BENEFITS OF OPTIMISING THE CONTROLLER WITH WINDSPEED FOR A CONSTANT SPEED HAWT

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1. INTRODUCTION

The standard commercial design for medium-scale constant -speed wind turbines is a horizontal-axis grid-connected up-wind machine. The rotor usually has two or three blades and the wind turbine is often regulated by the varying the pitch angle of either the full span of the blades or just the outer tips. In this paper a typical two-bladed and a typical three-bladed machine are considered, with full-span pitch regulation and rated power of 300 kW. The objectives for the control system are discussed elsewhere (1)(2)(3). The purpose of this paper is to investigate the design of controllers which change continously in such a way that the controller is always the most appropriate for the wind speed. The results of extensive simulations are presented comparing the performance of such nonlinear controllers with that of conventional linear controllers. It is important that fair comparisons are made, and to this end each controller studied is required to have similar stability margins and to operate within the same actuator restrictions.

The actuator characteristics, especially the limits on torque, are main restriction on the performance that can be achieved by a controller. In the case of a wind turbine, as the wind speed rises a conventional 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 not be used as fully at higher wind speeds. However, it is at these higher wind speeds that the loads are highest, and therefore controller performance is most critical. Theoretical studies (4)(5)(6) predict 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. An optimum exists due to the action of two competing factors. As wind speed rises, for a fixed controller the standard deviation of the power output also rises due to the increased level of turbulence. It is therefore attractive to increase the controller activity by raising the open-loop cross-over frequency, giving improved disturbance rejection. However, the wind experienced by a wind turbine contains large amounts of energy at frequencies corresponding to multiples of the rotational speed of the rotor, nP, and so the wind speed spectrum differs from that experienced at a static point (see e.g. (2)). Since it is necessary to protect the actuator by causing the open-loop transmittance to roll-off whilst maintaining adequate gain and phase margins, there is an inevitable tendency for the sensitivity function to increase the intensity of the nP peaks as the cross-over frequency is increased. Whether at any particular wind speed the resulting optimum cross-over frequency can be achieved in practice depends on the capabilities of the actuator.

For each of the wind turbine configurations studied three controllers are compared. These are (i) a linear controller designed using a classical loop-shaping methodology (1)(2), (ii) a nonlinear controller based on a strategy of tracking the optimum cross-over frequency as wind speed varies, and (iii) a simplified version of this nonlinear controller.

The paper is organised as follows. Section Two outlines the controller specifications, in Section Three the controllers are described, and in Section Four simulation results are presented comparing the performance of the controllers.

2. CONTROLLER SPECIFICATIONS

In order to provide a fair comparison between the various controllers studied, all are designed to meet the following requirements:

(i) Gain margin of at least 10 dB.

(ii) Phase margin of approximately 60 degrees.

(iii) Servo pitch acceleration standard deviation no more than approximately 20 deg/s^2.

As the wind speed increases, the gain of the plant increases since the rate of change of aerodynamic torque with pitch angle increases. If not catered for, the cross-over frequency of the open-loop system would increase and the accompanying change in phase in the region of the cross-over frequency would seriously reduce the stability margins. To counter this, it is standard practice for wind turbine controllers to include a nonlinear gain to compensate for the variation with wind speed in the sensitivity of aerodynamic torque to pitch change (see e.g. (1)). The representation of the aerodynamics is subject to considerable uncertainty and the gain of the controller is incapable of always being scheduled to match the varying windspeed. Consequently, good gain and phase margins are required to achieve adequate stability margins. If these are not achieved the system must sometimes destabilise, although not necessarily become unstable, when the wind turbine would experience large load fluctuations; that is, the drive-train would resonate. Requirement (iii) represents a practical limitation imposed by the blade servo system. It should be noted that this value of pitch acceleration is not that of the actual turbine blades but rather a normalised measure of the torque within the servo. In the context of the actuator model employed here, the limit of 20 deg/s^2 is typical of comparable commercial machines. Attention is restricted to continuous-time controller implementations.

