# On the Potential of Pitch Control for Increased Power Capture and Load Alleviation

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# On the Potential of Pitch Control for Increased Power Capture and Load Alleviation

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**Abstract.** Wind turbine control is a research area that is gaining increasing interest, and numerous simple and advanced control schemes have been suggested, especially for load alleviation. The performance of such controllers is often compared to the performance of simpler controllers, thus relative to a moving reference. This study is focused on estimating the upper limits of the power increase and load variation alleviation that are achievable through pitch actuation. Knowing these upper limits, the potential of improving existing controllers can be assessed. The achievable power output increase and load variation reduction are estimated through numerical optimization of the pitch and generator torque actuation. Results show that the potential of increased power output at below rated wind speeds through optimized pitch actuation is greatest for inflows that varies with the azimuthal position of the blades. It is shown that at above rated wind speeds, the potential of decreasing the wind shear induced load variations beyond what is possible with a simple cyclic pitch scheme is limited. The results presented in this study are all obtained from simulations with deterministic inflow because the absolute upper limits are sought, and turbulent inflow is assumed to decrease these limits.

## 1. Introduction

As wind turbines are becoming increasingly larger, the varying loads on the blades due to wind shear, wakes, turbulence etc. are becoming increasingly significant. To accommodate increasingly longer and lighter blades, load alleviation have been applied based on advanced sensors and actuators. Load alleviation can be achieved using for example blade pitch or flap actuation in combination with different types of sensory systems. In this study, the focus is on pitch actuation. Modern, industry standard, load alleviation control schemes include cyclic blade pitching based on blade root bending moment measurements. The performance of cyclic pitch control schemes is well described in the literature, e.g. [1, 2, 3]. Recent developments of advanced measurement systems such as Light Detection and Ranging (LiDAR) systems [4, 5] have lead to the development of control systems that are capable of exploiting preview measurements of the inflow. The performance of preview enabled control systems is indicated in several studies [5, 6, 7, 3, 8]. However, the theoretical potentials of increased power capture and load alleviation by pitching, in general, have not been studied. Because pitching involves turning the entire blade at once, it is expected that not all load variations can be alleviated. Knowing the upper levels of the achievable benefits by pitching will enable an assessment of the value of applying any additional sensors or complex pitch control schemes. For example, if it is found that the upper limits of what is achievable with optimal pitch control are only a few percent above what is already achieved using industry standard pitch controllers, then the benefits of adding any additional sensors to accommodate more advanced pitch control can only be these few percent.

The objective of this study is to investigate the upper levels of increased power output and load alleviation that are achievable using pitch actuation in deterministic inflow. For below rated wind speeds, the focus is on increasing the power capture, whereas the focus is on load alleviation at above rated wind speeds. The potentials of increased power output and load alleviation are investigated through numerical maximization and minimization of the power output and the loads, respectively, of a reference turbine. The potentials of increased power output and load alleviation are expected to be highly dependent on the inflow conditions. Thus, the maximization and minimization is performed with different types of inflow that contains both temporal variations of the mean inflow speed and azimuth angle dependent inflow variations as in a vertical wind shear. The following inflow types are tested for the power maximization at below rated wind speed: the extreme asymmetric inflow of a half-wake, and the symmetric inflow situation of a square-wave varying mean wind speed. For load minimization at above rated wind speed, the following types of inflows are tested: standard power law vertical wind shear, and the square-wave varying mean wind speed.

All simulations are performed using the aero-servo-elastic simulation tool HAWC2 and a model of the NREL 5MW reference turbine in deterministic inflow. For all optimization cases, except one, a stiff version of the reference turbine is simulated. The stiff turbine is chosen in this initial study because flexibility is assumed to add a complexity to the formulated optimization problem which will lower the achievable upper limits. Further studies will be focused on how the results change when the model complexity is increased by introducing the flexibility of the turbine.

## 2. Optimization Procedure

The maximization of the power output and the minimization of the loads are performed by solving an optimization problem. The optimization problem differs depending on the inflow type and the objective of the optimization. The two inflow types that are investigated in this study are: temporal variations of the mean wind speed, and azimuth angle dependent inflow. The objectives are: maximization of the power output at below rated wind speed, and minimization of the load variations at above rated wind speeds. The control inputs that are used to fulfill the optimization objectives are: prescribed time variations of collective pitch angle and generator torque for the inflow case of varying mean wind speed, and prescribed azimuthal variation of individual blade pitch angles allowing cyclic pitch variations and prescribed variation of generator torque for the azimuth angle dependent inflow. Because the optimization variables are discrete pitch or generator torque values, the actual control signals applied in the simulation are interpolations of the discrete optimization variables.

