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Evaluation of the Options for Control Design of Constant-Speed Wind Turbines

SYNOPSIS The design of the control system for constant-speed pitch-regulated wind turbines is investigated: in addition to synthesis of the controller transfer function, the choice of control strategy is investigated and the appropriate realisation of the controller, to cater for the nonlinear rotor aerodynamics, controller start-up/shut-down and actuator constraints, is identified. Whilst all of the general purpose linear synthesis methods achieve similar performance, marked improvements are readily achieved by adopting an appropriate realisation and by refining the control strategy. Hence, in control system design much greater emphasis should be placed on the choice of control strategy and choice of implementation rather than on the choice of synthesis method.

1. INTRODUCTION

In this paper the design of the control system for horizontal-axis grid-connected medium-scale constant-speed wind turbines is considered. The rotor has two or three blades and the pitch angle of the blades may be adjusted. The control design task is to exploit this capability in order to regulate the power output whilst minimising the load transients and thereby reducing fatigue damage. The objectives of the SISO control system are discussed fully by Leithead *et al.*(1991a, b).

It is required to design a control system suitable for regulating constant-speed wind turbines. In general, control system design must address several issues. In addition to the synthesis of the associated controller (transfer function) embedded within the control system, the appropriate choice of control strategy and the appropriate choice of controller implementation must be determined. To determine the most appropriate choice of control strategy, the various possible options must be explored and the strategy, which best meets the requirements of the customer, selected. To determine the appropriate choice of controller implementation, the implementation issues, such as accommodation of the variation in plant dynamics over the operational envelope, switching transients, actuator constraints *etc.*, which are most relevant to the application, must be identified and the controller realisation which best resolves them selected. Both the choice of control strategy and the choice of controller implementation are related to nonlinear aspects of the plant dynamics and require an investigation of the global behaviour of the system. In contrast, controller synthesis methods employ linear models of the plant and are concerned with only the local behaviour of the system; that is, they cannot address either of the previous two issues. There are many general purpose approaches to controller synthesis, *e.g.* Nyquist/Bode loop-shaping (classical control), optimal control, multivariable control, robust control, LQR, LQG, H_2, H_∞, μ-synthesis (the names describe the mathematical techniques employed to determine the control algorithm but not necessarily its properties; for example, optimal control uses a cost function minimisation procedure but the resulting controller need not be the best possible). However, controller synthesis is generally straightforward and much less time-consuming than the other aspects of control systems design and, provided the synthesis task is well specified and the methodology chosen is sufficiently familiar, the method of synthesis is essentially immaterial as all result in similar performance. (When the performance differs significantly, the underlying reason is a difference in the specification, such as a difference in cross-over frequency, stability margins, *etc.*).

The purpose of this paper is to investigate the design of the control system for constant-speed wind turbines. To be precise, in addition to synthesis of the controller, the choice of control strategy is investigated and the appropriate realisation of the controller, to cater for the nonlinear rotor aerodynamics, controller start-up/shut-down and actuator constraints, is identified.

The paper is organised as follows. In section 2, the wind turbine models are briefly described. In section 3, PI control is compared to general purpose linear control and the circumstances when PI control suffices are determined. In section 4, three general purpose linear synthesis methods, namely Nyquist/Bode loop-shaping, LQG and H_∞, are compared. In section 5, various nonlinear control strategies are compared and, in section 6, the implementation issues are discussed. Finally, in section 7, the conclusions are summarised.

2. PRELIMINARIES

In this paper, controllers are compared for two-bladed and three-bladed 300 kW wind turbines which are typical of their class. Details of the models of the machines are given in Leithead *et al.* (1991a, 1992a, b), Leith & Leithead (1994b, 1995b). Bode plots of the power-train dynamics of the wind turbines are shown in figure 1.

It is important that fair comparisons between controller performance are made. To this end, each controller is required to have similar stability margins and to operate within the same actuator restrictions. All of the controllers are designed to meet the following requirements: (i) gain margin of al least 10 dB, (ii) phase margin of approximately 60 degrees, (iii) servo pitch acceleration standard deviation not more than approximately 20 deg/s^2. Requirement (iii) represents a practical limitation on the level of activity of the blade servo. Servo pitch acceleration is a measure of the force or torque developed by the actuator and the standard deviation reflects the activity over the medium and long term. It should be emphasised that the value of pitch acceleration used is not that of the turbine blades. Rather, it is a normalised measure which permits comparisons to be made between different design of actuator. The restriction on actuator activity inherent in (iii) is always necessary to prevent saturation occurring too frequently but there may also be additional hardware-related reasons for its imposition.

