ENHANCED POWER REGULATION OF CONSTANT SPEED HAWTS BY APPROPRIATE CONTROLLER IMPLEMENTATIION

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ABSTRACT: Three of the controller implementation issues for pitch-regulated constant-speed wind turbines are considered. A widely employed technique for accommodating the nonlinear aerodynamics, originally developed on the basis of physical insight, is rigorously derived and extended to cater for all wind turbine configurations. Novel design guidelines are proposed which can significantly reduce the power transients at controller start-up. Restrictive position, velocity and acceleration constraints may all be present in wind turbines. A novel, and quite general, method, based on the start-up strategy, is proposed which caters for all these circumstances. The separate strategies for resolving these issues are combined to achieve a controller realisation which accommodates all the implementation issues in an integrated manner. The importance of adopting an appropriate controller realisation is demonstrated to be considerable.

Keywords: Control Systems, Large Machines, Robust Control, Control

1. Introduction

The control design task for constant-speed pitch-regulated machines is to exploit this capability in order to regulate the power output whilst minimising the load transients and thereby reducing fatigue damage (Leithead *et al.* 1991, 1992). In this paper, three of the implementation issues encountered, when developing controllers for pitch-regulated constant-speed wind turbines, are investigated.

The first implementation issue relates to the aerodynamic behaviour of the turbine blades. Whilst a linearised plant representation is typically employed during the synthesis of the controller transfer function, a wind turbine is a nonlinear system; in particular, the aerodynamic behaviour is highly nonlinear. Clearly, the nonlinear behaviour of the rotor exerts a substantial influence on the characteristics of the whole wind turbine and cannot be neglected (*e.g.*, Leithead *et al.* 1991, 1992).

The second implementation issue relates to the automatic start-up and shut-down the controller as the wind speed fluctuates. The controller has integral action to ensure rejection of steady wind disturbances and suitable low frequency shaping (Leithead *et al.* 1991, 1992) to ensure rejection of gusts (ramp-like increases or decreases in wind speed which persist over several seconds). Consequently, controller start-up requires to be treated with some care to avoid prolonged transients and minimise the loads on the wind turbine.

The third implementation issue relates to the actuator physical constraints, neglected during the controller transfer function synthesis. In low wind speeds, when the sensitivity of the aerodynamic torque to changes in the pitch angle is lowest, it is often necessary to move the blades of the turbine rapidly in order to achieve adequate power regulation. The hard limits on the accelerations (or torques) and velocities, internal to the actuator, are, therefore, often encountered during normal operation near rated wind speed. At present, the impact of the hard actuator limits on stability and performance, in the context of wind turbine applications, has received little consideration.

Strategies, which adequately address the implementation issues, are reported by Leithead *et al.* (1991, 1992). (Their effectiveness has been confirmed in field trials). However, these strategies were developed on the basis of physical insight, supported by simulation studies, and a more rigorous analytic approach remains desirable. A re-examination and analytic investigation of the implementation issues is further warranted by the recent development of high performance nonlinear controllers (Leith & Leithead 1995, 1996a, b), which operate the control system at its limits to a much greater extent than conventional linear controllers, and by the progression of the wind turbine rating from medium-scale to large-scale with the consequent trend towards a considerable tightening of the physical constraints on the control system.

A detailed discussion of the issues considered in this paper is presented in Leith & Leithead (1996c). In this paper, the controller implementation issues are illustrated with respect to a medium-scale 300 kW two-bladed grid-connected up-wind constant-speed full-span pitch-regulated wind turbine which is dynamically representative of commercial machines of its class (Leith & Leithead 1996c).

2. Review of Previous Strategies

2.1 Compensating for the Nonlinear Aerodynamics

The aerodynamic torque, T, depends nonlinearly on both the pitch angle, p, and the effective wind speed, V, as

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

For each effective wind speed, V, above rated wind speed, the rated aerodynamic torque, T_o, is attained at a unique pitch angle, p_V. These pitch angles together with their corresponding effective wind speeds define the locus of equilibrium operating points, (p_V, V), of the system. The requirement is to devise a means of accommodating the nonlinear aerodynamic behaviour such that a fixed linear control algorithm may be employed over the whole operational envelope. The discussion is confined, for the moment, to the issue of accommodating the nonlinear aerodynamics.

