Orthogonal Bases used for Feed Forward Control of Wind Turbines

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Abstract: In optimizing wind turbines it can be of a large help to use information of wind speeds at upwind turbine for the control of downwind turbines, it is, however, problematic to use these measurements directly since they are highly influenced by turbulence behind the wind turbine rotor plane. In this paper an orthogonal basis is use to extract the general trends in the wind signal, which are forward to the down wind turbines. This concept controller is designed and simulated on a generic 4.8 MW wind turbine model, which shows the potential of this proposed scheme.

1. INTRODUCTION

Improved control of wind turbines and wind farms are of increasing interest in order to improve the performance of wind turbines and farms with respect to a number of factors, which all in all deals with minimizing the production price per energy unit. One of the problems using more advanced type of control in wind turbine is the fact that wind measurements are difficult to obtain in a good quality. In a wind farm wind measurement from a turbine place upwind in relation to another turbine, could be used to predict further wind on a downwind turbine. The problem is, however, that this measurement is highly influenced by the turbulence behind the wind turbine blades.

A number of papers have been published regarding wind speed estimation for wind turbines. In Oestergaard et al. [2007] an estimator is designed to estimate the effective wind speed acting on the wind turbine. Other examples on wind speed estimations can be found in Boukhezzar and Siguerdidjane [2009], Odgaard et al. [2008] and Salas-Cabrera et al. [2010] in which different observer methods are used to estimate the wind speed. The basics of wind turbine and wind turbine control can be found in Johnson et al. [2006], Bianchi et al. [2007], Munteanu et al. [2008] and Burton et al. [2008].

Even though that it is difficult to use detailed information of the wind speed from an upwind turbine to a downwind turbine in the same direction, some information can be obtained. An increase in the wind speed will result in a wind speed increase at the downwind turbine delayed by a time interval given by the distance divided by the wind speed. A way to extract this trend in the wind speed from the upwind turbine wind speed measurement is to use an orthogonal basis to separate different trends and noises in the signal. Basically this method is related to the usage of wavelets to extract time-frequency based information from a signal, see Mallat [1999] or to construct a Karhunen-Loeve basis for extraction of the main signal trends, see citewickerhauser1994. Such schemes were used to design fault tolerant control of CD-players towards scratches and finger prints, see Odgaard et al. [2006] and Odgaard [2004].

In this paper some basis vectors are selected to support the main wind trends, these basis vectors are used to extract the major trends of the wind speed from the upwind turbines, placed on a row orthogonal to the wind direction. A wind trend signal is formed as the mean of the extracted trends from each upwind turbine. This wind trend signal is subsequently time shifted with the time delay between the wind turbines in the wind direction; this correction is multiplied with a feed forward gain before it is added to the control signal. It should be noticed that this scheme will improve the handling of wind gusts in a wind farm.

In Section 2 the wind turbine used in this work is introduced followed by a model description in Section 2.1. The proposed extraction scheme and controller structure can be seen in Section 3, followed by simulation of the scheme in Section 4. The paper is finalized with a conclusion in Section 5.

2. SYSTEM DESCRIPTION

In this paper a generic wind turbine of 4.8 MW described in Odgaard et al. [2009]. Notice that the model in this paper contains a number of fault scenarios which are disabled in the work presented in this paper. This turbine is a variable speed three blade pitch controlled turbine, with a front horizontal rotor.

2.1 Wind Turbine Model

The used wind turbine model are from, Odgaard et al. [2009], and is not described in details in this paper, the

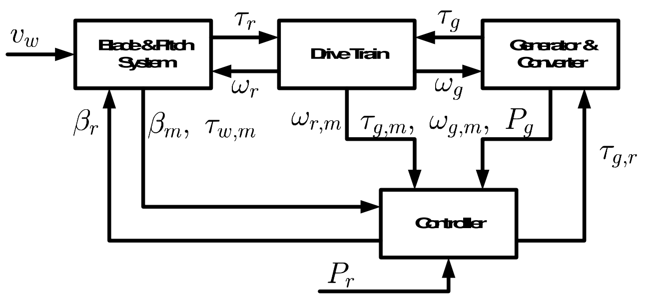

Fig. 1. This figure shows the overall model structure.

details can be found in the mentioned paper. An overview of the model can be seen in Fig. 1.