3. CONTROLLERS

3.1 Two-Bladed Configuration

Linear Classical Controller

A linear controller with the following transfer function was designed using a classical loop-shaping methodology (1)(2), and is denoted controller M1D.

$$871.229 \frac{(s+1.6)^2(s^2+7.243s+38.637)}{s(s+0.3)(s+3.7)(s+20)(s+50)}$$

$$\times \frac{(s^2+1.5s+104.04)(s^2+6s+416.16)}{(s^2+11s+104.04)(s^2+10s+416.16)(s^2+65.8s+2209)}$$

(gain margin 10 dB, phase margin 56.14 degrees, cross-over frequency 1.826 r/s)

Nonlinear Controller

The objective is to design a controller whose level of activity varies with wind speed so as to be near optimal, within the limitations allowed by the actuator. A measure of the controller activity is the cross-over frequency of the open-loop system; that is, the frequency at which its gain is 0 dB. Since the cross-over frequency is to vary with wind speed, the controller must also vary with wind speed to cater for the accompanying changes in phase in the region of the cross-over frequency. In practice, a measurement of wind speed is unavailable, indeed there is no such thing as "the windspeed" experienced by the wind turbine. Simple scheduling is therefore not appropriate and the wind speed must be inferred from the plant dynamics, in this case via the pitch demand. If the controller is operating correctly, the demanded pitch angle is a good indicator of wind speed. This approach is in widespread use for varying the nonlinear gain noted in Section Two, which is used to compensate for variations in the aerodynamic torque sensitivity. Using an internal state of the system, such as pitch demand, to change the controller as wind speed varies must be treated with some caution. It introduces an additional feedback loop, thereby changing the dynamics of the system by its very presence. The design task is to develop a varying controller which induces the required closed-loop dynamics at any wind speed, despite the presence of the additional feedback loop. The result is a nonlinear controller.

A series of linear 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 :

$$g \frac{(s^2+7.59s+68.06)}{(s^2+as+b)} \frac{(s+1.7)(s+1.8)(s^2+3s+416.16)}{s(s+0.3)(s+3.75)(s^2+8s+416.16)}$$

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

where,

$a=-0.033047p^2 + 0.75064p + 3.3749$
$b= 2.6002p + 58.040$
$g= (0.13779p + 0.29784)\ 68.06/b$

and p is the pitch angle demanded by the controller, in degrees. Upper and lower bounds are placed on a, b and g,. When p is less than 3.84 degrees (corresponding to12 m/s rated 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 rated 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 these controllers as p is varied are as follows:

p (deg)	gain margin (dB)	phase margin (deg)	cross-over freq (r/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 optimum cross-over frequencies to minimise the standard deviation of the power output are approximately1.5 r/s, 2.25 r/s, and 4 r/s at 12 m/s, 16 m/s, and 23 m/s respectively for this configuration of wind turbine (4)(5)(6). While at 24 m/s the optimum cross-over frequency of around 4 r/s is not achieved due to the physical limitations of the actuator, the minima is broad and the cross-over frequency of 3.25 r/s is near optimal. The dependance of performance on the controller cross-over frequency is illustrated in figure 1, on which the minima can be clearly seen.

The gain margin of the 12 m/s controller is rather higher than 10 dB. Since there is always a trade-off between performance and robustness, this controller will not achieve the best performance possible at low wind speeds. This choice of controller is necessary, however, if the variation between the transfer functions of the controllers is to be restricted to the values of a, b and g.

A nonlinear controller, denoted M3C, is obtained by interpolating continuously between these linear controllers as pitch demand varies. The validity of employing a linear approach in the design and analysis of this nonlinear controller is discussed in detail in (8). Both theoretical analysis and simulation results indicate that the nonlinear controller possesses very similar stability margins to its component linear controllers.

As an alternative to continuously varying between linear controllers, a simpler arrangement is to use a dual-mode controller, where at low wind speeds one linear controller is used, and at some point a switch is made to a second linear controller for use in higher wind speeds. It is to be expected that this will lead to some degredation in performance, the level depending on the characteristics of the aerodynamic torque variation with wind speed, and on the switching point used. A suitable compromise, denoted DM1D, was found to be the use of classical controller M1D at low wind speeds, switching to the 20 m/s M3C controller at rated wind speeds above 16 m/s (that is 11.14 degrees pitch demand).