The inflow, in the cases of temporal mean wind speed variations, is a number of unit-steps of the wind speed. The time between the steps is adjusted such that the turbine reaches a steady state between the steps, i.e. the wind speed steeps constitutes a number of square-waves. For each square-wave, the same control inputs are applied. Thus, the control inputs are periodic signals with a period corresponding to the length of the square-waves. The resulting power or load variations are averaged for all square-waves to ensure that a periodic solution is obtained.

In the case of the azimuth angle dependent inflow, the inflow to the turbine is either a standard wind shear or a half-wake. A schematic that illustrates the optimizations and the inflow types is given in Figure 1. The optimizations are performed iteratively in MATLAB, letting MATLAB start and post-process the HAWC2 simulations. The actual optimization is performed using an interior point method for the *fmincon* MATLAB routine.

The cost function indicated in Figure 1 differs depending on the inflow type and the objective of the optimization. In the following, the optimization problem is described for each of the

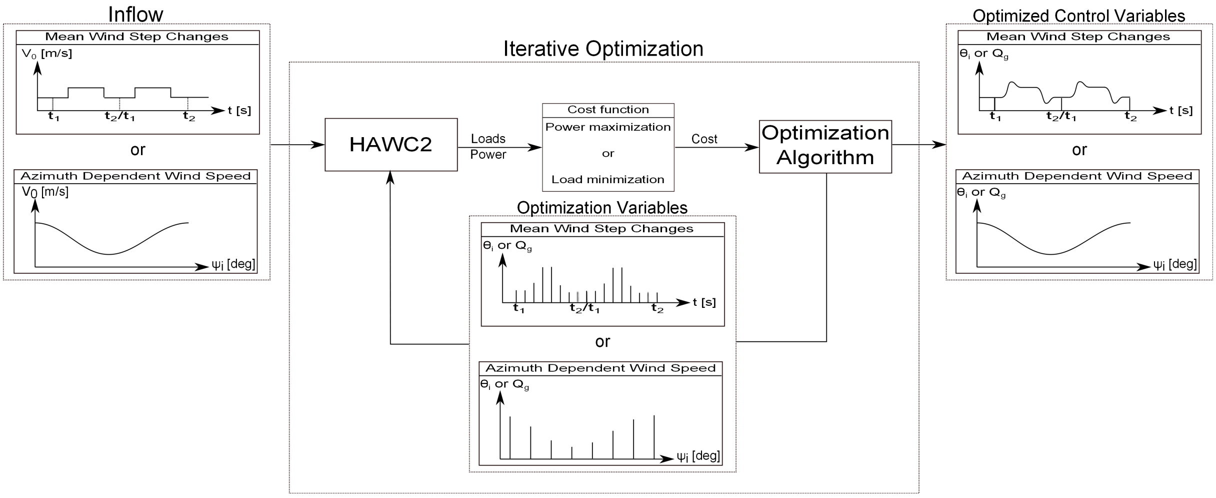


**Figure 1.** Illustration of the optimization procedure.

optimization cases presented in this study.

*2.1. Power Maximization at Below Rated Wind Speed for a Half-Wake Inflow*

A standard, partial load control law is implemented for regulating the generator torque. The control law is defined as:

$$Q_g = k\Omega^2, \tag{1}$$

where $\Omega$ is the rotor speed and $k$ is a constant. Usually, $k$ is estimated from the aerodynamic characteristics and dimensions of the wind turbine. However, in this study, $k$ is one of the optimization variables. The remaining optimization variables are: two reference pitch values and the azimuthal position of the two reference pitch values (the phase). The pitch values applied in the simulations at the intermediate azimuth angles are obtained by interpolation between the two reference pitch values using a cubic spline. The optimization problem is given as:

$$\max_{\mathbf{u}} \frac{1}{2\pi} \int_{-\pi}^{\pi} P(\psi_i) \frac{\bar{\Omega}}{\Omega(\psi_i)} d\psi_i \tag{2}$$

where $\mathbf{u} = (\theta(\psi_1), \theta(\psi_2), k)$ are the optimization variables, $\theta(\psi_i)$ is the pitch angle at the azimuth angle $\psi_i$, $P(\psi_i)$ is the obtained azimuth angle dependent power output, $\bar{\Omega}$ is the average steady state rotor speed and $\Omega(\psi_i)$ is the azimuth angle dependent rotor speed. Thus, the potential load increases are neglected.

