Pitch Control for Eliminating Tower Vibration Events on Active Stall Wind Turbines

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Abstract
Negative aerodynamic damping causes tower vibrations on turbines with stall rotors. Under certain conditions, these vibrations may rise to a level that causes a shutdown. Active stall turbines have a pitch system, and the objective of the work was to develop pitch control algorithms which would minimise the probability of tower vibrations rising to the shutdown level. The results of a root cause analysis show that vibrations are largest when coherence of the wind across the rotor is high, and turbulence intensity is low. High magnitude tower vibrations are found to occur if all blades have similar angles of attack and these are in the narrow region in which aerodynamic damping is negative. The first control algorithm uses individual pitch control to ensure that all three blades do not have the same angle of attack. The second algorithm uses de-rating to eliminate the forcing function that causes the instability. The algorithms are described and simulation results are presented. Measured data from thousands of V82-1.65MW turbines with the software in operation is presented. The control algorithms are found to reduce substantially the number of vibration shutdown events, as required. The tower vibration control software is now in operation on more than 5GW of installed wind turbines. The fact that high fatigue loads occur under conditions of unusually low turbulence and high coherence is the opposite from the normal design situation. This provides a different perspective on wind turbine loads and control.

Keywords: wind turbine; control; tower vibrations; active stall; stall; coherence; turbulence; aerodynamic damping; V82-1.65MW.

1 Introduction
As the turbulent wind spectrum contains all frequencies, a wind turbine tower will be excited whatever its frequency. Normally there is enough aerodynamic damping to prevent problems from arising, however negative aerodynamic damping sometimes causes tower vibrations on turbines with stall rotors, and these may rise to a level that causes an alarm and consequent shutdown.

Active stall turbines possess the following general characteristics:
- constant rotational speed when generating (occasionally 2-speed, with a lower speed for the lightest winds)
- a rotor with blades that stall in high wind
- a pitch control system
- an asynchronous induction generator, typically of the squirrel-cage type

As active stall turbines have a pitch system, this offers the possibility for the use of pitch control to mitigate tower vibrations.

Control algorithms for active stall turbines have previously been reported for the regulation of the power output [1, 2]. And similarly the control of tower vibrations of pitch-regulated variable-speed turbines has been widely investigated, see for example [3]. However the control of tower vibrations of active stall wind turbines has received little or no attention in the literature.

In the work reported here, control algorithms are developed for the reduction of tower vibrations of active stall turbines. Specifically, the aims were to develop control algorithms, where these algorithms would minimise the probability of tower vibrations of an active stall design rising to a level whereby a shutdown could be necessitated, thereby:
1. reducing the fatigue loads that would be caused by such shutdowns
2. increasing energy output per annum via increasing high wind availability
3. maintaining the firmness of power that would be produced by the affected wind power plant

2 Investigation of Root Cause

2.1 Damping

The factors that contribute to tower damping in a stall regulated or active stall turbine typically include:

- aerodynamic damping $d_a$ (positive or negative)
- tower material damping $d_t$ (positive)
- tower dampers, if fitted $d_{td}$ (positive)

Hence tower vibrations increase or decrease as follows:

\[ d_a + d_t + d_{td} > 0 \] means that tower vibrations are decreasing
\[ d_a + d_t + d_{td} < 0 \] means that tower vibrations are increasing

If $d_a + d_t + d_{td}$ is less than 0 for long enough, then the vibrations may be able to build up sufficiently to reach the level at which a vibration alarm and shutdown will occur.

Aerodynamic damping of tower vibrations arises from two sources. As seen by a given point along a blade, these are: changes in apparent wind-speed and changes in angle of attack. To explain these effects, consider first operation under conditions of positive aerodynamic damping:

- The tower top is moving fore-aft (and laterally) continuously, but the movements are small
- When the tower top moves upwind:
  - the apparent wind-speed, as seen by the turbine, and the angle of attack both increase
  - both of these effects give rise to increases in the rotor thrust force
  - the force increase counteracts tower upwind motion
  - this dampens the tower vibration

Conversely operation with negative aerodynamic damping is as follows:

- When the tower top moves upwind:
  - the apparent wind-speed and angle of attack increase
  - the rotor thrust force decreases
  - the decrease in thrust force increases tower upwind motion
  - this amplifies the tower vibration

2.2 Thrust – wind-speed relationship

The relationship between rotor thrust force and apparent wind-speed is illustrated in Figure 1. A V82-1.65MW Active Stall® wind turbine [4] is modelled here and the results are normalised to the thrust at rated wind-speed. The red stars give the operating curve, which depends on the air density, the nominal power level, and other factors. If the gradient of a given thrust – wind-speed curve in Figure 1 is positive, then aerodynamic damping is positive. Similarly if the gradient is negative, aerodynamic damping is negative. It can be seen that there is a small region in which negative aerodynamic damping is present at certain pitch angles, between 12 m/s and 14 m/s.