3.2 Three-Bladed Configuration

Linear Classical Controller

$$9.692 \frac{(s^2+4.753s+5.8806)(s^2+6.403s+51.29)}{s(s+0.3)(s+15)(s+18)(s+20)(s+50)(s+50)}$$

Denoted B1B.
(gain margin 9.99dB, phase margin 56.14 deg, cross-over frequency 2.78 rad/s).

NonLinear Controller

$$g \frac{(s^2+4s+6.25)}{(s^2+as+b)} \frac{(s^2+7.12s+79.21)}{s(s+0.3)(s+50)(s^2+140s+2500)}$$

where,

$a=1.8398p + 4.4064$
$b=0.28447p^2 + 14.443p + 111.32$
$g=0.02964p^2 + 1.6189p + 2.22$

This nonlinear controller is denoted B3 and was designed in a similar manner to that for the two-bladed configuration. Also as for the two-bladed case, a simplified dual-mode version, denoted DMB, of this full nonlinear controller was obtained by using controller B1B at low wind speeds and switching to the 20 m/s B3 above 16 m/s.

4. CONTROLLER COMPARISONS

The performance of the various controllers was investigated using a well validated simulation model. Simulations were run over a range of wind speeds and turbulence levels. Four mean wind speeds of 12, 16, 20 and 24 m/s were used at three nominal turbulence levels of 10, 15 and 20 %. The simulations were run for 260 seconds, giving four one minute periods of data. The nominal turbulence level only applies over a long time period, and the range of turbulence levels for the 1 minute samples was 6 - 26 %. These runs produced only 48 data points to cover the whole operational range of the machine, but this approach has nevertheless been found to be a good indicator of the comparative performance between controllers (7).

Probability distributions of the power time histories are given in figure 2 at a mean wind speed of 24 m/s and 20% turbulence intensity. A significant reduction in the time spent at high power levels is evident for both configurations with the nonlinear and dual-mode controllers. The relative reduction is similar for both configurations, as may be seen from the following table.

Controller	TWO BLADE Exceedance probability 425 kW	THREE BLADE Exceedance probability 375 kW
linear classical	10.26 %	10.74 %
nonlinear	2.82 %	3.48 %
dual-mode	3.25 %	4.10 %

Linear fits are made to the power maxima from the 1 minute samples with turbulence in the range 13-26% (figures 3 and 4). The equations of these fits are as follows.

Controller	Two Blades		Three Blades	
	Fit	Standard Deviation	Fit	Standard Deviation
linear classical	8.49*wind+ 280.05	20.02	7.31*wind +226.87	12.81
nonlinear	5.11*wind+ 330.49	14.52	4.62*wind+ 262.16	9.82
dual-mode	5.79*wind+ 317.17	16.62	4.91*wind+ 258.89	11.11

The linear controller's maxima increase at the fastest rate, followed by the dual-mode and nonlinear controllers, which have around two-thirds the rate of increase of the linear controller, and lower standard deviations, corresponding to a tighter bunching of the maximums. Again, the relative reduction is similar for both configurations. However, in the two-bladed case the power maximums experienced are higher, and as a consequence the absolute reduction is significantly greater than in the three-bladed case. It is known that a two-bladed full-span configuration such as the one under investigation presents a more demanding control problem than alternative configurations such as the three-bladed one, and the results confirm the expectation that the benifits of a more sophisticated control system are greater in the two-bladed case.

The pitch acceleration standard deviations for the 1 minute samples with turbulence in the range 13-26% are shown in figures 5 and 6. The linear controller works the actuator least, and has the lowest standard deviation. The standard deviation falls as the wind speed rises, due to the increase in the sensitivity of the aerodynamic torque to pitch changes. In contrast, the standard deviation for the nonlinear controllers remains roughly constant as wind speed rises, exploiting the extra actuator capacity available at higher wind speed, as intended. The pitch acceleration demanded by the dual-mode controllers is similar to that of the nonlinear controllers, but with a slight downward trend at higher wind speeds as might be expected.