One solution to this task, proposed by Leithead *et al.* (1991, 1992), is to augment the controller with a nonlinear gain corresponding to the reciprocal of the sensitivity of the aerodynamic torque to pitch changes, $\partial T/\partial p$. Whilst a direct measurement of the wind speed cannot be employed to adjust this gain. the controller should, irrespective of actuator bandwidth, attempt to ensure that the pitch angle is appropriately set at each wind speed. Consequently, assuming that the pitch angle is close to p_v, the need for a measurement of wind speed is avoided; that is, the wind speed may be inferred directly from the pitch angle. It is known that the performance of this approach to aerodynamic compensation is strongly dependent on the positioning of the nonlinear gain and that the appropriate position is after the main controller dynamics but before the pure integrator term (Leithead *et al* 1991, 1992)

However, whilst engineering insight provides a basis for understanding the effectiveness of this approach, a rigorous analysis is lacking and it is uncertain whether the method is appropriate for other wind turbine configurations; in particular, for large-scale machines which, owing to physical restrictions, can have very low bandwidth actuators.

2.2 Controller Start-Up/Shut-Down

A common approach to controller start-up is to simply freeze the controller integral action when below rated operation is detected; that is, when the demanded pitch angle of the turbine blades falls below a specified threshold value (zero degrees here), the accumulation sum in the integral calculation is suspended. However, this approach is not always effective in preventing large start-up transients. Intuitively, whilst this approach prevents the pure integrator in the controller from adopting an inappropriate state during below-rated operation, it does not cater for the low frequency pole in the controller with which the prolonged start-up transients are associated.

Leithead *et al.* (1991, 1992) propose an alternative start-up technique whereby a minor feedback loop is introduced within the controller which mimics the action of the physical wind turbine and switches in to permit the controller to continue operating below rated wind speed (equivalent to a negative pitch angle demand). Partitioning the controller transfer function as $C_{outer}(s)\ C_{inner}(s)$ and designing the controller, such that C_{outer} may be interpreted as an approximation to the inverse of the plant dynamics and C_{inner} may be interpreted as an approximation to the open-loop system, the minor loop may be implemented in a straightforward manner with the feedback gain approximating the plant aerodynamic gain. The start-up transients are substantially reduced with this strategy. When the dynamic inflow is thought to contribute significantly to the aerodynamics, it is natural to assume that a component, corresponding to the dynamic inflow, should be included in C_{outer} (Leithead *et al.* 1991). However, superior performance is obtained when it is omitted (Leithead *et al.* 1991, 1992). The distinction between the dynamics of C_{outer} and C_{inner} is now that the controller is partitioned such that the slow dynamics are contained in C_{inner}.

2.3 Accommodating Actuator Velocity/Acceleration Saturation

In the context of wind turbine applications, the presence of hard actuator limits is known (Leithead *et al.* 1991) to degrade performance by causing a reduction in stability. However, the impact of the hard actuator limits on stability and performance has received little consideration. Traditionally, the control specification requires that the controller avoids operating the actuator at its hard limits; for example, the permitted standard deviation of the constrained quantities may be suitably restricted. Nevertheless, in order to achieve satisfactory performance, it may be necessary to relax such restrictions, particularly for large-scale machines.

3. Compensating for the Nonlinear Aerodynamics

3.1 Gain-Scheduling

The gain-scheduling approach to compensation of the nonlinear aerodynamics is to incorporate the reciprocal of the aerodynamic 'gain', $\partial T/\partial p(p_v, V)$, within the controller and schedule this gain with respect to a variable which parameterises the locus of equilibrium operating points. (Since scheduling on a direct measurement of wind speed is impossible, the pitch angle may be employed provided the pitch angle is always sufficiently close to p_V). When the system is sufficiently weakly nonlinear, the stability of the gain-scheduled nonlinear system may be inferred from the stability of the members of the family of linear systems consisting of the linearisations of the nonlinear system at each equilibrium operating point.