*2.2. Power Maximization at Below Rated Wind Speed for a Square-Wave Inflow*

Two types of optimizations are performed for the case of step changes of the mean wind speed; one where optimized constant pitch and $k$ values for the partial load controller are found, and one where optimal periodic collective pitch and generator torque signals prescribed by two linear interpolations each described by 20 points are sought. The optimization problem is given as:

$$\max_{\mathbf{u}} \frac{1}{T} \int_{t}^{t+T} P(t) dt \tag{3}$$

where $\mathbf{u} = (\theta, k)$ and $\mathbf{u} = (\theta(t_i), Q_g(t_i)), i = 1...20$ for the two optimization cases ($Q_g$ is the applied generator torque), $t_i$ is time of the $i$'th input sample.

*2.3. Load Minimization at Above Rated Wind Speed for a Standard Wind Shear*

In contrast to the optimizations presented above, the optimizations at above rated wind speed are only focused on pitch angles because the generator torque is kept constant for above rated operation. The applied inflow is an IEC standard power law wind shear. The optimization variables are a number of azimuthally distributed pitch angles that are added to a collective pitch signal, and the azimuth positions of the added individual pitch changes. The collective pitch signal ensures that the rotor speed is kept at the rated value using a standard PI speed controller. The optimization is aimed at minimizing the standard deviation of the blade root, out-of-plane bending moment, and the optimization problem is given as:

$$\min_{\mathbf{u}} \sqrt{\frac{1}{TF_s - 1}\sum_{i=1}^{TF_s}(M_{bx,i} - \bar{M_{bx}})^2} \quad (4)$$

where $\mathbf{u} = \theta(\psi_i), i = 1...n$, $\theta(\psi_i)$ is a vector containing the discrete pitch angles for the $n$ azimuthally distributed optimization point, $\psi_i$ is the azimuth angle of the $i$'th optimization point, $T$ is the steady state simulation time, $F_s$ is the sampling frequency, $M_{bx,i}$ is the blade root out-of-plane bending moment at time step $i$ of one of the blades, and $\bar{M_{bx}}$ is the mean steady state blade root out-of-plane bending moment.

*2.4. Load Minimization at Above Rated Wind Speed for a Square-Wave Inflow*

A square-wave mean inflow is applied and optimization of collective pitch angles is carried out for minimizing the load variations. The optimization problem for the load minimization is defined as:

$$\min_{\mathbf{u}} \frac{1}{T}\int_{t}^{t+T} |P(t) - P_r| + |\tilde{M_{bx}}| dt \quad (5)$$

where $P_r$ is the rated power of the turbine, $\tilde{M_{bx}}$ is the high-pass filtered blade root out-of-plane bending moment signal, and $\mathbf{u} = \theta(t_i), i = 1...20$ is the vector containing the optimization variables, which are 20 periodic pitch angles that are repeated for each square-wave. The actual pitch angles applied in the simulations are linear interpolations between the 20 optimization points. Thus, both power and blade load variations are penalized. It is necessary to penalized the power output because deviations from the rated value caused by sudden collective pitch angle changes are unwanted. Static changes of the blade root bending moment cannot be avoided when the wind speed changes and the power is to be kept constant. Using the high-pass filtered blade root out-of-plane bending moment signal, variations, e.g. extreme loads, are penalized without affecting the static change. Hereby, the load variation minimization does not interfere with the objective to keep the power at rated.

## 3. Results of Power Maximization at Below Rated Wind Speed

In this section, the optimal power outputs at below rated wind speed are presented based on simulations of a stiff version of the reference turbine. First, the results for the half-wake inflow situation, then the results for a inflow with step changes of the mean wind speed are presented.

*3.1. Half-Wake Inflow*

The inflow to the turbine is shown in the top-plot of Figure 2. This inflow represents an extreme situation where the wind speed is significantly higher in one half of the rotor plane than in the other. The applied inflow is an idealization of what is expected for a turbine in a wind farm. In a real wind farm, the wake would meander and not remain constant in one half-plane [9]. The results of the power maximization are presented in Figure 2 that shows the results of two types of optimizations regarding the pitch angles; one where a constant pitch angle and one where the optimal individual pitch variations defined from two pitch angles and phase angles are found. In both optimizations, the constant $k$ is also found. The two optimization cases reflect an optimized collective pitch and an optimized 1P individual pitch controller. In Figure 2, it is seen that by applying the optimized cyclic pitch signal, the power output is raised compared to when only $k$ and the collective pitch angle is optimized. With the optimized cyclic pitch signal, the power integrated over one period is raised approximately 3.6%. However, the increased power output is penalized by increased load variations. Especially, the blade root load variations are increased.

