Control of variable speed pitch-regulated wind turbines in strong wind conditions using a combined feedforward and feedback technique

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Control of variable speed pitch-regulated wind turbines in strong wind conditions using a combined feedforward and feedback technique

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Abstract. Due to the increasing penetration of wind energy into power systems, it becomes critical to reduce the impact of wind energy on the stability and reliability of the overall power system. In precedent works, Shen and his co-workers developed a re-designed operation schema to run wind turbines in strong wind conditions based on optimization method and standard PI feedback control, which can prevent the typical shutdowns of wind turbines when reaching the cut-out wind speed. In this paper, a new control strategy combing the standard PI feedback control with feedforward controls using the optimization results is investigated for the operation of variable-speed pitch-regulated wind turbines in strong wind conditions. It is shown that the developed control strategy is capable of smoothening the power output of wind turbine and avoiding its sudden showdown at high wind speeds without worsening the loads on rotor and blades.

1. Introduction

There are two most important trends in the field of wind energy: upscaling of wind turbines and wind farms, and increasing penetration level of wind energy into power systems. Control systems play an important role in tackling the challenges emerged with both trends.

With the upscaling trend, modern wind turbines become larger with using lighter material, and thus more flexible [1]. To maximize and smoothen the power production and reduce the ultimate and fatigue loads on wind turbines, many advanced control methods are developed, such as individual blade pitch control [2], model predictive control [3] and $H\infty$ control [4].

With the increasing penetration level of wind energy into power systems, it has reached to a point that the impact of wind power on power systems becomes noticeable and must be handled [5]. Because of the variable nature of wind resources both spatially and temporally, wind energy has characteristics quite different from conventional power plants. Increasing the availability of wind farms and decreasing the impact on the stability and reliability of the overall electrical power system are of central importance to achieve even bigger share of wind power in the future, to which control systems in wind turbine level and wind farm level can contribute a lot.

One significant variation of power output of wind turbine arises from its standard operation schema. When the wind speed exceeds the cut-out wind speed, normally at 25 m/s, wind turbines are shut down to protect structures. Shutdowns at the same time of a number of wind turbines, or even a number of wind farms if they are in a relatively small geographical area, can introduce a deep and fast drop in power output from wind energy, which will produce large impact on the local electrical grid.

In order to lower this impact and smoothen the power supply from wind energy, different operation schemas by using specially developed control strategies have been investigated. Enercon has used a special storm control feature in its wind turbines to enable reduced wind turbine operation in the event of extremely high wind speeds and to prevent typical shutdowns [6]. Markou and Larsen developed a control strategy to operate wind turbine at wind speeds beyond normal cut-out wind speed with additional controllers to reduce loads on tower using acceleration measurements [7].

In precedent works, a method to continue operating wind turbines beyond normal cut-out wind speed (25 m/s) until re-designed shutdown wind speed (40 m/s) was proposed by Shen and his co-workers based on optimization study [8]. In this investigation, both constant speed and variable speed wind turbines were considered and standard PI control was used to implement the operation design.

To fully utilize the information gained from optimization study in [8], a new control strategy by using a combined feedforward and feedback technique is investigated in this paper. The reference values of power output, generator torque, pitch angle, rotational speed at different mean wind speeds are derived from the optimization results and then used in the form as a lookup table to find control set points in different wind conditions. A gain scheduling procedure for the PI feedback control loop is also included. By simulation study on a variable speed pitch regulated 2 MW wind turbine using a set of 600s wind speed data ranged from 15 m/s to 40 m/s, the proposed control strategy is found to be able to work quite well in both high and middle wind speed conditions. The loads conditions of the wind turbine are also investigated.

2. Aero-elastic model and operation design

In nearly all research fields related to wind turbines, a reliable aerodynamic/aeroelastic prediction tool is of central importance. To meet this need, there have been many different kinds of commercial and academic codes developed, which are widely used in various industrial and research applications.