5. CONCLUSIONS

To conclude, for both a typical two-bladed and a typical three-bladed configuration of wind turbine, extensive simulations using a well validated model indicate that significant performance improvements may be gained by using either a continuously varying nonlinear controller or a simpler dual-mode controller when compared with a conventional linear controller. In particular, both the peak power, and the time spent at high power levels are reduced, with a consequent reduction in drive-train loads. The is found to be greatest for the two-bladed configuration. It is known that a two-bladed full-span configuration presents a more demanding control problem than alternative configurations, such as the three-bladed one, and these results confirm that the benefits of a more sophisticated control system are greater in the two-bladed case. This improvement is obtained by exploiting the actuator capability that is left unused at higher wind speeds by linear time-invariant controllers.

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Figure 1 - Predicted variance of power output vs open-loop cross-over frequency and wind speed (6) (two-bladed configuration)

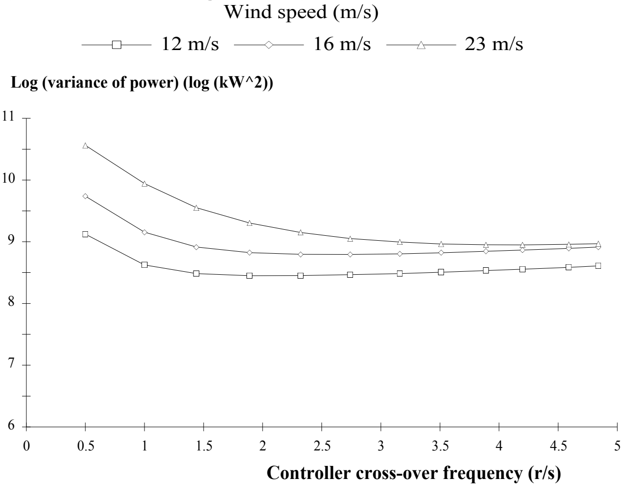

Figure 2 - Probability distribution of power (24 m/s wind, 20% TI)

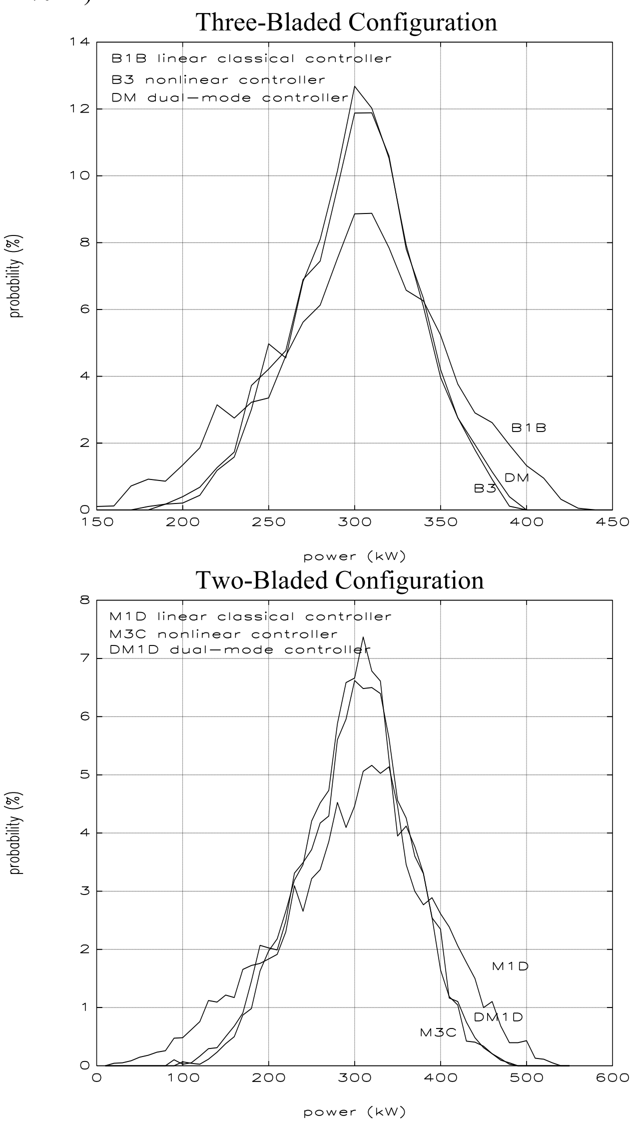

Figure 3 - One-minute data, 13-26% TI (three-bladed configuration)