![Figure 1. Rotor thrust versus wind-speed for various pitch angles](image-url)
For further analysis of the derivative of rotor thrust with wind-speed, and the underlying aerodynamic contributions to negative aerodynamic damping, see [5].

2.3 Measured data

2.3.1 Shutdowns

Analysis of site data showed that a relatively small number of turbines experienced a relatively high number of high vibration events. This is illustrated by Figure 2, which presents the probability distribution of shutdowns per turbine of more than 600 V82-1.65MW turbines operating in the year 2006. The data is normalised to the highest value of shutdowns per turbine.

![Figure 2. Distribution of shutdowns per turbine in 2006](image)

Analysis of the shutdowns per site showed that a relatively small number of sites experienced a relatively high mean number of shutdowns per turbine. This is illustrated in Figure 3, in which the same data is used and is normalised to the highest value of shutdowns per site.

![Figure 3. Distribution of shutdowns per turbine per site in 2006](image)

It is notable that, for wind power plant with high numbers of shutdowns per turbine, a high degree of variability from turbine-to-turbine within the site still exists. This is illustrated with reference to the site with the second highest number of shutdowns in Figure 3, for which the distribution of shutdowns per turbine is presented in Figure 4. There are more than 50 turbines at this site and the data is normalised to the same value as for Figure 2.

From Figures 2, 3 and 4 it is concluded that local climatic conditions are a potential root cause.

2.3.2 Time domain results

Measured data from an individual V82-1.65MW turbine is presented in Figure 5, illustrating the build-up of vibrations to a shutdown event. The sampling interval is 0.1 s. The first row is wind-speed at hub height. The second row is blade pitch angle, which is approximately -5° during generation and then moves towards -95° during shutdown. The third row is generator active power, normalised to nominal power. The effect of tower vibrations on power can clearly be seen. The fourth row is tower top acceleration, filtered to contain only the component at the tower natural frequency, and for both the downwind and lateral directions. These two curves are normalised to the acceleration value at the point of shutdown.

The tower vibrations are already increasing at the start of the plot and they reach the shutdown level at time = 95 s. The effect of the vibrations on the power signal can be clearly seen during this period. There are 29 periods of oscillation at the tower natural frequency from normal operation to shutdown. This is a typical value for the build-up time, and indicates that the conditions causing the vibrations need to be in place for a significant period of time relative to the time periods of the higher frequency components in the turbulent wind. That is, individual gusts or steps in wind-direction are not the cause of tower vibration events.

It is notable that the turbulence intensity is 2.85%, with a minimum:maximum wind-speed range of 14.5 m/s : 16.8 m/s over the period prior to shutdown. Statistical analysis of data from a range of turbines showed that shutdowns due to tower vibration events often, but not exclusively, took place
under conditions of very low turbulence intensity.

Given the results in Figure 1, the relationship between shutdowns and windspeed was investigated. Tower fore-aft acceleration data was recorded at high frequency on a single turbine and the acceleration data was then filtered to the tower natural frequency. Figure 6 illustrates the results, which are normalised to the shutdown acceleration level. It can be seen that tower vibrations build up at approximately 15 m/s.

To give a view across a larger number of turbines, 30 turbines were randomly selected from the group of more than 600 for which data is presented in Figure 2. For the full year 2006, the shutdown events were sorted by wind-speed at the time of each shutdown, and the data values were normalised to the highest value across the wind-speed range. The results are in Figure 7 and again there is a clear peak, in this case at 14 m/s.