In Shen and co-workers' earlier work [9], an aerodynamic/aeroelastic code based on structural dynamics of the blades and Blade Element Momentum (BEM) theory [10] with the tip loss correction model [11] was developed and validated against measurements. This code was originally based on a 11 degrees of freedom model (axial displacement of tower, azimuth displacement of rotor, first and second flapwise modes and first edgewise mode of the 3 blades) and was used to optimize wind turbine blade shape [9]. Later this code was extended by including 2 more degrees of freedom, i.e., transversal displacement of tower and yaw, and was employed to analyse the aerodynamic performance of a wind turbine in strong wind conditions [12]. The degrees of freedom of the model are shown in figure 1.

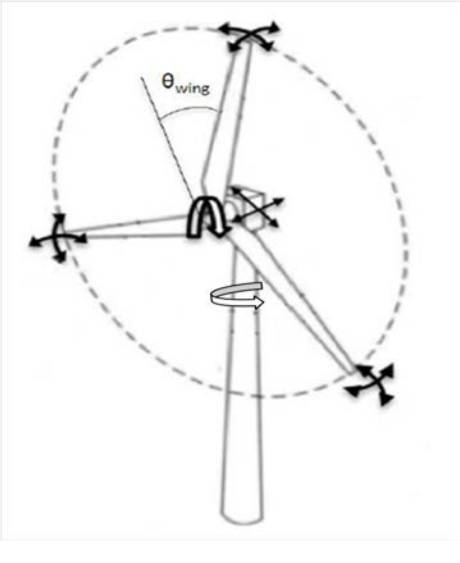

Figure 1. Degrees of freedom of the aero-elastic model.

To operate wind turbines at high wind speeds up to 40 m/s, instead of shutting down wind turbines at the normal cut-out wind speed of 25 m/s, the operation designs of both constant speed and variable speed pitch regulated wind turbines in strong wind conditions were proposed in [8, 13] using the extended code. The operation design problem was formulated as an optimization problem with the AEP as the objective function. The constrains included: the maximum rotational speed less than the rated rotational speed, the maximal loading and bending moments less than the maximal values of loading and bending moments calculated from the turbines operating at wind speeds between 5 and 25 m/s. Then the optimization problem was solved by using the Matlab toolbox optimizer fmincon.

The designed power curve and torque curve of a variable speed pitch regulated wind turbine, which was modified and extended from the constant speed pitch regulated Tjæreborg 2 MW win turbine, was obtained in [13]. It can be seen in figures 2 and 3 that using the redesigned operation the wind turbine will continue operating beyond the original cut-out wind speed 25 m/s and generally decrease the torque and power output until the wind speed exceeds 40 m/s.

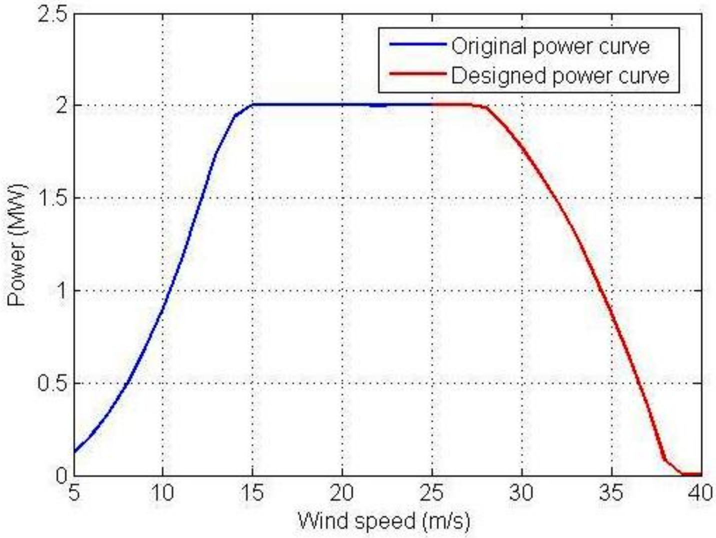

Figure 2. Redesigned power curve from optimization.