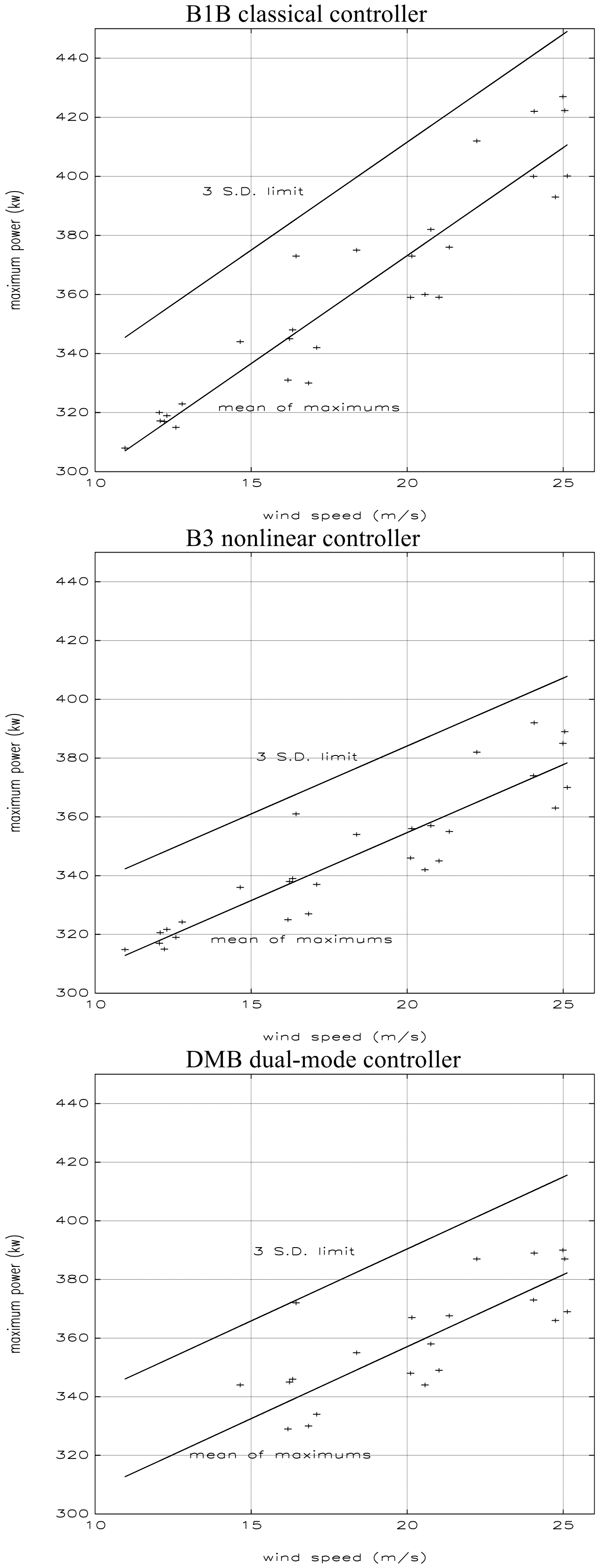

Figure 4 - One minute data, 13-26% TI (two-bladed configuration)