*3.2. Square-Wave Inflow*

The time series of the applied inflow is shown in the top-plot of Figure 3. The square wave represents a very extreme situation that is not seen in real operating conditions. This type of inflow is chosen because it represents a very severe challenge for a turbine control system and the results represent a first attempt of estimating the maximum potential of applying power maximization using collective pitch control. Such a control scheme could for example be based on preview of the inflow provided by a LiDAR. The results of the optimization are presented in

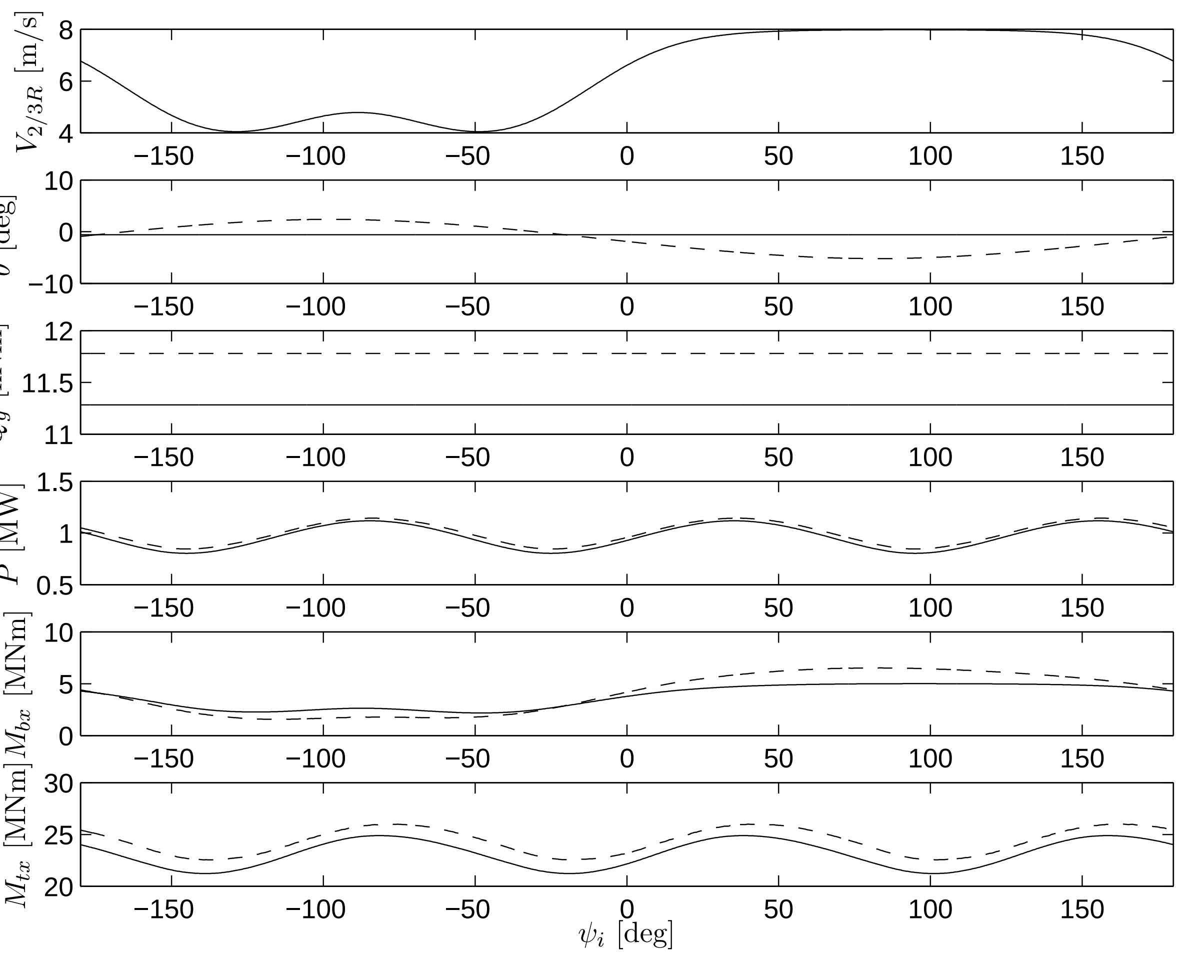


**Figure 2.** Results of the power maximization at below rated wind speeds in half-wake operation. Optimized constant pitch and $k$ (—), optimized $k$ and pitch values for cyclic pitch (− − −). From the top and down: Free wind speed at the two-thirds radius of the rotor, pitch angle, generator torque, power output, blade root out-of-plane bending moment and tower bottom fore-aft bending moment.

Figure 3. For the case with optimized pitch and generator torque, the actuations are applied slightly before the wind speed change occurs. However, it is seen that the actuations have very limited effect on the power output, and the observed increase in integrated power output is negligible (0.04%).