Each element of the model is shortly described.

2.1.0.1. Wind Model The wind speed is given by a wind model including turbulence, wind shear and tower shadow. In order to model the upwind and downwind turbine relation, it is assumed that the same wind trends is driving both turbines, with a time delay from the upwind to the downwind corresponding to the distance between turbines divided by the mean wind speed. The wind speed measurement used for the trend extraction is the modeled as the wind at the upwind turbine added with random noise.

2.1.0.2. Aerodynamic and Pitch Actuator Model Aerodynamics and pitch actuators are model in Blade and Pitch System model, the pitch actuator is modeled as a second order transfer function with constraints. The aerodynamics are modeled by a static mapping from the pitch angle, rotor and wind speeds to the torque acting on the wind turbine rotor.

2.1.0.3. Drive Train Model The drive train, which is used to increase the speed from rotor to generator, is modeled with a flexible 2 mass system. The drive train model includes the inertia of the rotor(which includes blades and the main shaft) and generator.

2.1.0.4. Converter Model The converter which controls the generator torque is modeled by a first order system with constraints. This model covers both the electrical behavior of the generator and converter.

2.1.0.5. Sensor Models The model contains a number of sensors, generator and rotor speed, pitch angles, wind speed, converter torque, electrical power. All the sensors are modeled as the measured variable added with random noise.

2.1.0.6. Controller The wind turbine operates in principle in 4 Regions, Region 1 in which wind speeds are too low for the wind turbine to operate, Region 2 in which the turbine operates up to a nominal wind speed (partial load), Region 3 between nominal and rated wind speed, where the nominal power can be produced, Region 4 above rated wind speed, where the wind turbine is closed down in order to limit extreme loads on the wind turbine.

The controller is active in Region 2 & 3. In Region 2, in which an optimal rotor speed, is obtained by using the converter torque as control signal. In Region 3 the rotor speed is kept at a given reference value by pitching the blades, (the converter keeps the power at the reference taking care of fast variations in the speed). In this paper only the second region control is considered.

3. WIND SPEED TREND EXTRACTION AND PREDICTION

3.1 Wind Speed Trend Extraction

The wind speed measurement of the upwind turbines is stored in time signal matrix with a given length K, and the number of upwind turbines are M, this matrix can be viewed as vectors of coefficient to each element in a time basis $<\mathbf{X}>$ for each wind turbine. This wind speed matrix is stored for each sample n, the vector is denoted $\mathbf{W}[n]$ and is defined as

$$\mathbf{W}[n] = \begin{bmatrix} w_1[n] & \dots & w_M[n] \\ w_1[n-1] & \dots & w_M[n-1] \\ \vdots & \ddots & \vdots \\ w_1[n-(K-1)] & \dots & w_M[n-(K-1)] \end{bmatrix}. \quad (1)$$

Now, assume a basis shift towards a basis which supports certain features in the signal $\mathbf{w}[n]$. This means that

$$\mathbf{W}[n]* <\mathbf{X}> = \mathbf{V}_B[n]* <\mathbf{B}>, \quad (2)$$

in which $\mathbf{V}_B$ is the coefficients of the wind measurement matrix in the new basis, and $<\mathbf{B}>$ is this new basis.

The interesting trends in the wind speed measurements can be supported by a few basis vectors if the basis is rightly designed. The remainder of the basis vectors supports the remaining energy in the measurement which do not relate to the general trend of wind.

The coefficients of these general trends are computed as

$$\mathbf{X}_w[k,n] = \mathbf{W}[n] * \mathbf{W}_k, \quad (3)$$

now compute $x_w[k,N]$ as the mean of the rows in $\mathbf{X}_w[k,n]$ such that a set of mean of coefficients over the different wind turbines are computed.