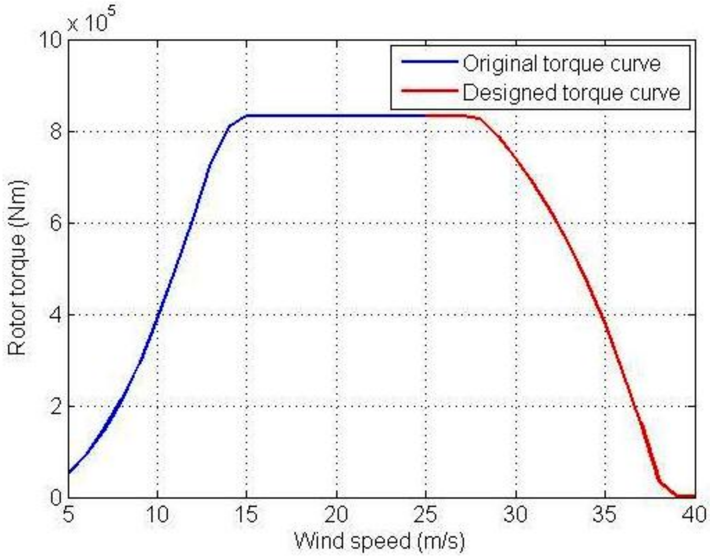

Figure 3. Redesigned torque curve from optimization.

3. Control strategy

In this section, the operation design described in section 2 will be implemented by using a control strategy based on a combined feedforward and feedback technique.

3.1. *Control schema*

Instead of the standard PI controller used in [8], two feedforward control loops using measured mean wind speed are added to the PI feedback control loop. The control schema is depicted in figure 4.

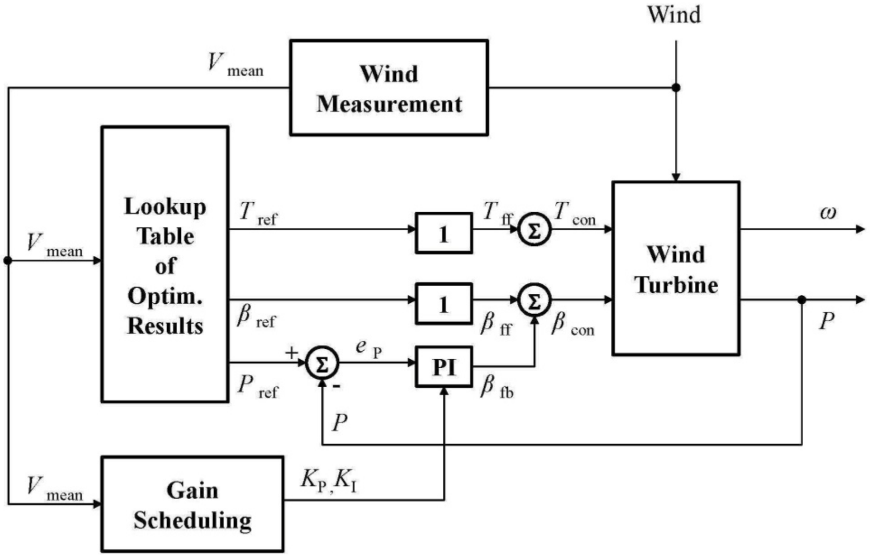

Figure 4. Control schema of the proposed control strategy.

Based on the optimization results and the operation design described in the above section, the reference values of power output (P_{ref}), generator torque (T_{ref}), pitch angle (β_{ref}) at different mean wind speeds can be used in the form as a lookup table to find control set points in different wind conditions.