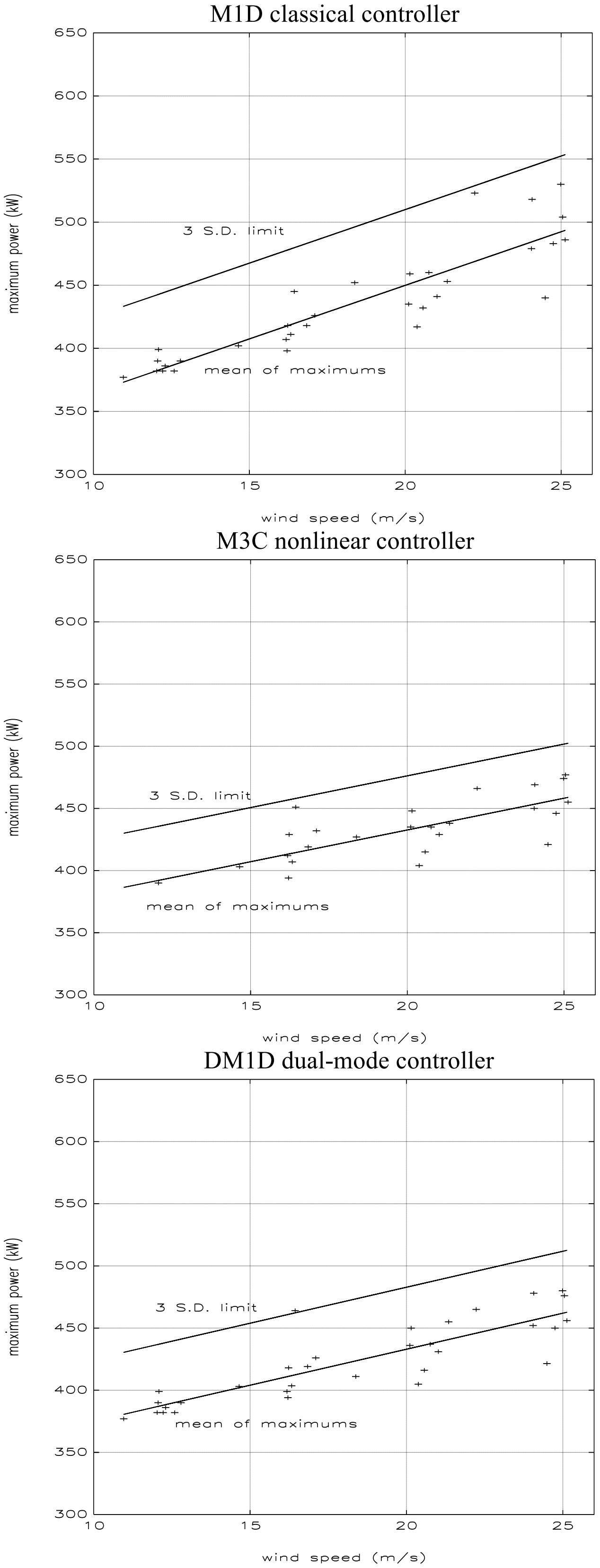

Figure 5 - Pitch acceleration standard deviation (three-bladed configuration)

+ linear classical controller B1B
* nonlinear controller B3
o dual-mode controller DM

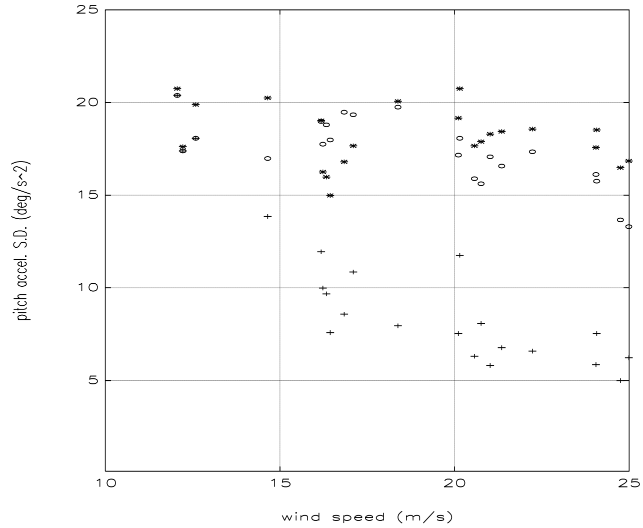

Figure 6 - Pitch acceleration standard deviation (two-bladed configuration)

+ linear classical controller M1D
* nonlinear controller M3C
o dual-mode controller DM1D