However, the wind speed fluctuations are highly stochastic and the operating point of the wind turbine varies rapidly and continuously over the whole operating envelope. Moreover, large, rapid fluctuations in wind speed are common, in particular gusts; that is, steady increases or decreases in the wind speed which persist for relatively long periods and produce substantial and prolonged perturbations from equilibrium. Hence, *a priori*, the system cannot be assumed to be weakly nonlinear and the emphasis must be on the nonlinear and non-local behaviour and performance of the controller.

Leith & Leithead (1996a) propose that, with regard to a gain-scheduled controller, appropriate non-local behaviour may be ensured by adopting a controller realisation which satisfies an extended local linear equivalence condition. For the wind turbine controller, this is achieved by placing the scheduled gain after the main controller dynamics but before the pure integrator term and by incorporating a model of the actuator dynamics and its inverse in the controller (Leith & Leithead 1996a). When the actuator bandwidth is sufficiently large, this formulation reduces to that of Leithead *et al.* (1991).

However, for appropriate non-local behaviour, it is required that the complete system, not just the controller, must satisfy the extended local linear equivalence condition. Since this is not the case here, analytic support for the nonlinear gain-scheduled controller is, really, only provided by the above discussion for sufficiently slow perturbations which are local to the locus of equilibrium operating points and not for prolonged non-local perturbations. A nonlinear analysis of the nonlinear gain-scheduled controller is required.

3.2 Separability of the Nonlinear Aerodynamics

It is known that the dependence, on pitch angle and wind speed, of the aerodynamic pitching moment of the turbine blades can be explicitly separated. The same methodology may be applied to the aerodynamic torque

(Leith & Leithead 1996c) to show that, locally to the locus of equilibrium operating points, (1) satisfies

$$T(p,V) \equiv \tau(\varepsilon); \qquad \varepsilon = h(p)-g(V) \qquad (2)$$

for some function τ such that, $\tau(0) = T_o$; $d\tau/d\varepsilon(0) = 1$. The nonlinear function, $g(\bullet)$, embodies the time-varying nonlinear dependence on wind speed and $\tau(\bullet)$ represents the nonlinear dependence on displacement from the locus of equilibrium operating points. It is stressed that (2) is valid non-locally in the sense that it is not confined to describing the behaviour about a single equilibrium operating point but rather describes the behaviour in a neighbourhood about the complete locus of equilibrium operating points. The neighbourhood of the locus of equilibrium points for which (2) is an adequate representation of the nonlinear aerodynamics is substantial (Leith & Leithead 1996c). The separability of the nonlinear aerodynamics is not unexpected because there are underlying physical reasons why the representation (2) should hold for a wide neighbourhood for all wind turbines.

3.3 Direct Linearisation

Owing to the separability of the nonlinear aerodynamics, the compensation problem may be reformulated as one of linearising the nonlinearity, h(p), whilst accommodating the dynamics, $\hat{A}_u$, of the actuator (which lie between the controller and the nonlinearity). It follows immediately that this is achieved by selecting the input signal applied to the actuator, z, according to

$$z = \hat{A}_u^{-1}\,\hat{h}^{-1}(C_{inner}\,C_{outer}\,\hat{A}_u\,e) \qquad (3)$$

where e is the power error signal and $\hat{h}^{-1}$, $\hat{A}_u$, $\hat{A}_u^{-1}$ are suitable approximations to, respectively, h^{-1}, the unconstrained actuator dynamics and the inverse actuator dynamics. (Exact linearisation is achieved when there is no approximation error). Of course, $h^{-1}(\bullet)$, must exist (which requires $dh/dp(\bullet)$, and so $\partial T/\partial p(p_v,V)$, to be monotonic).

