The remedy is to introduce a minor feedback loop as shown in Fig. 1 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.

Since the aerodynamic gain (the rate of change of rotor torque with pitch angle) undergoes large and rapid changes, it is necessary that the controller be non-linear also. Ideally, the controller includes a non-linear gain which would be function of wind speed. Unfortunately, it is not possible to measure the wind speed. However, if the control system is effective, wind speed and the non-linear gain are parameterised by the pitch angle. By positioning the non-linear gain after all the controller dynamics except for the $1/s$ term, which comes last, the system is essentially linearised with the non-linear aerodynamic gain and the non-linear control gain mutually cancelling.

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 Fig. 1.

2.4 Dependence on Configuration

Control systems for a variety of wind turbines have been designed to meet the above criteria. 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. There is a large 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 Fig. 2 for mean wind speeds of 12, 16 and 23 m/s. Typically the cross-over frequency would be between 1 rad/s and 3 rad/s. The actuator r.m.s. acceleration (shown on Fig. 2) 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.

2.5 Large Scale Turbines

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.

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 restricting the performance which can be achieved by a controller. Secondly, undesirable non-linear dynamic effects due to the large inertia of the rotor are noticeable in full-span regulated machines. They restrict the rate at which the pitch of the blades can be changed, typically to a maximum 5 degree/s – 10 degree/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 Fig. 1 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 non-linear gain in Fig. 1 is no longer adequate and requires improvement.

The structure of the controller in Fig. 1 needs to be adapted to meet these additional requirements.

2.6 Non-linear Control

As discussed previously, the rotor aerodynamics exhibit strongly non-linear behaviour. However, the dynamics of the plant, as far as the aerodynamics are concerned, can be made essentially linear by the inclusion, as discussed above, of a compensating non-linear gain in the controller. Nevertheless, the application of non-linear control to wind turbines is still indicated by the requirement to exploit the actuators to their maximum potential. The actuator characteristics and limitations are one of the main restrictions on the performance that can be achieved by the control system.

As 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 fixed controller, while the actuator may be worked to its full capacity at low wind speeds, it may only be worked to part capacity at high wind speeds. However, it is at these higher wind speeds that loads are greatest and therefore controller performance is most critical. It has been established, that there is some 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 the optimum cross-over frequency can actually be achieved at any particular wind speed depends of course on the capabilities of the actuator.

Approaches to exploiting this behaviour are described in [8], where non-linear control strategies are developed to approximately track the optimum level of control activity as the wind speed varies. The resulting controller is non-linear. Significant improvement in performance is achieved over conventional linear controllers. As usual no measurement of wind speed is available. Some typical results are the probability distributions of the power output for a linear controller designed using a classical loop-shaping methodology [2] and a non-linear controller, Fig. 3.

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. An example of the performance improvement that may be obtained is indicated by Fig. 4, 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 non-linear strategies.

3 Variable Speed Wind Turbines

3.1 Control Objectives

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 [9] rather than the rotor speed/wind speed plane because of the impossibility of measuring the wind speed, the non-linear 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 choice 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.

3.2 Plant Characteristics

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.

3.3 Control Design Task

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.

3.4 Below Rated Wind Speed

The aerodynamic characteristics of the rotor strongly influence 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 Fig. 5 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 Fig. 6), 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 practice. 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.

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.

3.5 Above Rated Wind Speed

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 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 rotor speed range can be reduced, and thereby the peak loads, by increasing the activity of the speed controller. However, increasing the crossover frequency may result in oscillations appearing in the rotor speed and the drive-train torque. The usual non-linear 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 generator torque, curves bd, cd and cf, respectively, in Fig. 6. Depending on the rotor characteristics, a combination of all three strategies may be required. In each case the plant is SISO.

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 point 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. The difference in tracking curve 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.

4 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 non-linear. 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 non-linear 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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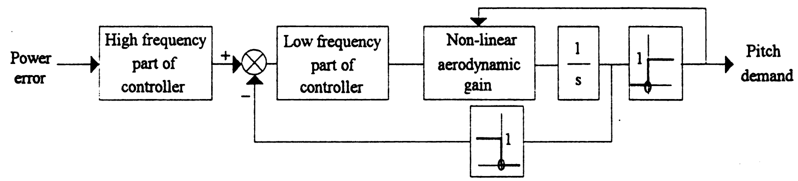
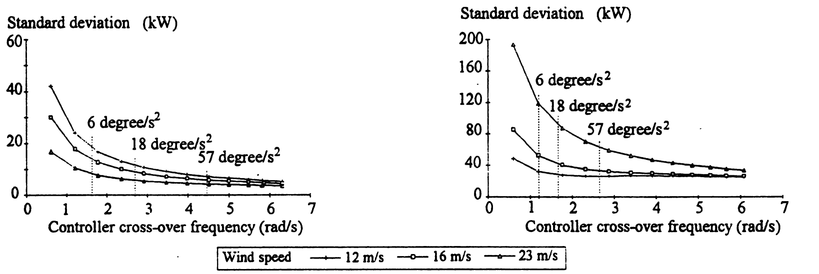


Figure 1 Structure of the controller



a) Three bladed tip regulated machine with first drive-train mode = 7 rad/s

b) Two bladed full-span pitch regulated machine with first drive-train mode = 6 rad/s

Figure 2 Performance at various wind speeds

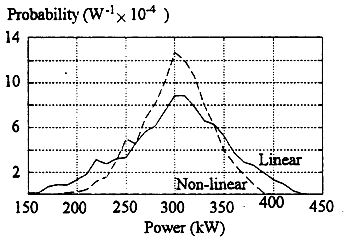


Figure 3 Performance of linear and non-linear controllers (24 m/s wind, 20% TI, 3-bladed m/c)

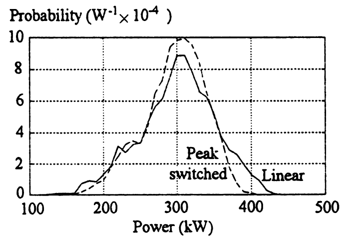


Figure 4 Improvement by switching on power peaks (24 m/s wind, 20% TI, 3-bladed m/c)

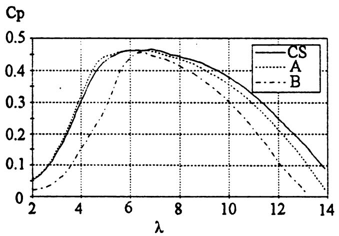


Figure 5 C_p–λ curves for Rotor A, Rotor B and constant speed rotor

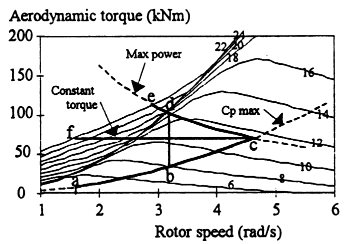


Figure 6 Constant wind speed curves and operational strategy for variable speed wind turbine (Rotor A)