## 4. Results of Load Minimization at Above Rated Wind Speed

In this section, the focus is on minimizing the loads for above rated operation. First, results are presented for a standard vertical wind shear and optimization of azimuth angle dependent pitch values. Then, results are presented for a inflow containing step-changes of the mean wind speed and temporal optimization of periodic pitch angles. For the standard vertical wind shear, results are presented for both a stiff and a flexible version of the reference turbine. For the inflow with step-changes of the mean wind speed, results are only presented for a stiff turbine because optimization studies of the flexible turbine are ongoing.

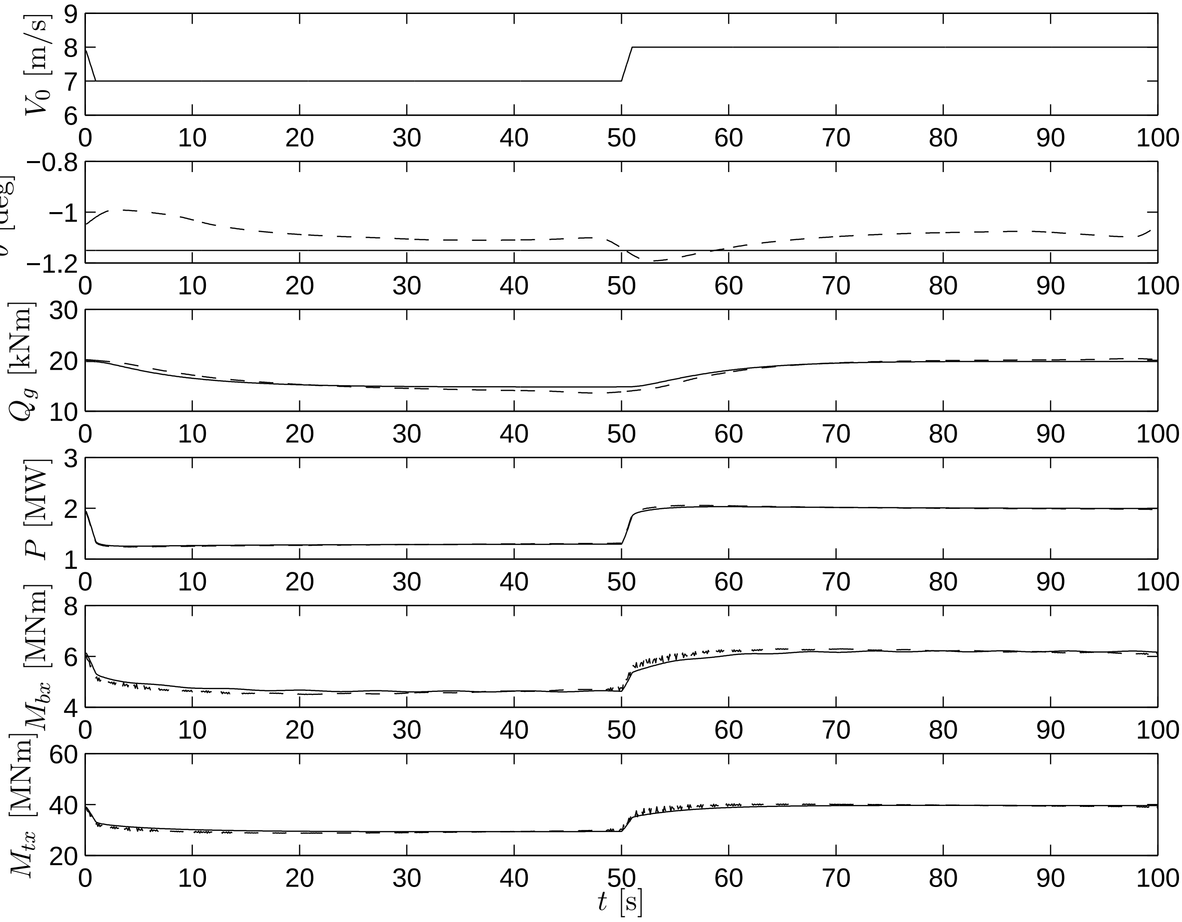


**Figure 3.** Results of the power maximization at below rated wind speeds and step changes of the collective wind speed. Optimized constant pitch and $k$ (—), optimized periodic pitch and generator torque actuations (− − −). From the top and down: Free wind speed, pitch angle, generator torque, power output, blade root out-of-plane bending moment and tower bottom fore-aft bending moment.

### *4.1. Standard Vertical Wind Shear*

Figure 4 and 5 shows the results of the blade load minimization of a stiff version of the reference turbine. Figure 4 shows the results of the optimization normalized with results obtained with a standard collective pitch controller. For comparison, the figure also shows results obtained with a simple cyclic pitch controller [1]. Figure 5 shows the optimized azimuth angle dependent pitch signals. For all the optimizations, the power output is unaffected. The blade load variations for a resolution of two azimuthal optimization points are similar to those of the simple cyclic pitch controller; as expected because the two pitch optimization points only allows for a 1P varying pitch signal. With additional optimization points, the optimized pitch signal tries to alleviate the loads caused by the tower shadow and the load variations decrease slightly. Inspecting the tower bottom load variations, it is seen that these are smallest when four optimization points are applied, thus, it appears that applying a very complex pitch signal is not beneficial.