There are several implementation issues which need to be considered. The actuator, in addition to requirement (iii), is subject to hard limits on torque, velocity and position and effective anti-wind-up measures are therefore important. There is, also, the requirement to ensure smooth and timely start-up of the controller and to schedule the controller over the complete operating range.

3. COMPARISON OF PI & CLASSICAL LINEAR CONTROLLERS

Although PI control is not a general purpose synthesis method it can frequently be very effective. Whether it is so depends on the dynamics of the plant. PI control (Leithead *et al.* 1991a, Leith & Leithead 1994c) is compared here to the longest established general purpose synthesis method, namely Nyquist/Bode loop-shaping, for the two and three-bladed machines (Leithead *et al.* 1991a, 1992a, Leith & Leithead 1995b). From figure 2, the performance of both controllers, as judged from the generated power, is very similar for the two-bladed machine. However, from figure 3, the performance of the two controllers is very different for the three-bladed machine with the classical controller achieving substantially better regulation than the PI controller (Leithead *et al.* 1991a, 1992a).

The fundamental difference in the plant dynamics, between the two and three-bladed machines, is that the former is much better damped than the latter. The only way that PI control can cater for under-damping of this type is by rolling-off the gain, which requires a low cross-over frequency for the controller. There is no difficulty in achieving a cross-over frequency of 1.7 rad/s with PI control for the two-bladed machine but the cross-over frequency must be reduced to 0.26 rad/s for the three-bladed machine in order to achieve a gain margin of 10 dB in the presence of the under-damped plant dynamics. Hence, the PI controller is much less effective for the three-bladed wind turbine. It should be noted that the classical controller easily caters for the under-damped plant dynamics of the three-bladed machine and achieves a cross-over frequency of around 2 rad/s with a gain margin of 10 dB. (For the two-bladed machine the classical controller has a cross-over frequency of 1.8 rad/s).

4. COMPARISON OF CLASSICAL, LQG AND H_∞ CONTROLLERS

Three general purpose controller synthesis methods are compared, namely classical, LQG and H_∞ control. Provided that all are designed to the same specification, the performance is very similar. Although performance must be assessed from a large set of data for different wind conditions and turbine configurations, the similarity in the performance of LQG (Leithead *et al.* 1991a, 1991c), H_∞ (Connor *et al.* 1992) controllers to the performance of the classical controller (Leithead *et al.* 1991a, 1992a) is illustrated, for the three-bladed machine, by figure 4. The slight differences in performance are due to the specifications, although similar, not being identical. With respect to performance, no general purpose synthesis method is inherently better than any other.

5. COMPARISON OF LINEAR & NONLINEAR CONTROLLERS

5.1 Introduction

The actuator characteristics are one of the main restrictions on the performance that can be achieved by a controller. Consequently, it is important that the available actuator capability is exploited as fully as possible. There always exist hard limits on the position, velocity, and acceleration/torque which may be developed within a real actuator. In addition, there is often an effective restriction on the standard deviation of the velocity and/or torque in order to prevent saturation at these hard limits from occurring too frequently. This type of restriction may also be required for hardware-related reasons; for example, when the actuator is an electro-mechanical system, a restriction on servo motor current, and hence servo pitch acceleration, is imposed to prevent over-heating. This is a soft type of constraint in the sense that it does not directly limit the magnitude of quantities within the actuator. Hence, while it is not acceptable to work the actuator continuously at its hard velocity/acceleration/torque constraints due to the overheating that would result, it is possible to intermittently work the actuator at these limits for short periods. In the following sections, control strategies are developed with the objective of improving performance by more fully exploiting the available actuator capability.

5.2 Maintaining actuator activity with wind speed

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, whilst the actuator may be worked to its full capability at low wind speed, it is not 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 (Rogers & Leithead 1993, 1994 and Leithead and Rogers 1993) 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 operates near to its optimal level of activity in all wind speeds, subject to actuator constraints. Whilst it is possible to develop a continuously varying controller which induces the appropriate closed-loop dynamics at any wind speed (Leith & Leithead 1994c, 1995b), an alternative approach is to employ a dual-mode control strategy which switches between two linear controllers, one suitable for low wind speeds and the other suitable for high wind speeds. The dual-mode strategy permits direct exploitation of existing knowledge and experience of linear control. Furthermore, design and implementation of the switched linear control algorithm is typically more straightforward than that of the continuous nonlinear algorithm and the stability margins of the turbine with this dual-mode control strategy can be firmly established. Contrary to expectation, the dual-mode control strategy achieves very similar performance to the continuously varying nonlinear control strategy; that is, the performance is near optimal over the operational envelope (Leith & Leithead 1994b, 1995b).