3.2. *Torque controller dynamics*

Control command for torque controller is derived from feedforward control based on the reference value of generator torque. It can be stated in the following equation:

$$T_{\text{con}} = T_{\text{ref}}(V_{\text{mean}}) \tag{1}$$

Although the generator torque T_{gen} can be controlled for a variable speed wind turbine, it can not be changed instantaneously. Therefore, the dynamics for torque controller is modelled by a first order linear model with time constant τ_T:

$$\dot{T}_{\text{gen}} = -\frac{1}{\tau_T} T_{\text{gen}} + \frac{1}{\tau_T} T_{\text{con}} \tag{2}$$

3.3. *Pitch controller dynamics*

Control command for pitch controller is composed of a feedforward part and a feedback part. The feedforward part is equal to the reference value of pitch angle. The feedback part is based on a standard PI controller using error of power output as input. The control parameters of PI controller are determined from a gain scheduling procedure according to the mean wind speed. So the total control command for pitch angle is governed by equation as follows:

$$\begin{aligned} \beta_{\text{con}} &= \beta_{\text{ff}} + \beta_{\text{fb}} \\ &= \beta_{\text{ref}}(V_{\text{mean}}) + K_{\text{P}} \times [P_{\text{ref}}(V_{\text{mean}}) - P] + K_{\text{I}} \times \int [P_{\text{ref}}(V_{\text{mean}}) - P] dt \end{aligned} \tag{3}$$

The pitch angle of blades is usually changed by hydraulic/mechanical actuator. The dynamics of the pitch controller can be properly modelled as a second order differential equation:

$$\ddot{\beta}+\xi_{\mathrm{p}}\omega_{\mathrm{p}}\dot{\beta}+\omega_{\mathrm{p}}^{2}\beta=\omega_{\mathrm{p}}^{2}\beta_{\mathrm{con}} \tag{4}$$

3.4. Controller tuning and gain scheduling

The only controller parameters need to be tuned in this control strategy are the proportional gain K_{P} and the integral gain K_{I}. Due to the variable nature of wind, a set of prefixed values of controller gains will not maintain a reasonable performance of the control system for a wide range of wind speed. Therefore, a gain scheduling procedure is developed in this study. First, optimal control gains for the wind turbine at different wind speeds are tuned using the Ziegler-Nichols frequency response tuning method [14]. Then the results are stored as a lookup table. When implementing the control strategy, measured mean wind speed of a short time range before the present moment is used to choose the proper control gains from the lookup table. In this paper, a mean wind speed measured in the past 360 seconds is used.

4. Results and discussion

To evaluate the performance of the proposed control strategy, the operation of a variable speed pitch regulated wind turbine, i.e., the modified Tjæreborg 2 MW wind turbine model developed in [13], in strong wind conditions is investigated in this section. Wind data from field measurements, which is downloaded from the internet database: “Database on Wind Charscteristics” [15], is used as input to the simulations. The proposed control strategy is implemented on the wind turbine model in both high wind speed conditions (25-40 m/s) and middle wind speed conditions (15-25 m/s).

In the high wind speed conditions, a 600 seconds wind speed time series is used. With the proposed control strategy using the mean wind speed measured in the past 360 seconds, the power output and the pitch angle are shown in figure 5. To evaluate the effectiveness of feedback control, both control strategy with a feedback control part and without a feedback control part are simulated. It is seen that with the proposed control strategy the electrical power is well controlled with a quite exact tracking of the reference value while the mechanical power has a small variation around the reference value. The difference of the pitch angle between the cases with and without feedback gives a visual intuition of the feedback part of the pitch controller.