The extracted trend signal can be computed as

$$\mathbf{w}_{\text{trend}}[n] = x_w[k,n] * \mathbf{W}_k, \quad (4)$$

A number of possible trends can be interesting, the most dominating one is chosen as the trend prediction. In this example we are only considering changes in the wind speed, and therefore uses a basis vector $[-1,-1,-1,-1,-1,1,1,1,1,1]$. This means that

$$\mathbf{W}_1 = \begin{bmatrix} -1 \\ -1 \\ -1 \\ -1 \\ -1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \end{bmatrix}. \tag{5}$$

The remaining vectors in the basis are constructed to form an orthogonal basis. They are, however, not relevant in this scheme since they supports the parts of the wind signals which are not a part of this relevant trend, and can thereby be viewed as noises witch should be filtered out by this extraction. However, it might be relevant to include more than one basis vector to extract the relevant trends in the wind speed.

The wind trend at sample n is the last element of the vector $\mathbf{w}_{\text{trend}}[n]$, define this element as $w_{\text{trend}}[n]$

3.2 Prediction

Basically the wind moves with the wind speed meaning that a change in the wind speed will hit the downwind turbine delayed by the distance divided by the mean wind speed. It is, however, uncertain what this the time delay between turbines actually is.

This means that

$$w_{\text{ff}}[n] = w_{\text{trend}}[n - M], \tag{6}$$

where $w_{\text{ff}}[n]$ is wind speed component used in the feed forward part of the controller, and M denotes the delay period from the upwind turbine to the downwind turbine.

It should be noticed here that the scheme is sensitive to the prediction of time delay, which depends on the mean wind speed and wind direction, since the wind direction determines which turbines are in the upwind row of wind turbines and which turbines are in the downwind row of wind turbines. Due to the layout of the wind farm paired with the wind direction, a change in wind speed will not necessarily meet the upwind row of turbines at the same time, and the subsequently the downwind row of wind turbines. This means that these time differences within the rows of turbines should be taken into account then computing the wind trends as well as computing the feed forward signals.

In this paper the specific solution to this problem is not described, but an outline of the solution is given, the scheme is described in more details in Odgaard and Stoustrup [2011]. Basically the idea is to use an orthogonal basis formed by typical features in the wind speed measurement to extract features of the wind speed, the orthogonal basis used for this feature extraction could be Karhunen-Loeve basis formed by sets of wind data, for more details on this basis, see Wickerhauser [1994]. Subsequently it is determined at which time the specific features of the wind are computed for the different wind turbines. This enables a possibility to determine the wind direction and time delay from the upwind to the downwind turbines. This feature extraction gives time difference from the time that

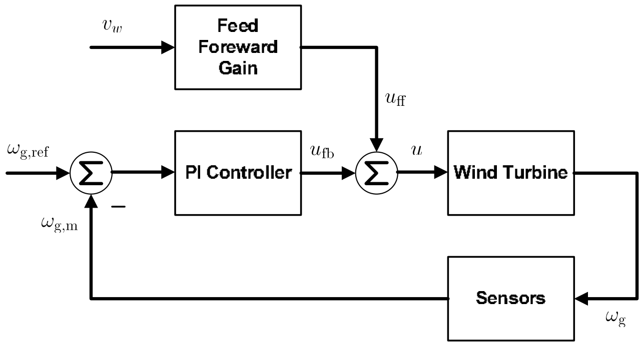

Fig. 2. This figure shows the outline of the control structure.

a certain wind feature is extracted at wind turbine to each of the other turbines in the farm. Combining these time differences/delays with the outline of the wind farm, the direction and time delay between upwind and downwind rows of turbines can be computed. Also the time difference with in the located rows should be taken into account in the computation of wind trend extractions and feed forward signals.

3.3 Controller Structure

The idea of this feed forward controller is to add a feed forward component to the control signal computed by the standard controller which uses the generator speed as feedback signal. In Fig. 2 the overview of the control structure is shown. The PI controller is the same as described in the System description, see Sec. 2.