Employing the well-validated assessment approach of Leithead & Agius (1991), the curves in figure 5 provide an indication of the maximum power likely to be encountered during normal operation of the various control strategies. It is evident that, in comparison with linear control, the dual-mode control strategy achieves a significant overall reduction in the peak power excursions likely to be experienced with a consequent reduction in drive-train load transients. More detailed results are contained in Leith & Leithead (1994b, 1995b).

5.3 Peak Rejection

It is usually possible to intermittently demand a high level of activity for short periods, taking the actuator up to its hard velocity and/or acceleration constraints. This may be exploited to improve the control system response to the worst peaks in the power output by working the actuator temporarily at its maximum level when the start of an unacceptably high peak in the power output is detected, therefore responding as rapidly as possible to the disturbance. The resulting switching strategy may be employed to augment the previously discussed linear and nonlinear control strategies. It can be seen from figure 5 that an augmented linear controller has similar performance to the dual-mode controller of section 5.2. However, in comparison with the other control strategies discussed, the augmented dual-mode control strategy leads to a considerable reduction in the peak power excursions at higher wind speeds; that is, the augmentation curtails the worst peak power transients, as intended.

6. IMPACT OF CONTROLLER REALISATION ON PERFORMANCE

Three of the main implementation issues encountered when developing controllers for pitch-regulated constant-speed wind turbines, are compensation of the strongly nonlinear rotor aerodynamics, automatic controller start-up/shut-down, and accommodation of velocity and acceleration constraints within the actuator. These issues must be adequately resolved in order to achieve the performance requirement and, furthermore, it is essential that the separate strategies for resolving these issues are compatible with one another and lead to a straightforward controller realisation.

The first 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. Since the role of the turbine rotor in converting wind energy into mechanical energy is a central one, the nonlinear behaviour of the rotor exerts a substantial influence on the characteristics of the whole wind turbine and cannot be neglected (see, for example, Leithead *et al.* 1991a, 1992a). One commonly employed solution is to augment the controller with a nonlinear gain corresponding to the reciprocal of the sensitivity of the aerodynamic torque to pitch changes. It is known that the performance of this approach to aerodynamic compensation is strongly dependent on the positioning of the nonlinear gain and that it may be rigorously established that, for medium-scale machines, the appropriate position is after the main controller dynamics but before the pure integrator term (Leith & Leithead 1995b, 1996).

The second implementation issue relates to the wind turbine operational requirements. Below rated wind speed the power generated is less than the turbine rating and no control action is required. However, when the wind speed rises above rated, the power output is regulated at the rated value of the turbine by suitably adjusting the pitch angle of the rotor blades. Hence, it is necessary to automatically 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.* 1991a, 1992a) 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. Whilst a common approach to controller

start-up is to simply freeze the controller integral action when the demanded pitch angle of the turbine blades falls below a specified threshold value, this is not always effective in preventing large start-up transients. An alternative start-up technique is to introduce a minor feedback loop within the controller which switches in to permit the controller to continue operating below rated wind speed. With this approach the start-up transients may be substantially reduced.

The third implementation issue relates to the actuator physical constraints, typically 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. It is well known that hard actuator limits can degrade performance and reduce the stability margins or, indeed, induce instability and ,typically, an actuator velocity constraint can reduce the gain margin of a pitch-regulated wind turbine by around 20%. If adequate stability margins are not achieved a wind turbine system must sometimes destabilise, although not necessarily become unstable, in which case the wind turbine would experience large load fluctuations. 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. However, this may be avoided by employing an anti-wind-up strategy (Leith & Leithead 1995b, 1996) which recovers adequate stability margins without de-tuning the controller.

The foregoing separate strategies for resolving the implementation issues are compatible and may be combined to achieve a controller realisation which accommodates all the implementation issues in an integrated manner (Leith & Leithead 1995b, 1996). The importance of adopting an appropriate controller realisation is considerable, figure 6.