Given the results presented in Figures 1-7, it was hypothesised that tower vibrations would grow to shutdown levels when:

(a) the angle of attack of all three blades is the same

and

(b) the angle of attack of the three blades is in the narrow range of angle of attack that causes negative aerodynamic damping of the maximum magnitude.
2.4 Simulation Test-Bed

To test this hypothesis, the aero-elastic simulation tool used for simulating this class of turbine, FLEX5, was modified to comply with the site measurements. Some parameters were modified to achieve operating conditions with tower vibrations varying from neutral stability to unstable, see [5] for detailed results. The main objectives of the parameter tailoring were to achieve broad agreement with the site observations. Results were generated for comparison with those of Figures 6 and 7, and these are presented in Figure 8. These runs were carried out to investigate the sensitivity of tower vibrations to coherence of the wind from blade-to-blade, and to low levels of turbulence intensity. “I” in the legend is turbulence intensity. The data presented in Figure 8 is the 10-minute maximum values of tower-top acceleration.

![Figure 8](image)

Figure 8. Maximum tower top fore-aft acceleration at natural frequency, sensitivity to coherence and turbulence intensity

2.5 Sensitivity of vibrations to coherence and turbulence

It is concluded from Figure 8 that high levels of vibrations occur if there is high coherence of the wind-speed across the rotor, and particularly if there is high coherence combined with low turbulence. This gives rise to the following conclusions:

- if the turbulent wind field is more coherent across the rotor plane, a larger part of the rotor will experience similar angles of attack and the associated excitation force will be larger
- if the turbulence intensity is lower, the blades will experience a lower standard deviation of angle of attack. Therefore if the average angle of attack is in the narrow band in which aerodynamic damping is negative, the aerodynamic damping will remain consistently negative. As significant time periods are needed to cause tower vibrations to build up, of at least 1 minute, the lower standard deviation of angle of attack may contribute significantly to higher levels of tower vibration.

3 Pitch Control Strategies

3.1 Control Aims

The control aim is to avoid tower vibrations rising to a level where a shutdown would be necessitated.

3.2 ‘Split Pitch’ Control

3.2.1 Algorithm

One approach is to use individual blade pitching to force the blades to have different angles of attack from one another, under conditions when tower vibrations are increasing. Let:

\[ a_d = \text{component of tower-top acceleration at the tower natural frequency, in the downwind direction} \]
\(a_l\) = component of tower-top acceleration at the tower natural frequency, in the lateral direction
\(A_s\) = shutdown acceleration level

“collective pitch demand” = the pitch demand generated by the power control algorithm [1]. This demand is always identical for all three blades.

The following algorithm was developed:
1. If \(a_d > 0.33\ A_s\) or \(a_l > 0.33\ A_s\), then superimpose off-sets of +/-2° on the collective pitch demand
2. If \(a_d\) and \(a_l\) fall, such that \(a_d < 0.26\ A_s\) and \(a_l < 0.26\ A_s\), return to normal operation or if \(a_d\) or \(a_l\) rise further, such that \(a_d > 0.49\ A_s\) or \(a_l > 0.49\ A_s\), superimpose off-sets of +/-4° on the collective pitch demand
3. If \(a_d\) and \(a_l\) fall, such that \(a_d < 0.26\ A_s\) and \(a_l < 0.26\ A_s\), return to normal operation

A simple step-wise control scheme was used in preference to, for example, a change in offset that is proportional to the magnitude of the tower vibrations, because then it is possible to carry out standard 10-minute aero-elastic simulations under the +/-2° and +/-4° operating conditions, and therefore calculate the fatigue damage contribution from the modified operation.

### 3.2.2 Simulation Results

Results for +/-2° and +/-4° were found to reduce the rate of increase of the vibrations [5].

### 3.2.3 Measurements

**Time domain**

Typical operation of the split pitch algorithm on a V82-1.65MW wind turbine is illustrated in Figure 9. The sampling interval is 0.25 s and the signals plotted and normalisation values used are as per Figure 5, with the exception of the wind-speed, which is a 1-minute running average. The tower vibrations are initially low but then start to increase until, at time 93 s, they exceed the threshold and the split pitch action takes place. From the acceleration plot it can be seen that, after the blades angles split away from one another, there is a further short period until the fore-aft acceleration reaches a maximum, then it starts to fall. The decrease in acceleration is then monotonic, apart from one further peak at time 111 s, until normal operation is again achieved. Many other data sets with split pitch actions have been captured, and this behaviour is typical of the response, although the duration of the operation can vary significantly, and occasionally the vibrations continue to rise, requiring either +/-4 deg split pitch and/or the de-rating action described later.