The "Feed Forward Controller" consists of a gain multiplied with the $w_{\text{ff}}[n]$ value. This gain depends on the pitch angle at the starting point of the change in wind speed.

$$u_{\text{ff}}[n] = \alpha_{\text{ff}}(\beta_{\text{m}}[n]) \cdot w_{\text{ff}}[n], \tag{7}$$

where $\alpha_{\text{ff}}(\beta_{\text{m}}[n])$ is feed forward coefficient depending on mean value of the last 20 pitch angles, $\beta_{\text{m}}[n]$. e.g.

$$\beta_{\text{m}}[n] = \sum_{j=0:19} \beta[n-j], \tag{8}$$

In this design $\alpha_{\text{ff}}(\beta_{\text{m}}[n])$ is found to be

β	α_{ff}
0	0.34
9	0.32
10	0.28
11	0.24
12	0.2
13	0.18
14	0.16
16	0.12
18	0.10
20	0.08

4. SIMULATIONS

The proposed scheme is tested on the described simulation model. In the first scenario a step response is applied to the mean wind speed, the wind speed increases from 14 m/s to 16 m/s, the model also includes turbulence, wind

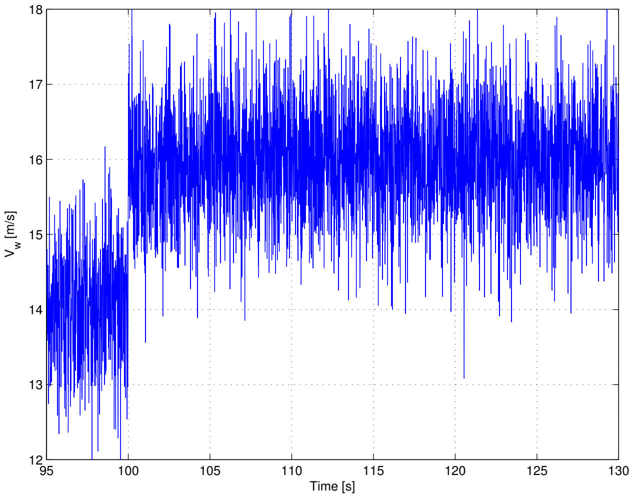

Fig. 3. This plot shows the wind speed (v_w) from 95 s to 130 s.

share and tower shadow. In the second scenario the wind speed increase with a constant gradient from 14 m/s to 24 m/s in 10s.

4.1 Scenario one - step in wind speed from 14m/s-16 m/s

In Fig. 3 the wind speed measured at the upwind turbine is plotted; this wind speed is delayed with approximately 6 s to the downwind turbine. In the Figs. 4-7 the outcome of the proposed scheme can be seen, by $\omega_r[n]$, $\omega_g[n]$, $\beta[n]$ and $\tau_r[n]$ respectively. From the plots of $\omega_r[n]$ and $\omega_g[n]$ it can be seen that the proposed scheme entirely removes the influence by a speed increase due to this step in the wind speed. The proposed scheme results in an increase in the pitch angle prior to the wind speed increases, as a reaction to the prediction of the wind speed, while the generator torque actually increases a bit in order to keep the generated power at the reference level, see fig. 6 and 7 respectively.

All in all it can be concluded that the proposed scheme in this scenario clearly keeps the rotor and generator speeds around their respective reference values, in comparison to the standard approach.

4.2 Scenario two - slope in wind speed from 14m/s-24 m/s

. In Fig. 8 the wind speed measured at the up wind turbine is plotted; this wind speed is delayed with approximately 6 s to the down wind turbine. In the Figs. 9-12 the outcome of the proposed scheme can be seen, by $\omega_r[n]$, $\omega_g[n]$, $\beta[n]$ and $\tau_r[n]$ respectively. From the plots of $\omega_r[n]$ and $\omega_g[n]$ it can be seen that the proposed scheme entirely removes the dc part of the speed increase due to this step in the wind speed, however, increases the variance of the speed signals. The proposed scheme results in an increase in the pitch angle prior to the wind speed increases, as a reaction to the prediction of the wind speed, while the generator torque actually increases a bit in order to keep the generated power at the reference level, see fig. 11 and 12 respectively.