7. CONCLUSIONS

Several different control strategies for constant-speed wind turbines are explored in this paper, including linear control, nonlinear control, peak rejection, and nonlinear control with peak rejection. In the context of linear control, a distinction must be made between PI control and the general purpose synthesis methods such as Nyquist/Bode loop-shaping, LQG, H_∞. Whether the latter are more effective depends on the degree of drive-train damping. All of the general purpose linear synthesis methods achieve similar performance. Indeed, to further refine the linear controllers in order to improve the performance even slightly requires great effort. In contrast, marked improvements in performance are readily achieved by refining the control strategy; that is, by nonlinear control. Hence, in control system design much greater emphasis should be placed on the choice of control strategy rather than on the choice of synthesis method. The other facet of control system design, the choice of implementation of the controller, also has a marked impact on performance and should have a similar emphasis to the choice of control strategy.

Acknowledgements

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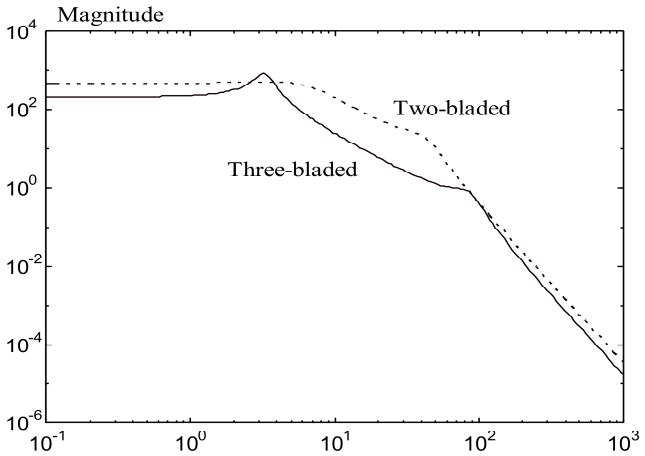


Figure 1 Bode plots of power-train dynamics

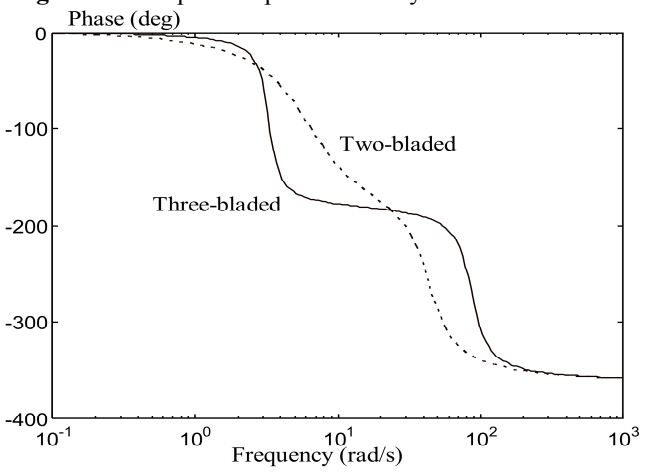
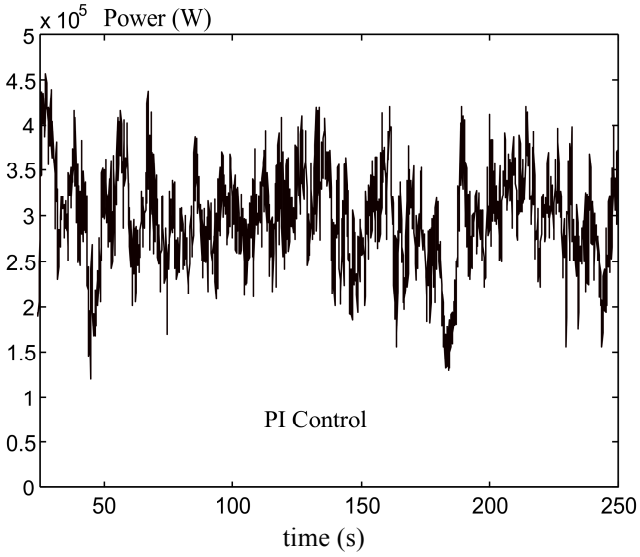