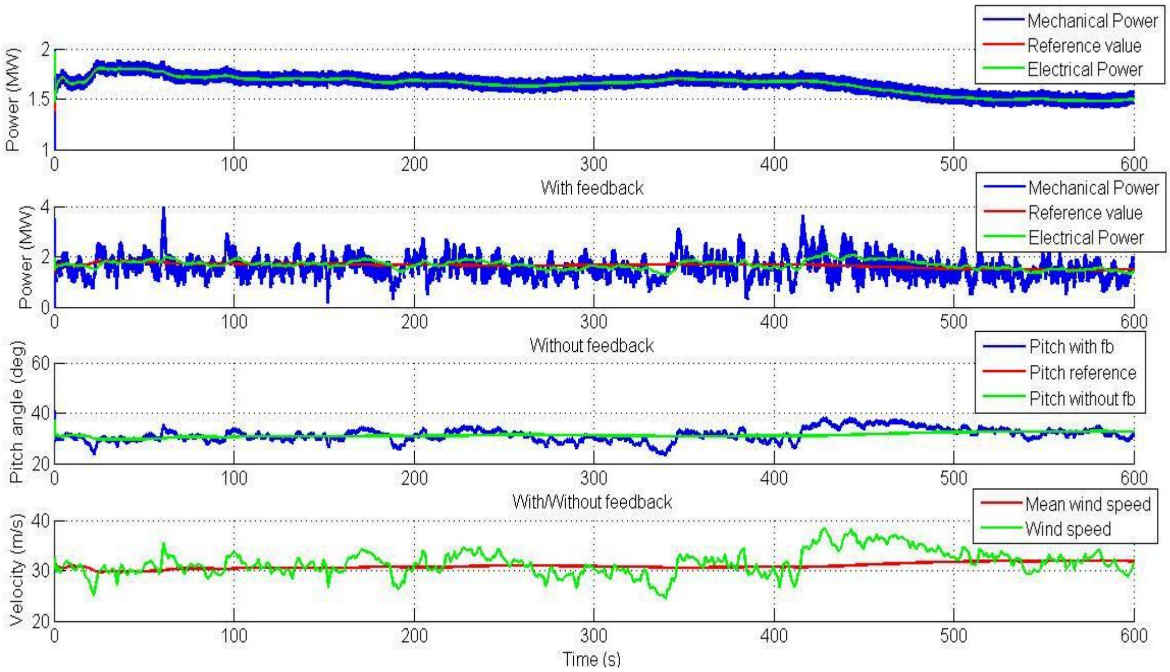

Figure 5. Power output and pitch angle of the wind turbine by feedforward control with/without feedback in high wind speed conditions.

Figure 6 shows the loads conditions of the wind turbine under feedforward control with and without feedback, including flapwise and edgewise bending moments of one blade, fore-aft and lateral bending moments of the tower. It is seen that the feedback control loop has the reduction effect of the amplitudes and the frequencies of the loads, thus improving the loads conditions.