In Figure 6 and 7, the results of the load minimization with a flexible version of the reference turbine are shown. As for the stiff turbine, similar load variations are experienced for the simple cyclic pitch controller and the two point optimization, and the blade load variations are decreased slightly more when a more complex pitch signal is applied. In contrast to the stiff turbine, for the flexible turbine, the tower bottom load variations are significantly decreased when a complex pitch signal is applied.

### *4.2. Square Wave Inflow*

The results of the optimization are summarized in Figure 8. It is seen that with the optimized signal applied, the pitch actuation is initiated prior to the wind speed change. Hereby, both the

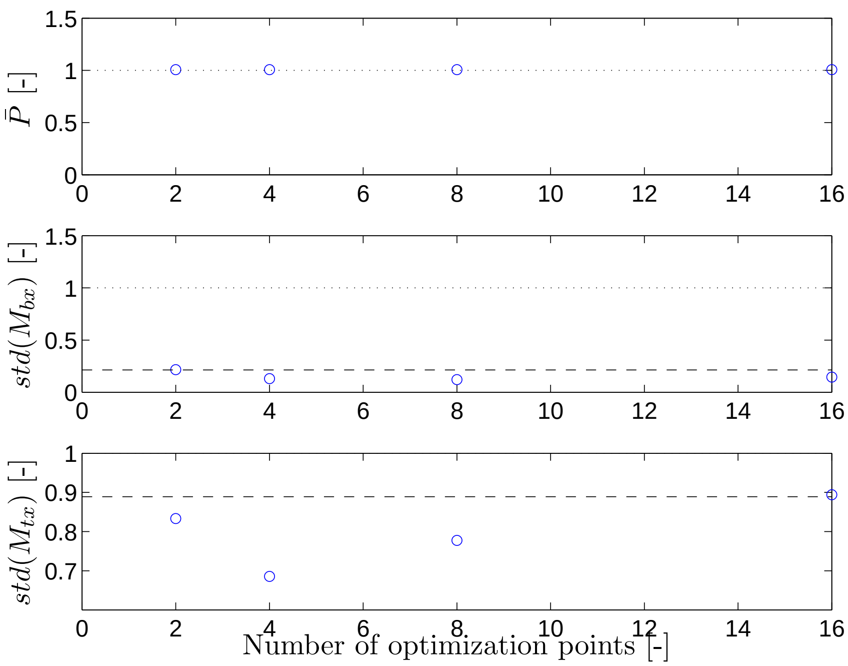


**Figure 4.** Results of the load variation minimization at above rated wind speed (15 m/s and power law vertical wind shear) for the stiff turbine. From the top and down, mean steady state power output, steady state standard deviation of the blade root out-of-plane bending moment, and steady state standard deviation of the tower bottom fore-aft bending moment. All results have been normalized with the results of a simulation with a standard collective pitch controller applied. Results obtained with a simple cyclic pitch controller are shown for comparison (− − −).

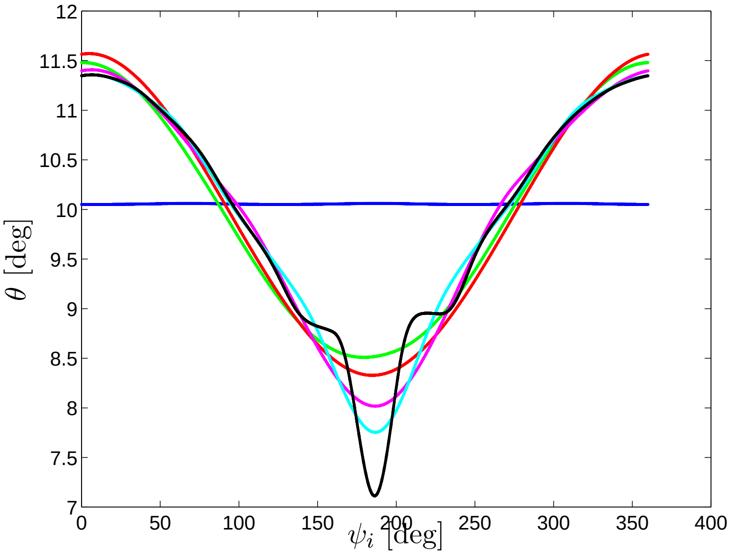


**Figure 5.** The applied steady state pitch signals for the stiff turbine. Blue: collective pitch control, green: simple cyclic pitch control, red: 2 optimized pitch angles, magenta: 4 optimized pitch angles, cyan: 8 optimized pitch angles, and black: 16 optimized pitch angles.