All in all it can be concluded that the proposed scheme in this scenario clearly keeps the rotor and generator speeds

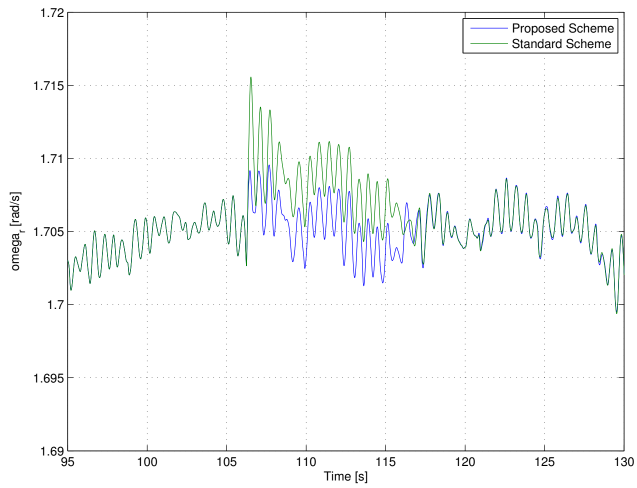

Fig. 4. This plot shows the rotor speed (ω_r) from 95 s to 130 s.

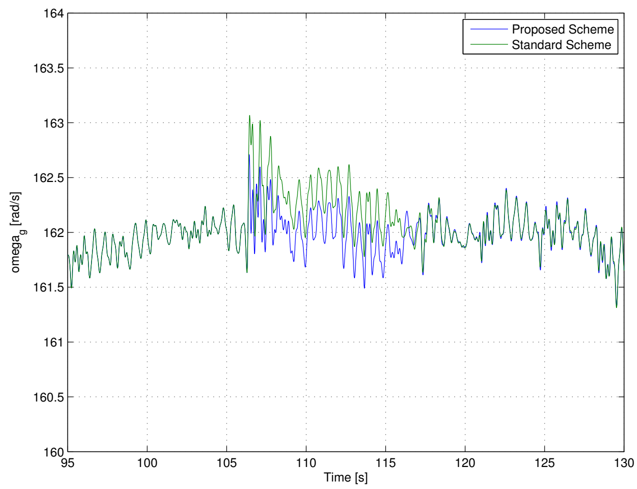

Fig. 5. This plot shows the generator speed (ω_r) from 95 s to 130 s.

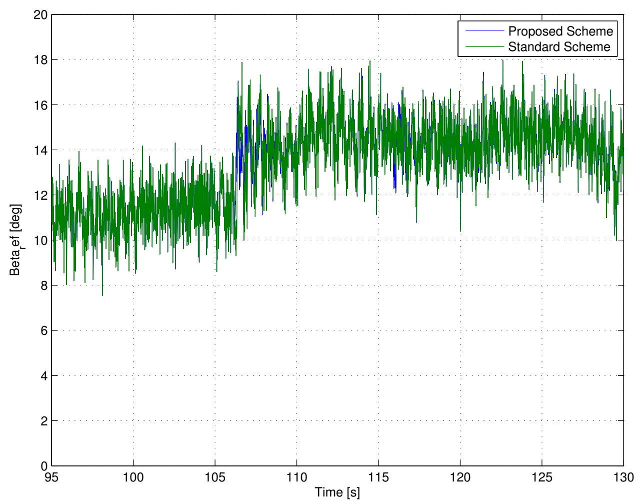

Fig. 6. This plot shows the pitch angle (β) from 95 s to 130 s.

