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Nonlinear Control of Variable Speed Wind Turbines without wind speed measurement

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Abstract— **A nonlinear approach, for variable speed wind turbines control, is presented by considering that there is no wind speed measurement. The control objective below rated wind speed is to maximize the extracted energy from the wind while reducing mechanical loads. The existing control techniques do not take into account the dynamical aspect of the wind and the turbine, which leads to significant power losses, besides, they are not robust. In order to bring some improvement and to evaluate the applicability efficiency of the nonlinear controllers, so then, nonlinear static and dynamic state feedback controllers with wind speed estimator are derived. The controllers are tested upon a mathematical model and are validated with a wind turbine simulator, in presence of disturbances and measurement noise. The results indeed show significant improvements in comparison with the existing controllers.**

I. INTRODUCTION

Advances in wind turbine technology [1] made necessary the design of more powerful control systems. This is in order to improve wind turbines behavior, namely to make them more profitable and more reliable.
Compared to fixed speed turbines, variable speed wind turbines feature higher energy yields, lower component stress, and fewer grid connection power peaks. To be fully exploited, variable speed should be controlled in meaningful way. Many of the works in the wind energy conversion systems control deal with the optimization of the extracted aerodynamic power in partial load area. For this purpose, classical controllers have been extensively used, particularly the PI regulator [2], [3]. Optimal control has been applied in the *LQ* [4], and *LQG* form [5], [6].
Robust control of wind energy conversion systems (WECS) has been introduced in [7] and also used in [8] - [9].
By assuming the wind turbine operating in steady state conditions, most of these papers do not take into consideration the dynamical aspect of the wind and the turbine, because wind energy conversion systems have strong nonlinear characteristics. Furthermore, in the major part of these investigations, the wind speed is assumed to be measurable. In spite of using an anemometer to measure the wind speed, the obtained value is, as matter of fact, different from the one that appears in the wind turbine model equations, since its a mean value. The objective of this work is to design robust nonlinear controllers that take into consideration the dynamical aspect of the wind speed and the wind turbine, without a need of wind speed measurement.
This paper is organized as follows : Section II describes the wind turbine modelling, the control objectives are exposed. Section III briefly recalls some existing control techniques, the aerodynamic torque and wind speed estimators are described. A nonlinear static and dynamic state feedback linearization with asymptotic rotor speed reference tracking are developed in order to reach the required specifications : In section IV, simulation results show quite good performance of the proposed approach on the basis of the mathematical model and have been validated through a wind turbine simulator.

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II. WIND TURBINE MODELLING

A. system modelling

The power extraction of wind turbine is being known to be a function of three main parameters : the wind power available, the power curve of the machine and the ability of the machine to respond to wind fluctuations [10]. The global scheme of a variable speed wind turbine is displayed in Fig. 1. Roughly speaking, a variable speed wind turbine (FPVS), mainly consists of an aeroturbine, a gearbox and a generator.
The expression for aerodynamic power captured by the wind turbine is given by the nonlinear expression

$$P_a = \frac{1}{2}\rho\pi R^2 C_p(\lambda,\beta)v^3 \quad (1)$$

where

$$\lambda = \frac{\omega_r R}{v}$$

is the so-called tip speed ratio, namely the ratio between the linear blade tip speed and the wind speed v. R is the rotor radius, β is the blades pitch angle.
For the reader convenience, table of the symbols description is given at the end of this paper.
So, any change in the rotor speed or the wind speed induces change in the tip-speed ratio, thus leading to the power coefficient $C_p(\lambda,\beta)$ variation and therefore to the generated power one. The $C_p(\lambda,\beta)$ curve is displayed in Fig. 3.
The aerodynamic power is

$$P_a = \omega_r T_a \quad (2)$$

where the aerodynamic torque T_a expression is

$$T_a = \frac{1}{2}\rho\pi R^3 C_q(\lambda,\beta)v^2 \quad (3)$$

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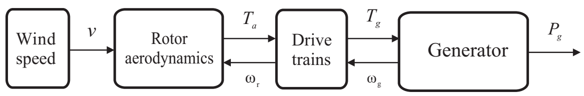


Fig. 1. Wind turbine scheme

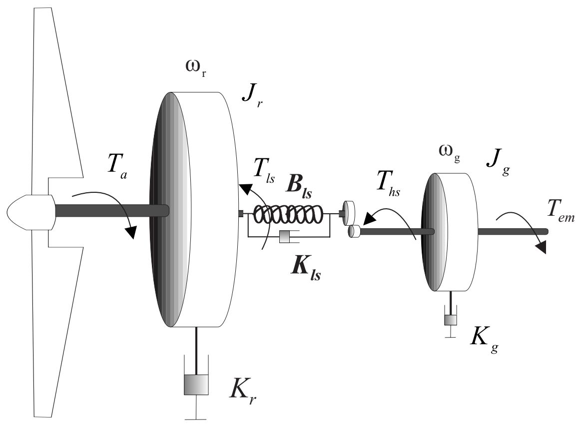


Fig. 2. Drive train dynamics

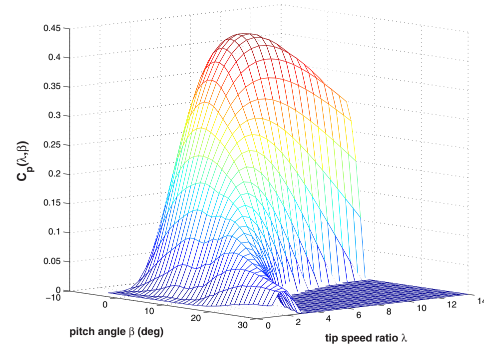


Fig. 3. Power coefficient curve

where

$$J_t = J_r + n_g^2 J_g$$
$$K_t = K_r + n_g^2 K_g$$
$$T_g = n_g T_{em}$$

$C_q(\lambda,\beta)$ is the torque coefficient depending nonlinearly upon the tip speed ratio.
From equations (1)-(3), it comes out that