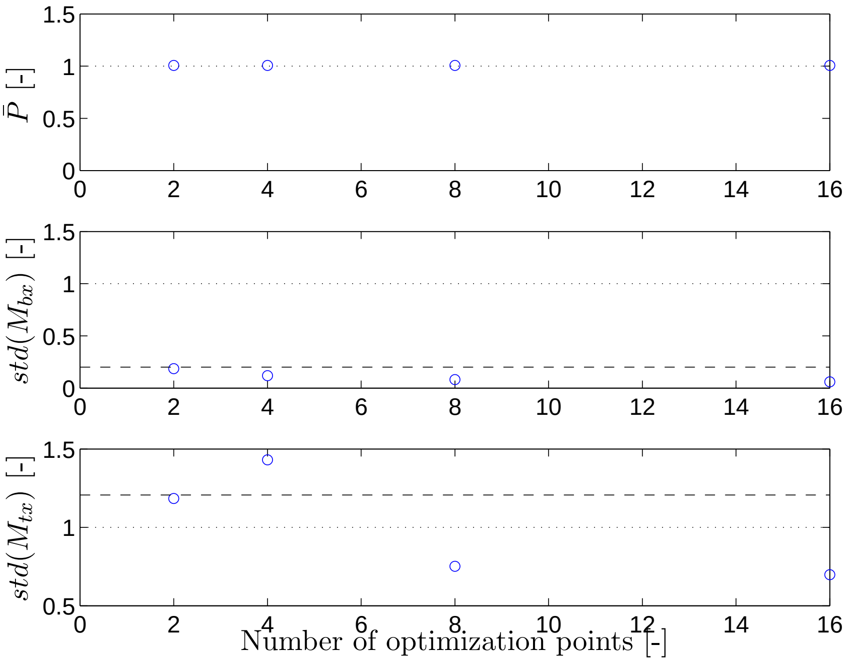


**Figure 6.** Results of the load variation minimization at above rated wind speed (15 m/s and power law vertical wind shear) for the flexible turbine. From the top and down, mean steady state power output, steady state standard deviation of the blade root out-of-plane bending moment, and steady state standard deviation of the tower bottom fore-aft bending moment. All results have been normalized with the results of a simulation with a standard collective pitch controller applied. Results obtained with a simple cyclic pitch controller are shown for comparison (− − −).

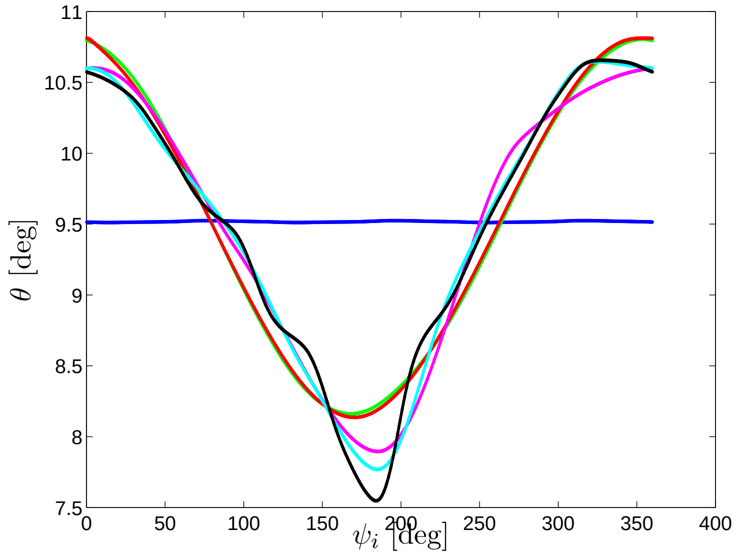


**Figure 7.** The applied steady state pitch signals for the flexible turbine. Blue: collective pitch control, green: simple cyclic pitch control, red: 2 optimized pitch increments, magenta: 4 optimized pitch increments, cyan: 8 optimized pitch increments, and black: 16 optimized pitch increments.

power and load variations are decreased compared to the results with the standard collective pitch controller. Furthermore, it is observed that even with the optimized pitch signal applied, some discontinuous load and power changes are observed in the results. These discontinuities are expected because the wind speed changes are discontinuous, and the applied pitch signal is continuous.