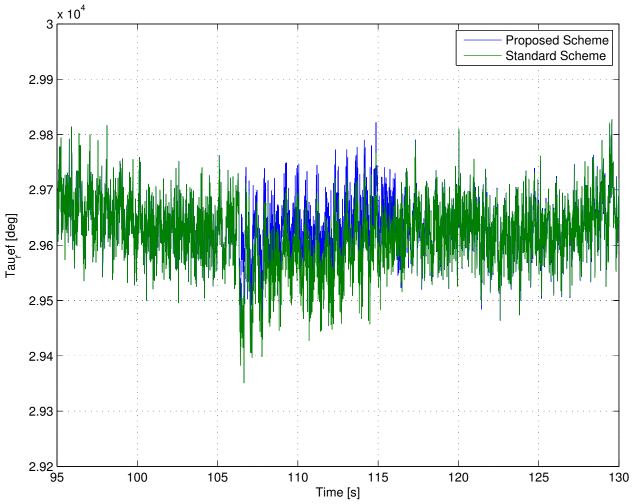

Fig. 7. This plot shows the generator torque (τ_r) from 95 s to 130 s.

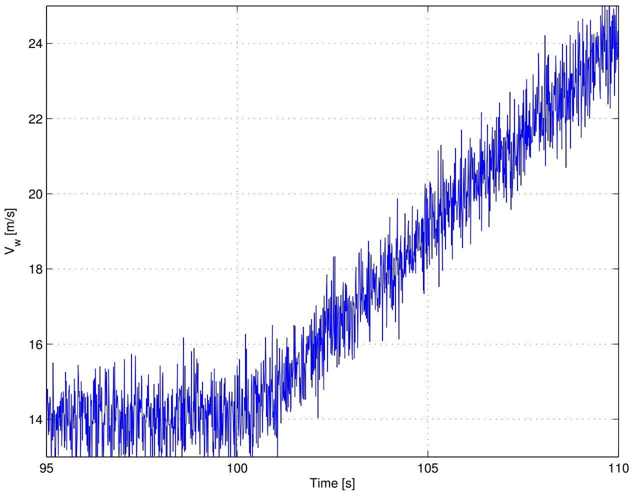

Fig. 8. This plot shows the wind speed (v_w) from 95 s to 110 s.

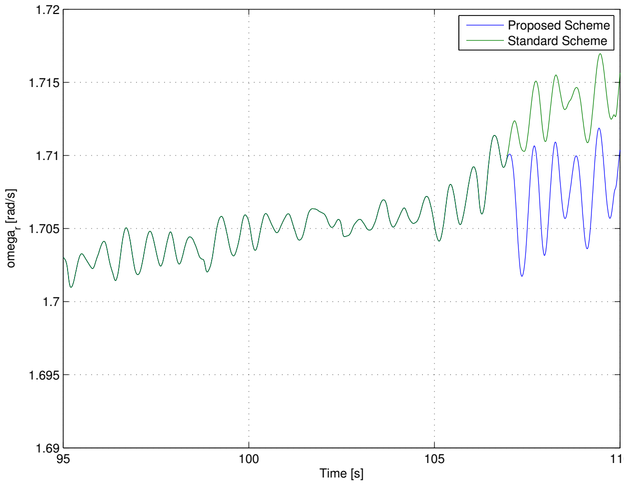

Fig. 9. This plot shows the rotor speed (ω_r) from 95 s to 110 s.

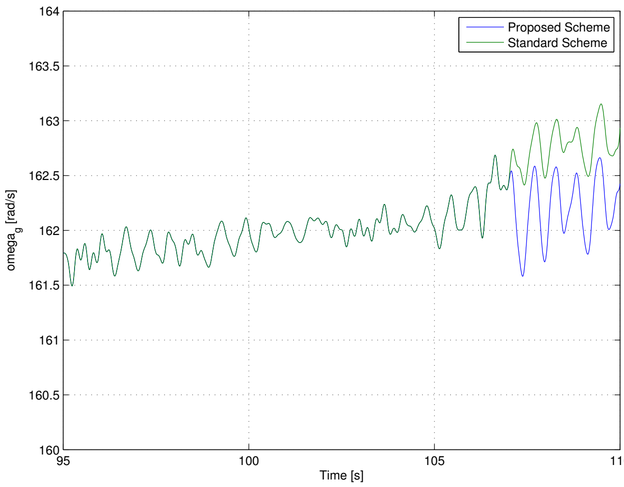

Fig. 10. This plot shows the generator speed (ω_r) from 95 s to 110 s.