This strategy is, however, not unique. For example, since $d/dt\,\hat{h}^{-1}(\hat{\phi}) = \dot{\hat{\phi}} / \frac{d\hat{h}}{d\hat{p}}(\hat{p})$ it follows that the foregoing strategy may be reformulated as

$$z = \hat{A}_u^{-1} \int \frac{1}{\frac{d\hat{h}}{d\hat{p}}(\hat{p})} \frac{d}{dt} C_{inner}\,C_{outer}\,\hat{A}\,e\,dt \qquad (4)$$

(The differentiation operator in this formulation can be incorporated without difficulty into the linear controller owing to the integral action of the latter). The non-local linearisation (4) is essentially identical in form to the local linearisation derived using gain-scheduling methods. Hence, the gain-scheduling approach to accommodating the nonlinear aerodynamics, whilst derived on the basis of local analysis, in fact achieves, albeit inadvertently, non-local linearisation. Moreover, when the actuator bandwidth is sufficiently large, (4) reduces to the strategy of Leithead *et al* (1991, 1992), thereby, providing a rigorous theoretical basis for this approach. However, when the actuator bandwidth is low, the strategy of Leithead *et al.* (1991, 1992) may not be appropriate.

4. Controller Start-Up/Shut-Down (Switching Between Below & Above Rated Operation)

The dynamics of the wind turbine drive-train introduce a lag between changes in the wind speed and the corresponding changes in the power output; that is, when the wind speed rises above rated, there is a lag before the power output responds and control action is resumed. It follows that the start-up performance might be improved by anticipating the transition from below to above rated power generation and, thereby, compensating somewhat for the dynamics of the drive-train. Predictive action may be incorporated in the start-up/shut-down approach of Leithead *et al.* (1991, 1992) by augmenting the C_{outer} block with a filter, P, possessing suitable phase lead. In order to recover the controller transfer function for above-rated operation, the inverse of this filter must be included in the C_{inner} block. It is required that both the filter transfer function, P(s), and its inverse, $P^{-1}(s)$, are stable and both $C_{outer}P$ and $C_{inner}P^{-1}$ are realisable. For the 300 kW machine, a simple filter with transfer function $(s+0.75)/(s+1.5)$ introduces appropriate phase lead. The start-up transient is reduced by over 50 kW so as to be well within the range of power fluctuation experienced during normal above-rated operation at low wind speeds.

The stability and robustness properties of both the conventional start-up/shut-down approach of Leithead *et al.* (1991, 1992) and the foregoing augmented approach may be analysed, in a straightforward manner, by small gain methods (Leith & Leithead 1996c).

5. Actuator Velocity/Acceleration Saturation

Whilst a constraint on the output of the actuator can have a considerable impact on closed-loop performance, the effect on performance of velocity and acceleration constraints is typically less marked since these are normally only encountered for short periods of time. Velocity and acceleration constraints may, nevertheless, degrade the closed-loop stability margins. For example, for the 300 kW turbine the actuator velocity constraints reduce the gain margin by 20%.

The requirement is to devise a method to accommodate the presence of velocity and acceleration constraints within the actuator. Some simplification is possible, however, since it is almost always the case that only one of the velocity and acceleration constraints proves restrictive in practice and it is, therefore, sufficient to consider actuators with a single velocity or acceleration constraint. The discussion in this section is confined to a single velocity/acceleration constraint in the actuator. Other than requiring compatibility with the controller start-up arrangements discussed in section 5, the other implementation issues considered in this paper are ignored. The controller start-up approach, developed in section 5, may be directly extended to accommodate velocity/acceleration constraints (Leith & Leithead 1996c). The formulation employs feedback of the difference, between the output of the real actuator, A, and a linear (unconstrained) model, $\hat{A}_u$, to the input of the C_{inner} block in the controller via a suitable filter, F.

6. Integrated Controller Realisation

In the preceding sections, the implementation issues are considered separately and appropriate strategies for their resolution are developed. When the aerodynamic linearisation strategy of (4) is employed, the controller realisation depicted in figure 1 provides an integrated strategy for resolving the issues of nonlinear aerodynamics, controller start-up and actuator saturation. Its effectiveness has been confirmed by extensive simulation studies. When

the actuator dynamics are sufficiently fast and the actuator saturation limits are such that they may be neglected, the realisation of figure 1 reduces, essentially, to that of Leithead *et al.* (1991, 1992). An equivalent realisation, based on the linearisation strategy of (3), is readily obtained.

