THE IMPORTANCE OF IMPLEMENTATION ISSUES IN ACHIEVING CONTROL GOALS

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1. Introduction

The development of a control solution almost always involves the initial synthesis of a simplified control law based on consideration of an idealised linear formulation. The control law is then augmented in order to address practical implementation issues neglected during the previous stage. The performance achieved by a controller often depends extremely strongly on the extent to which the implementation issues are resolved. Moreover, owing to the continuing pressure for the development of high performance control systems coupled with the trend towards operating closer to the physical constraints on the system, these implementation issues are likely to become of even greater importance.

In this paper, strategies for adequately resolving some common implementation issues are considered. Since the implementation issues encountered in wind turbine regulation have many features in common with those encountered in a broad range of applications, including the aerospace field, in order to be specific the strategies are discussed with reference to wind turbine regulation. The implementation issues considered include the compensation of the highly nonlinear aerodynamics, minimising transients during changes in the mode of controller operation and accommodation of the hard limits on actuator accelerations (or torques) and velocities.

2. Compensating for the Nonlinear Aerodynamics

The gain-scheduling approach to compensation of the nonlinear aerodynamics is to incorporate the reciprocal of the aerodynamic 'gain' within the controller and schedule this gain with respect to the effective wind speed. Since scheduling on a direct measurement of wind speed is impossible, the pitch angle is usually employed. 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, including 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 (1996) propose that appropriate non-local behaviour may be ensured by adopting a gain-scheduled 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. 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.

Employing rigorous nonlinear analysis techniques it may be shown that the foregoing gain-scheduling approach to accommodating the nonlinear aerodynamics, whilst derived on the basis of local analysis, also achieves, albeit inadvertently, non-local linearisation of the aerodynamic nonlinearities. The nonlinear analysis also indicates that the behaviour of the gain-scheduling solution is extremely sensitive to the realisation adopted and the choice of scheduling variable (figure 1). The analysis provides considerable insight into these issues and

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indicates that realisations satisfying the extended local linear equivalence condition of Leith & Leithead (1996) give rise to the required non-local linearisation.

3. Automatic Controller Start-Up/Shut-Down

In common with many applications, a wind turbine controller is required to automatically adjust its mode of operation in accordance with changing conditions. In particular, control action is suspended when the wind speed drops below the level at which the rated power output can be generated and re-starts when the wind speed increases again. A common approach to controller start-up/shut-down is to simply freeze the controller integral action when below rated operation is detected. However, this approach is not always effective in preventing large start-up transients, figure 2. 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 other low frequency dynamics in the controller with which the prolonged start-up transients are associated.

Leithead *et al.* (1991) propose an alternative technique whereby a minor feedback loop is introduced within the controller. The controller transfer is partitioned such that the slow dynamics are contained within the minor loop and during below rated operation this loop switches in to permit the controller to continue operating. The start-up transients are substantially reduced with this strategy, figure 2. However, with this approach the start-up transients remain somewhat greater than the normal power fluctuations experienced during continuous 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. Hence, when the wind speed rises above rated, there is a lag before the power output responds and control action is resumed and so the start-up performance might be improved by anticipating the transition from below to above rated operation, thereby compensating somewhat for the dynamics of the drive-train. Predictive action may be incorporated by augmenting the partitioned controller elements with appropriate filters possessing suitable phase lead (Leith & Leithead 1997). For a typical 300 kW machine, the start-up transient is reduced by over 50 kW with this strategy (figure 2) so as to be well within the range of power fluctuation experienced during normal above-rated operation.

The issue of automatic controller start-up/shut-down is closely related to that of anti-wind-up (see, for example, Leith & Leithead 1997). Whilst consideration is almost always restricted, in the general anti-wind-up context, to static compensation, it is emphasised that the results discussed here indicate that, in appropriate circumstances, dynamic compensation can achieve superior anti-wind-up performance.

4. Actuator Velocity/Acceleration Saturation

All real actuation systems are subject to a variety of physical constraints and it is known that the presence of hard actuator limits can degrade performance and stability; for example, actuator velocity constraints reduce the gain margin of a typical medium-scale turbine by 20%, see figure 3 (Leith & Leithead 1997). In the wind turbine context, the control specification traditionally 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 common with many applications, in order to achieve satisfactory performance it may be necessary to relax such restrictions. Hence, unless alternative corrective measures are employed the controller must be de-tuned in order to achieve adequate stability margins. However, this typically results in a substantial degradation in performance. The requirement is, therefore, to devise a method to accommodate the presence of velocity and acceleration constraints within the actuator without de-tuning the controller.

The controller start-up approach of section 3 may be directly extended to accommodate velocity/acceleration constraints. The formulation employs feedback of the difference, between the output of the real actuator and a linear (unconstrained) model to the input of the minor loop in the controller via a suitable filter (Leith & Leithead 1997). This strategy is quite general and enables adequate stability margins to be recovered without unnecessary degradation in the closed-loop performance, figure 3.

5. Integrated Controller Realisation

In the preceding sections, the implementation issues are considered separately and appropriate strategies for their resolution are developed. However, it remains to combine these strategies to achieve a controller realisation which caters for all of the implementation issues in an integrated manner. Whilst this issue is largely neglected in the literature, it is essential that the strategies are, in this sense, mutually compatible. The foregoing strategies are indeed mutually compatible and an elegant integrated realisation may be readily obtained (Leith & Leithead 1997).