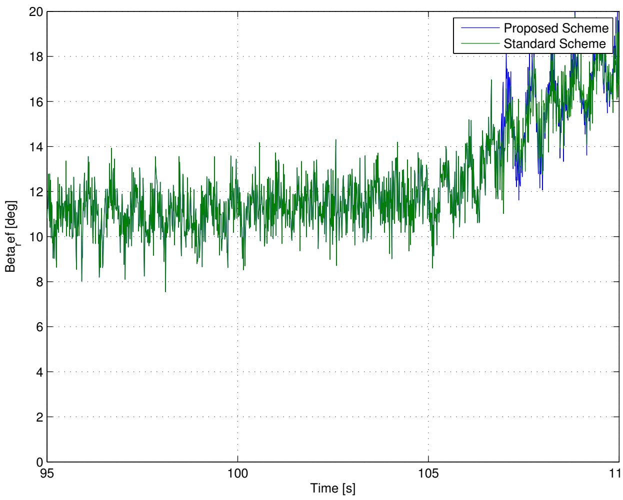

Fig. 11. This plot shows the pitch angle (β) from 95 s to 110 s.

around their respective reference values, in comparison to the standard approach, but with an increase in the variance of the control error.

4.2.0.7. Robustness Towards Uncertainties of the Time Delay Simulations have been made to find the consequences of the uncertain time delay of the wind between the upwind and downwind turbine. Time delays in the interval of -5%..5% of the time delay, have been simulated. From which it can be seen that the mean speed error is increasing from 0 to half of the error in case of no feed forward controller part. This means that the performance of the scheme might be lowered due to a wrong assumption of the time delay, but still results in an improvement compared with the standard control solution.

5. CONCLUSION

In this paper a scheme using elements of an orthogonal basis is used to extract wind trends from upwind turbines to be used as feed forward in a down wind turbine. The scheme is applied to a generic wind turbine model of

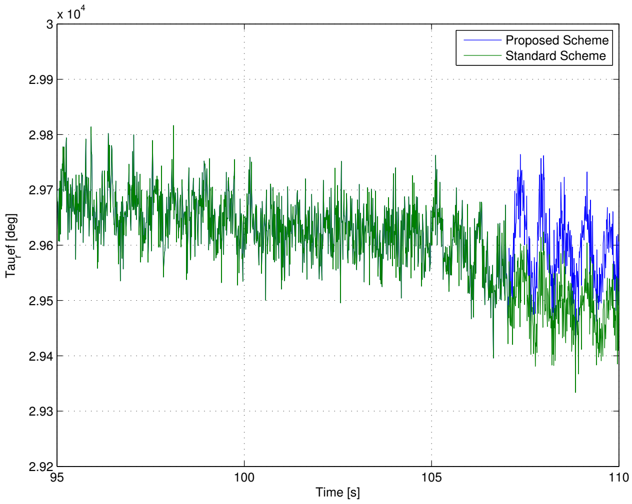

Fig. 12. This plot shows the generator torque (τ_r) from 95 s to 110 s.

a 4.8 MW turbine. Simulation shows that the proposed scheme has a potential to improve the control of wind turbines using extracted wind trends from an upstream wind turbine. In terms of keeping the rotor and generator speed constant in the full load region of the wind turbine even though large wind speed larges are present. It is of important to have correct timing of feed forward signal, which is based on a prediction of the time delay of the wind from the upwind to the down wind turbines. A study of the robustness towards this problem indicates that even though the performance of this proposed scheme decreases, it is still better than not using this feed forward correction.

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