The importance of adopting an appropriate controller realisation is illustrated by figure 2 for the medium-scale wind turbine. The appropriate controller realisation enables a substantial improvement in performance to be obtained in comparison to a poor controller realisation (with the nonlinear aerodynamic gain positioned after the pure integrator in the controller, conditional integration anti-wind-up at start-up, no velocity anti-windup and consequently the requirement for a reduction in the controller gain in order to maintain adequate stability margins). The poor controller realisation is quite plausible and, indeed, its use has been observed on commercial wind turbines.

7. Summary and Conclusions

Several strategies for accommodating the nonlinear aerodynamics are rigorously established. The existing strategy for accommodating the nonlinear aerodynamics, originally developed on the basis of physical insight, is rigorously derived and the analysis enables this strategy to be directly extended to cater for all machines.

With respect to the issue of automatic start-up/shut-down of the wind turbine controller, novel design guidelines are proposed which can significantly reduce the power transients at controller start-up (by over 50 kW for a machine rated at 300 kW).

It is demonstrated that hard actuator limits can, typically, reduce the gain margin of a medium-scale pitch-regulated wind turbine by around 20%. The reduction in the stability margins is, furthermore, likely to be exacerbated on large-scale machines where, owing to the increased size and inertia of the turbine blades, the actuator may require to be operated at its hard limits to a greater extent in order to meet the performance specification. Since actuator constraints are always present, it follows that it is necessary, unless alternative corrective measures are employed, to de-tune the controller in comparison to the linear unconstrained situation in order to achieve adequate stability margins. Restrictive position, velocity and acceleration constraints may all be present in wind turbines and the dynamic behaviour of the actuator cannot be neglected. A novel, and quite general, strategy is proposed which caters for all these circumstances without de-tuning the controller.

The separate strategies for resolving the implementation issues are combined to achieve a controller realisation which accommodates all the implementation issues in an integrated manner. The importance of adopting an appropriate controller realisation is considerable and is illustrated for a 300 kW wind turbine.

Acknowledgements

The support of the EPSRC, DTI (formerly D.En) and ETSU, by whose permission this paper is published, is gratefully acknowledged..

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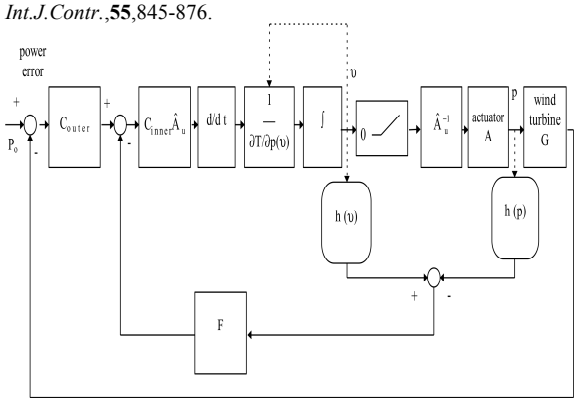

Figure 1 Integrated controller realisation

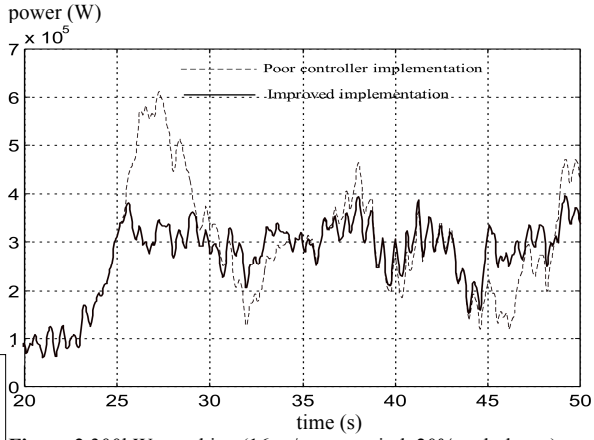

Figure 2 300kW machine (16 m/s mean wind, 20% turbulence).