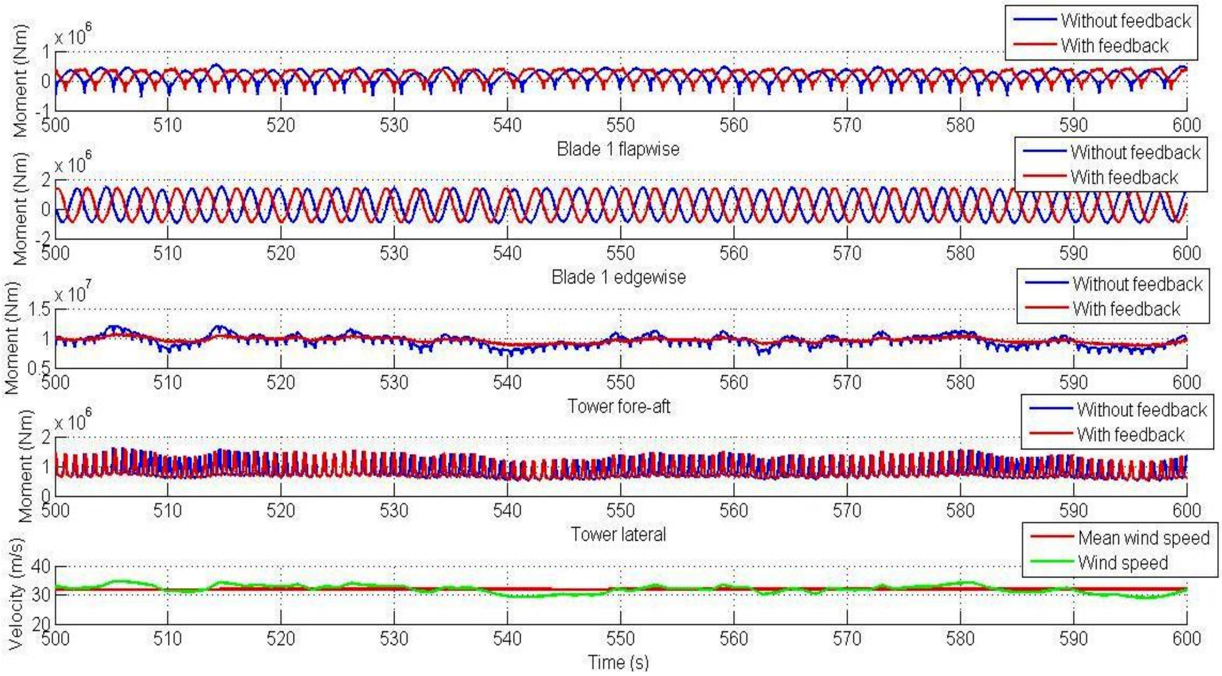

Figure 6. Blade bending moments and tower bending moments of the wind turbine by feedforward control with/without feedback in high wind speed conditions.

One advantage of the proposed control strategy is that it can be used in both high wind speed conditions and middle wind speed conditions without a transition procedure. In the middle wind speed conditions, i.e., with wind speeds above the rated wind speed 15 m/s and below the original cut-out wind speed 25 m/s, the wind turbine is operated to produce a constant power. The performance of the control strategy is shown in figure 7 and figure 8. Similar results can be found as in the high wind speed conditions.

To fully investigate the loads conditions of the wind turbine with the proposed control strategy, the statistics of the different loads of the wind turbine with different control schemas and in different wind speed conditions are given in table 1. Six cases are considered. It can be seen that the proposed control strategy can obtain the best loading results comparing to the other control schemas in high wind speed conditions (25-38 m/s), with regards to flapwise and edgewise bending moments of blade, fore-aft and lateral bending moments at the tower bottom, and also rotor thrust. In middle wind speed conditions (15-25 m/s), the proposed control strategy also shows a superiority over the control schema without feedback. Comparing the proposed control strategy's performance in different wind speed regions, it can be seen that maximums of the bending moments of the blade in high wind speed conditions are smaller than those in middle wind speed conditions, but the loads of the tower at high wind speeds are worse than those at middle wind speeds.