![Figure 9. Measured data for the split pitch control action](image_url)
The split pitch control was designed to be robust to a variety of operating conditions, for example blade icing, and it is concluded that the split pitch algorithm is robust to a significant degree of variability in the rotor aerodynamics [5]. This robustness is important because, viewed across complete fleets of turbines globally, transient disturbances to rotor aerodynamics should not be ignored [6].

**Time at level statistics**

Internal statistics have been recorded at high frequency across all turbines for the time spent with the acceleration (component at tower natural frequency) above given thresholds. The sampling interval is 20 ms. Employing these statistics allows the performance of tower vibration mitigation algorithms to be rapidly evaluated. Measured statistics from a group of more than 20 V82-1.65MW turbines indicate a reduction in the number of shutdowns by a factor of 10 [5].

**Shutdowns as function of wind-speed**

For a sample of 15 turbines at one wind power plant, shutdown events were recorded and sorted into wind-speed intervals, to get a shutdowns/month figure for all intervals across the wind-speed range. Then the shutdowns/month values were combined with the IECII wind-speed probability distribution to give the predicted shutdowns per annum for each wind-speed interval. The results are presented in Figure 10 and are normalised to the same number of shutdowns as is used for the randomly-sampled group in Figure 7. The results in Figure 10 can be directly compared with the results in Figures 6, 7 and 8, and they indicate that the split pitch control is effective in reducing the number of shutdowns.

![Figure 10. Shutdowns per annum without and with split pitch control](image)

**Total number of shutdowns per annum**

Two-sample t tests [7] were carried out to evaluate the overall change in numbers of shutdowns per month. This allowed the site tests to continue until a statistically significant test result was achieved. For one wind power plant of more than 20 V82-1.65MW turbines, the machines were divided into two groups. This site was the most severe in terms of numbers of shutdowns per annum. With a baseline period before the tests, this method allows group-to-group changes to be examined while accounting for changes in wind-speed from the before-test period to the during-test period. The tests were run until a given level of confidence in the results was achieved. Box plots for the effect of the split pitch on shutdowns at one site are presented in Figure 11. The values of shutdowns/month are all normalised to the overall maximum value of shutdowns/month.

![Figure 11. Box plots for two-sample t tests of split pitch software across a wind power plant](image)

For the reference group, there is a reduction in the number of shutdowns due to a change in wind conditions. However for the group with split pitch software, the reduction in number of shutdowns is much larger. The overall effect is approximately a 50% reduction in the number of shutdown events.

Across multiple sites, it was found that the split pitch software reduces the number of shutdowns by approximately 50-80%, depending on the site. As the split pitch control is not a complete solution, a further method was sought to eliminate the remaining shutdowns.
3.3 De-Rating Control

3.3.1 Algorithm

In this case, the energy input to the system under conditions of high tower vibrations was reduced to a minimum, while still keeping the turbine connecting to the grid. This was achieved via the following algorithm:

1. If $a_d > 0.66 A_s$ or $a_i > 0.66 A_s$, step the power demand to $P_{DLO}$
2. If $a_d$ and $a_i$ fall, such that $a_d < 0.26 A_s$ and $a_i < 0.26 A_s$, step the power demand back to nominal power

$P_{DLO} = 0$ MW in the final, tuned, version of the algorithm. By lowering the power demand to 0 MW, the aerodynamic damping is not increased but rather the forcing function is reduced to a negligible level. The tower vibrations should then fall due to the damping contributions from the tower material damping and, if fitted, tower dampers.

3.3.2 Results

Simulation results for De-Rating Control were found to reduce the vibrations, and $P_{DLO}$ and the ramp rate for the reduction in power demand were both tuned in site tests [5].

3.4 Full Tower Vibration Control

3.4.1 Transient response

The combined algorithm keeps both the split pitch control and de-rating control active simultaneously. As vibration levels rise, the split pitch control intervenes first. If this is successful, then normal operation is resumed. However, if the vibrations continue to increase, the de-rating control takes place. A plot illustrating all phases of operation of tower vibration control is presented in Figure 12. The sampling interval is 0.25 s and the signals plotted are as per Figure 9. The normalisation values are as per Figures 5 and 9.