Figure 1(cont) Bode plots of power-train dynamics



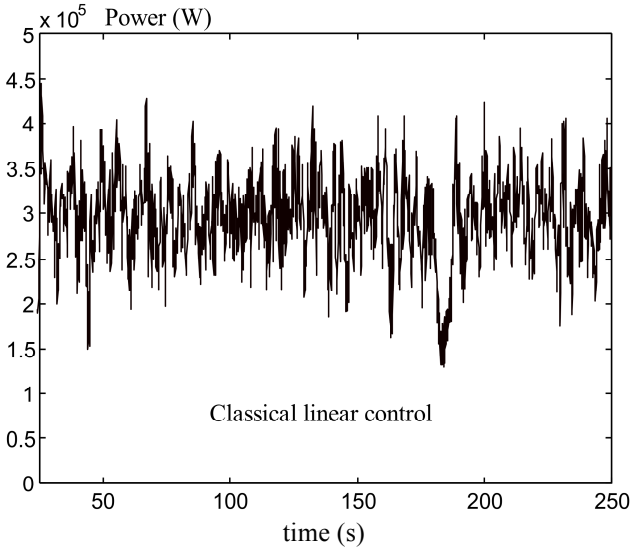
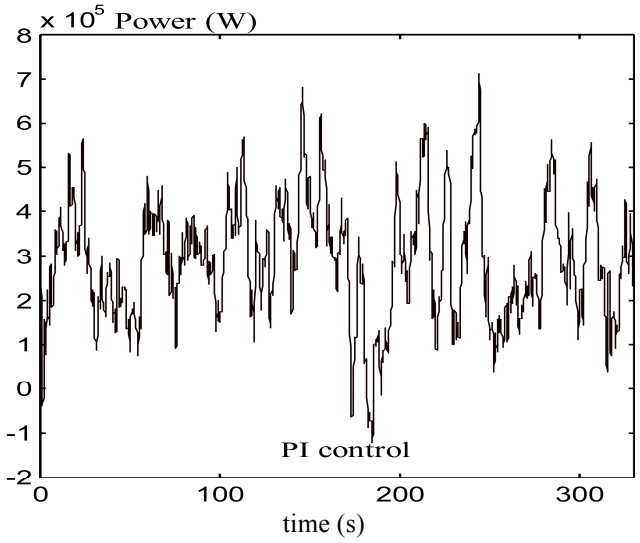


Figure 2 Typical power time histories with PI and classical linear control (two-bladed machine, 16 m/s mean wind speed)



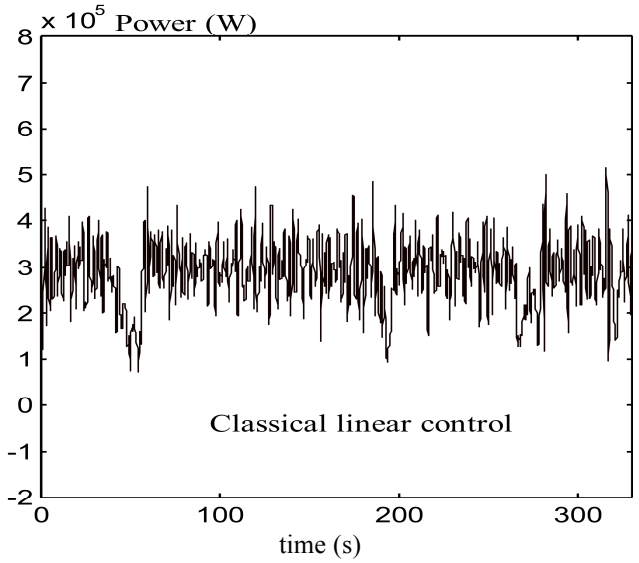


Figure 3 Typical power time histories with PI and classical linear control (three-bladed machine, 16 m/s mean wind speed)

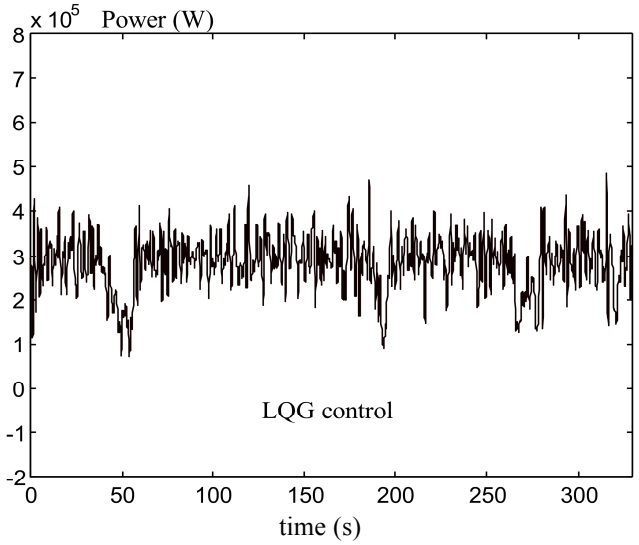


Figure 4a Typical power time histories with LQG control (three-bladed machine, 16 m/s mean wind speed)