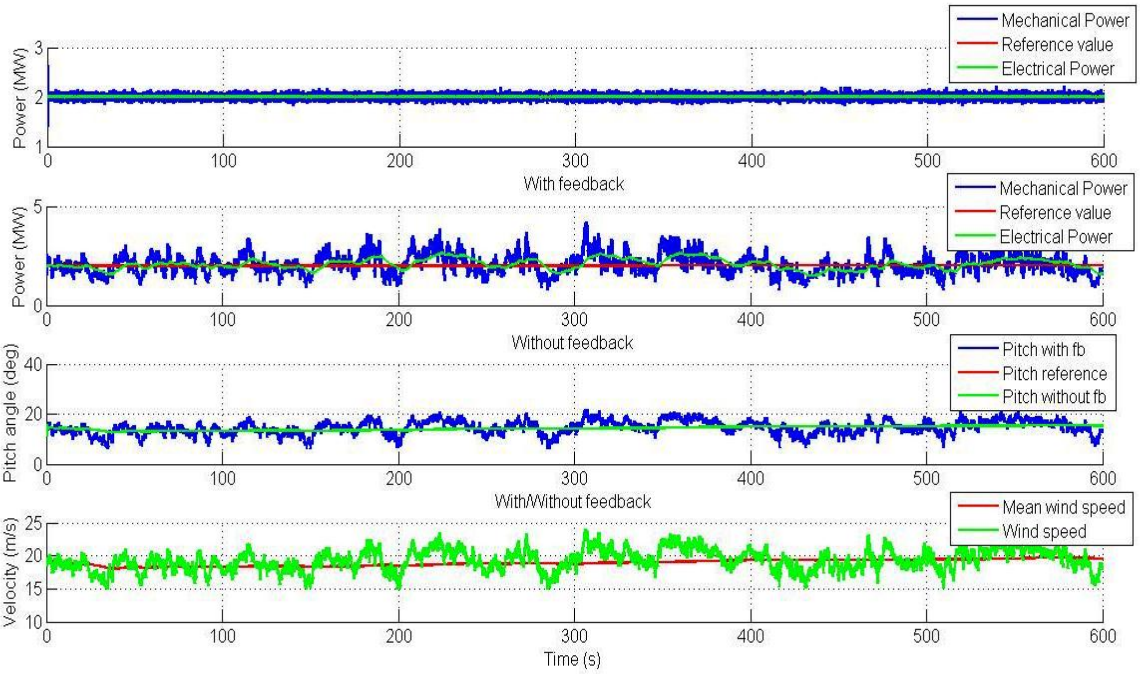

Figure 7. Power output and pitch angle of the wind turbine by feedforward control with/without feedback in middle wind speed conditions.

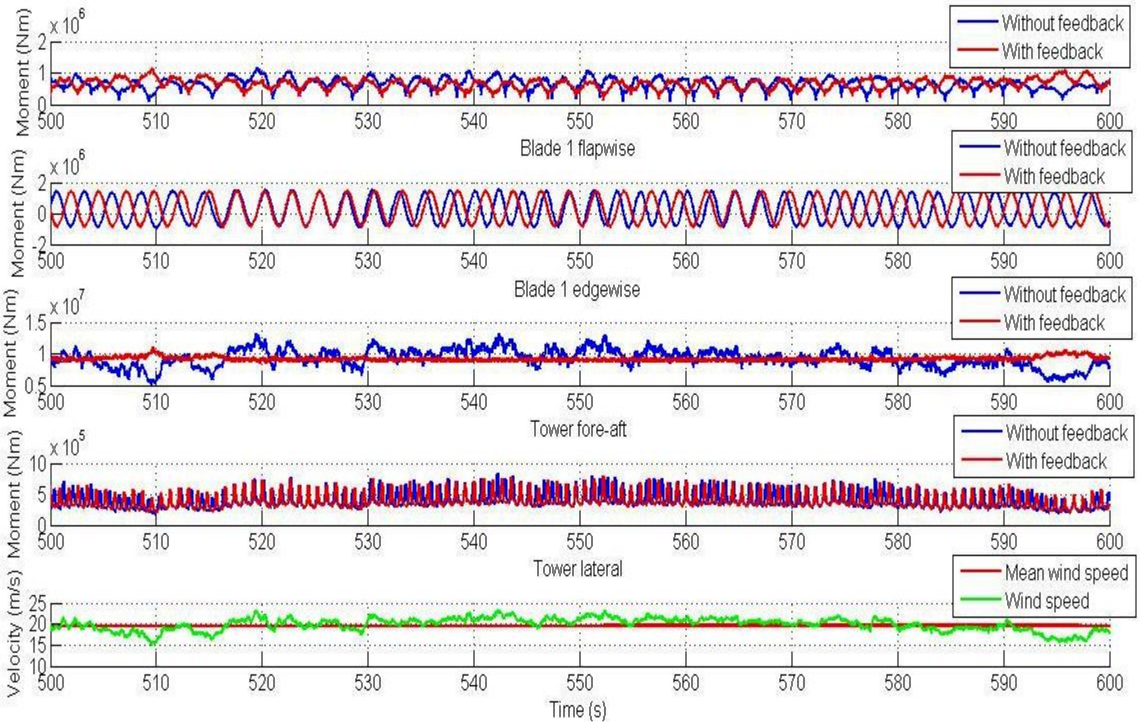

Figure 8. Blade bending moments and tower bending moments of the wind turbine by feedforward control with/without feedback in middle wind speed conditions.