The first split pitch mode is entered at time 40 s, however the vibrations continue to rise and so the second split pitch mode is entered at time 51 s. In this example the wind conditions are particularly severe, the vibrations continue to increase, and consequently the de-rating mode is entered at time 63 s. At this point the blade generating the most lift, blade 2, is brought rapidly back to the collective pitch demand, which blade 1 has been following. Both blades 1 and 2 then follow the collective pitch demand which moves steadily negative to reduce the power towards the power demand of 0 MW. While this is taking place between time 63 s and 67 s, blade 3 is frozen in place until the collective pitch demand reaches blade 3. All three blades
follow the collective pitch thereafter. At time 128 s, both $a_r < 0.26 A_s$ and $a_r < 0.26 A_s$ and therefore the power demand is stepped back to nominal power. Normal operation is regained at time 147 s.

### 3.4.2 Shutdowns

**2006 to 2009 comparison**

A probability distribution of shutdowns per turbine for the complete year 2009 is presented in Figure 13. The data is for the same set of turbines for which data was presented in Figure 2, and is normalised to the same value, so Figure 13 is directly comparable with Figure 2. In addition to receiving the new control software, some turbines received an aerodynamic modification, and so the results will tend to over-estimate the improvements due to control software alone. However, given the performance of the aerodynamic modifications (not reported here), it can nevertheless be concluded that the new control software is effective at reducing the number of shutdowns.

![Figure 13 Distribution of shutdowns per turbine in 2009, with tower vibration control, group from 2006](image)

The data from Figure 13 is analysed by site, as per Figure 3, and is normalised to the same value as used for Figure 3. The results are in Figure 14 and, by comparison to Figure 3, again the effectiveness of the control software can be seen.

![Figure 14. Distribution of shutdowns per turbine per site in 2009, group from 2006](image)

For the group of 30 turbines for which shutdowns are plotted with wind-speed in Figure 7, data for 2009 is now added to the Figure 7 plot to indicate the change with the addition of the tower vibration control software, see Figure 15. Some of these turbines received the aerodynamic modification, but again given the performance of this change (not reported here) the data indicates that the control software delivers a considerable reduction in number of shutdowns.

![Figure 15. Distribution of shutdowns for 30 turbines in 2006 and 2009](image)

### 2009 turbines

A further probability distribution of shutdowns per turbine for the complete year 2009 is presented in Figure 16. The data is for more than 2000 turbines and is normalised to the same value as used in Figures 2 and 13. When comparing to Figure 2, it should be noted that the sample set is different, some turbines have had aerodynamic modifications, and later turbines have been erected with a tower damper of higher damping factor. However given the performance of these changes (not reported here) it can again be concluded that the control software delivers a considerable improvement over the performance in Figure 2.

![Figure 16. Distribution of shutdowns per turbine per site in 2009, with tower vibration control](image)

### 3.4.3 Change in energy output p.a.

Target 2 of the work was to increase energy capture per annum via the increase in high wind availability. As has been shown, the shutdowns occur in winds above rated wind-speed and below upper cut-out wind-speed. Therefore every shutdown causes full rated power to be lost during the subsequent period of downtime. To
investigate the change in energy output lost per annum, the energy capture lost due to shutdowns for the year 2006 was calculated for the randomly-selected group of 30 turbines that were analysed for Figures 7 and 15. Then the energy capture lost in 2009 due to shutdowns plus de-rating events was calculated for the same group of turbines in 2009. The results are presented as box plots in Figure 17, and are normalised to the highest value from 2006.

It is found that the control software is highly effective at substantially reducing the number of shutdowns due to tower vibration events.

The tower vibration control software is in operation on more than 5GW of installed wind turbines.

The fact that high fatigue loads are found to occur under conditions of unusually low turbulence and high coherence is the opposite from the normal design situation, in which the areas of focus for fatigue load calculations are high turbulence and operation in complex terrain or under wake conditions. This provides a different perspective on wind turbine loads and control.

4 Conclusions

For tower vibrations of stall or active stall turbines to rise to high levels, the angles of attack experienced by the three blades all need to be within the narrow band in which aerodynamic damping is negative. This will occur if there is high coherence of the wind-speed across the rotor, or high coherence combined with low turbulence.

Control algorithms have been designed for active stall turbines that have been found to reduce to a negligible level the probability that the tower vibrations will rise to unacceptably high levels. These algorithms incorporate the use of individual blade pitching. The results have been validated across thousands of operational turbines.

References