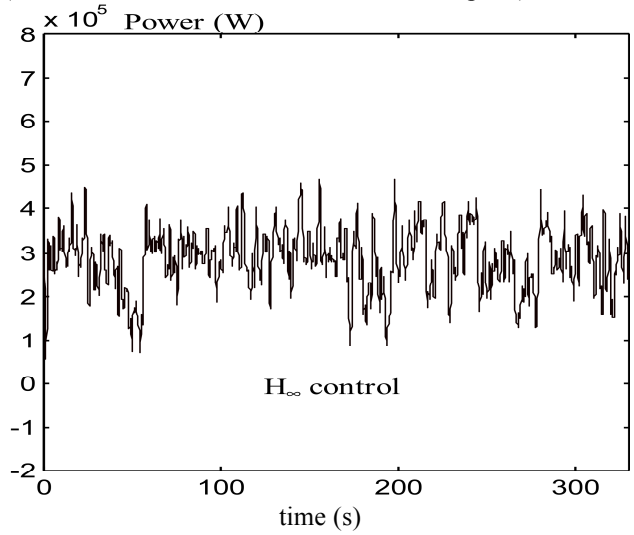


Figure 4b Typical power time histories with H_∞ control (three-bladed machine, 16 m/s mean wind speed)

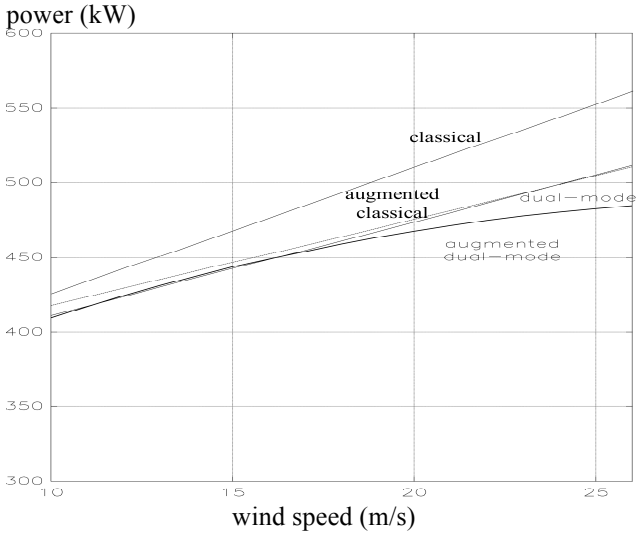


Figure 5 Relative performance of linear & nonlinear control strategies (two-bladed machine)

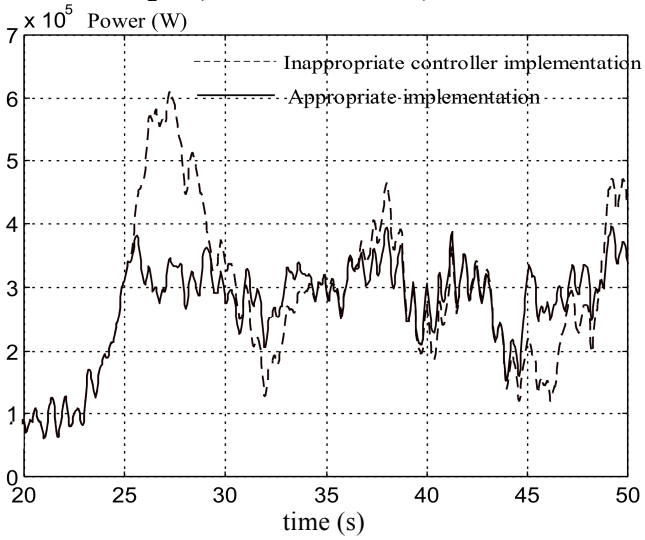


Figure 6 Impact of controller implementation on power output (two-bladed machine, 16 m/s mean wind speed)