Table 1. Loads statistics of the wind turbine with different control schemas and different wind speed conditions.

Case	Case Details			Blade Flapwise Bending Moment (kN·m)			Blade Edgewise Bending Moment (kN·m)		
Case No.	Control Schema[*]	Wind Speed	Reference Value	Max	Mean	Std	Max	Mean	Std
1	1fb+2ff	25-38	V_{mean} (360s)	571.9	201.9	192.1	1403.0	230.6	805.5
2	0fb+2ff	25-38	V_{mean} (360s)	790.9	200.3	210.8	1677.5	230.9	808.2
3	1fb+2ff	25-38	25	661.7	282.4	192.4	1442.0	277.1	805.9
4	0fb+0ff	25-38	/	1314.8	420.7	304.3	1740.8	275.3	813.3
5	1fb+2ff	15-25	V_{mean} (360s)	1149.8	686.9	160.4	1434.5	272.9	797.5
6	0fb+2ff	15-25	V_{mean} (360s)	1349.2	690.6	182.5	1623.8	271.6	799.9

Case	Rotor Thrust Force (kN)			Tower Bottom Fore-Aft Moment (kN·m)			Tower Bottom Lateral Moment (kN·m)		
Case No.	Max	Mean	Std	Max	Mean	Std	Max	Mean	Std
1	91.0	70.9	5.2	12294.0	9809.7	704.0	1880.9	782.3	246.0
2	139.9	71.6	14.0	15178.7	9847.6	1406.1	1971.7	786.9	251.0
3	103.1	83.5	4.4	12896.5	10513.3	678.5	1891.7	787.0	245.6
4	219.2	123.1	22.9	19619.7	12731.4	1951.3	2066.8	842.5	261.2
5	172.7	127.0	11.9	11042.9	9299.5	344.4	805.9	356.0	103.9
6	213.6	128.7	21.7	15310.8	9395.2	1533.2	861.8	355.4	109.1

[*] Note: ‘fb’ means the feedback control loop, ‘ff’ means the feedforward control loop, e.g., ‘Case 1’ (1fb+2ff) means the proposed control schema as in figure 4.

Taking the power output performance into consideration, it can be concluded that implementing the proposed control strategy in high wind speed conditions will smoothen the power output, vanish the sudden shut-downs, without worsening the loads of rotor and blades.

5. Conclusion

In this paper, control of variable speed wind turbines in strong wind conditions by using a combined feedforward and feedback technique is investigated. To illustrate the effectiveness, a modified variable speed pitch regulated 2 MW wind turbine is used with a set of field measured wind data ranging from 15 m/s to 40 m/s. By combing feedforward control loops based on optimization results and PI feedback control loop using error of power output, the control strategy can achieve quite good performance in power output smoothness without worsening the loads on rotor and blades. Since only mean wind speed averaged over a past short time is needed to get the reference values and schedule the control gains, this strategy is quite simple and easy to implement, while many other feedforward loops included control techniques need to employ advanced and expensive wind measuring and forecasting equipments. The proposed control strategy performs quite well both in high wind speed conditions (decreasing power region) and middle wind speed conditions (constant power region) and needs no transition procedure between these two regions. Although the loads on rotor and blades in high wind speed conditions are limited below the amplitudes in normal wind speed conditions, those on tower are worsened, which suggests that additional controller dealing with the loads on tower might be needed in future investigations.

Acknowledgements

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