6. Conclusions

Strategies for accommodating the nonlinear aerodynamics are rigorously established. With respect to the issue of automatic start-up/shut-down of the wind turbine controller, a novel strategy is 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 and the dynamic behaviour of the actuator cannot be neglected. A novel, and quite general, strategy is discussed which caters for restrictive position, velocity and acceleration actuator constraints and achieves adequate stability margins without de-tuning the controller. The separate strategies for resolving the implementation issues are mutually compatible and may be combined to achieve an elegant 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, figure 4. (It is emphasised that the poor controller realisations considered are quite plausible and, indeed, their use has been observed on commercial wind turbines).

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References

LEITH,D.J.,LEITHEAD,W.E.,1996,Appropriate Realisation of Gain-Scheduled Controllers with Application to Wind Turbine Regulation. *Int.J. Contr*, **65**, 223-248; 1997, Implementation of Wind Turbine Controllers. *Int. J. Contr*, to appear.

LEITHEAD, W.E., DE LA SALLE, S.A., REARDON, D.L., GRIMBLE, M.J., 1991, Wind Turbine Control Systems Modelling and Design Phase I & II. Department of Trade & Industry Report No. ETSU WN 5108.

Fig1. Cost of incorrect treatment of nonlinear aerodynamics

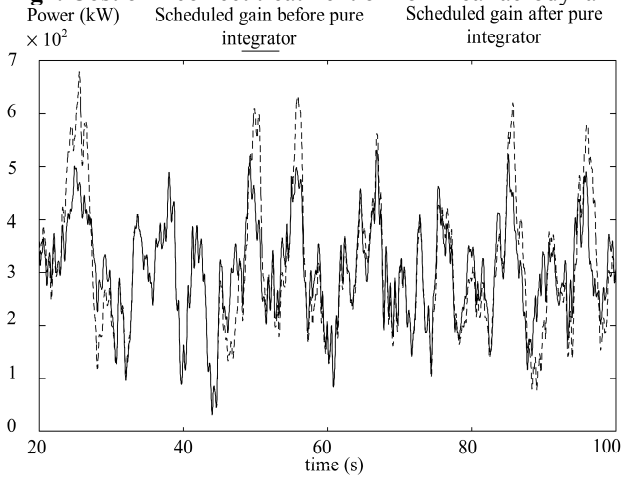

Fig 2. Cost of incorrect treatment of controller start-up

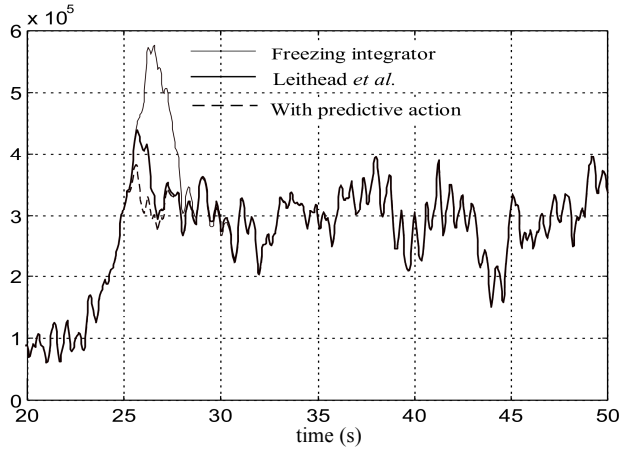

Fig 3. Effect of incorrect treatment of actuator constraints

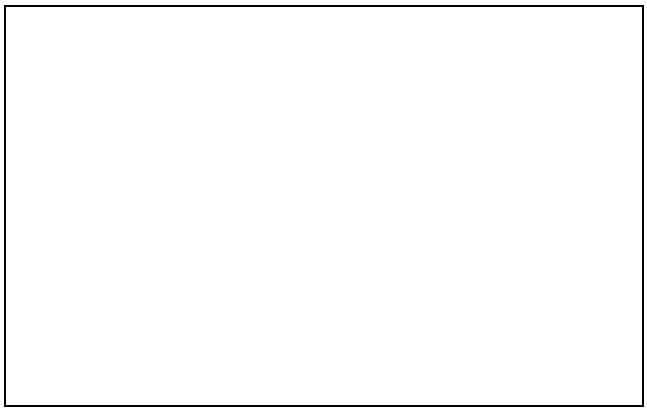
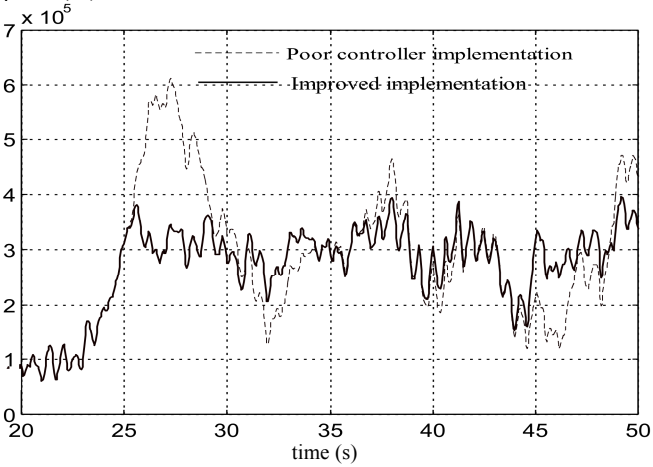
Fig4. Overall cost of poor controller implementation