## 5. Conclusions and Further Work

In this study, an approach was presented for estimating the upper limits of power maximization and load variation minimization using pitch actuation. It was shown that, for below rated operation, the greatest potential of increased power output by pitch actuation is for situations with azimuth angle dependent inflow. For the tested half-wake situation, an averaged power output increase of approximately 3.5% was observed compare to an optimized collective pitch controller. For above rated operation, it was shown that the majority of the wind shear induced load variations can be alleviated using a simple 1P pitch signal, and only limited additional blade load alleviation was observed when a more complex pitch signal is applied. For stepwise mean wind speed changes it was shown that pitch actuation prior to an extreme event can significantly decrease the load and power variations. In summary, the study indicates that there is a potential for power maximization at below rated wind speed, and that preview measurements would allow significant alleviation of extreme loads. However, the potential of decreasing the wind shear induced blade load variations more than what is possible with a simple cyclic pitch controller is limited. Further work should be aimed at increasing the complexity of the turbine and performing optimizations for cases that more resembles a real turbine operating in common inflow.

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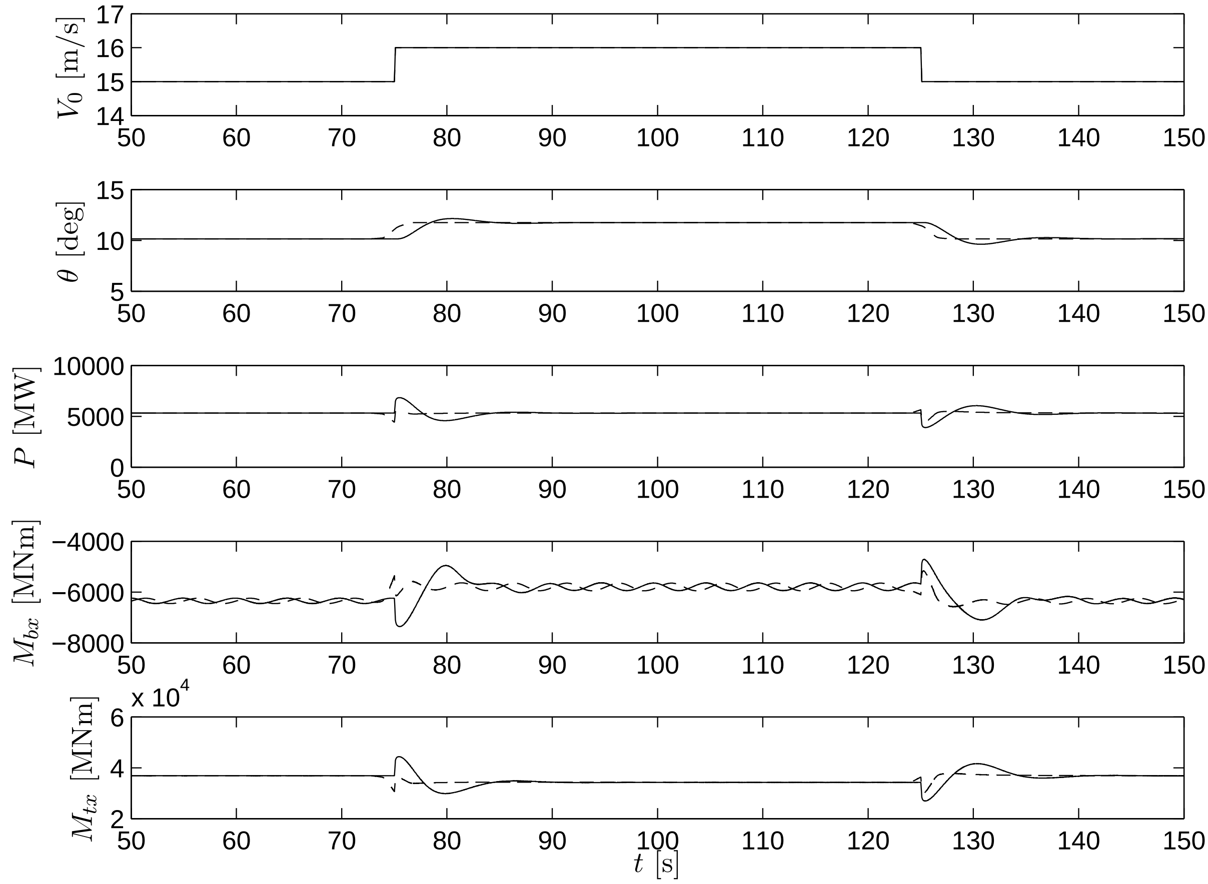


**Figure 8.** Results of the load variation minimization at above rated wind speeds and step changes of the mean wind speed. Standard collective pitch control (—), optimized periodic pitch values (− − −). From the top and down: Free wind speed, pitch angle, power output, blade root out-of-plane bending moment and tower bottom fore-aft bending moment.


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