$$C_q(\lambda,\beta) = \frac{C_p(\lambda,\beta)}{\lambda}$$

Driving by the aerodynamic torque T_a, the rotor of the wind turbine runs at the speed ω_r. The low speed shaft torque T_{ls} acts as a braking torque on the rotor (Fig. 2).
The dynamics of the rotor is characterized by the first order differential equation

$$J_r\dot{\omega}_r = T_a - T_{ls} - K_r\omega_r \tag{4}$$

the low speed shaft results from the torsion and friction effects due to the difference between ω_r and ω_{ls}

$$T_{ls} = B_{ls}(\theta_r - \theta_{ls}) + K_{ls}(\omega_r - \omega_{ls}) \tag{5}$$

The generator is driven by the high speed shaft torque T_{hs} and braked by the generator electromagnetic torque T_{em}.

$$J_g\dot{\omega}_g = T_{hs} - K_g\omega_g - T_{em} \tag{6}$$

Through the gearbox, the low shaft speed ω_{ls} is increased by the gearbox ratio n_g to obtain the generator speed ω_g while the low speed shaft T_{ls} torque is augmented.

$$n_g = \frac{T_{ls}}{T_{hs}} = \frac{\omega_g}{\omega_{ls}} \tag{7}$$

the generator dynamics are brought back to the low speed side,

$$n_g^2 J_g\dot{\omega}_{ls} = T_{ls} - n_g^2 K_g\omega_{ls} - n_g T_{em} \tag{8}$$

if a perfectly rigid low speed shaft is assumed, $\omega_r = \omega_{ls}$, a one mass model of the turbine can then be considered

$$J_t\dot{\omega}_r = T_a - K_t\omega_r - T_g \tag{9}$$

B. control objectives

The wind speed time repartition makes that, in most of time, the wind turbines are operating in wind speed less than rated one, hence the importance of control efficiency arises in this operating regime. While energy is captured from the wind, the aerodynamic power should be maximized below rated wind speed.
The $C_p(\lambda,\beta)$ curve involved in the aerodynamic power expression (1) has a unique maximum

$$C_p(\lambda_{opt},\beta_{opt}) = C_{p_{opt}} \tag{10}$$

that corresponds to a maximum power production, where

$$\lambda_{opt} = \frac{\omega_{opt}R}{v} \tag{11}$$

For this, in the below rated power area, to maximize wind power extraction, the blades pitch angle β is fixed to the optimal value β_{opt} and in order to maintain λ at its optimal value, the rotor speed must be adjusted to track the reference ω_{opt} which has the same shape as wind speed since they are proportional.

$$\omega_{opt} = \frac{\lambda_{opt}}{R}v \tag{12}$$

the objective of the controller is to track the optimal rotor speed ω_{opt} that ensure the best power efficiency while reducing control loads.

III. CONTROL STRATEGY

In variable speed wind turbines, the generator is connected to the grid via a rectifier and inverter. When connecting the generator to the grid via the frequency converter, the generator rotational speed ω_g will thus be independent of the grid frequency.
The wind turbine is controlled through the adjustment of the

generator torque. The choice of T_{em} as a control input is motivated by the fact that when controlling the firing angle of the converter, it is possible to control the electrical torque in the generator. Well known control strategies have been used and achieve a fast and decoupled responses of torque and flux like vector control [11], [12] and Direct Torque Control (DTC) [13]. The torque control using the frequency converter allows the wind turbine to run at variable speed resulting in the reduction of the drive train mechanical stress and electrical power fluctuations, and also the increase of power capture [2].

In this context, the dynamics are sufficiently fast that no distinction needs to be made between the actual and the demanded generator torque. In the aim of making a comparison between the proposed and existing control laws, a brief description of these last ones is given below.

In [14], an Aerodynamic Torque Feed forward (ATF) is used, the aerodynamic torque T_a and the rotor speed ω_r are estimated using a Kalman Filter. The estimated aerodynamic torque is fed into the generator torque reference. It is also mentioned in [14] that since the tracked wind speed constantly changes , no need for eliminating the steady-state error with an integral action. Therefore, a proportional controller is used

$$T_g = K_c(\hat{\omega}_r - \omega_{ref}) + \hat{T}_a - K_t\hat{\omega}_r \tag{13}$$

where

$$\omega_{ref} = \sqrt{\frac{\hat{T}_a}{k_t}} \tag{14}$$

with

$$k_t = \frac{\rho}{2}\pi R^5 C_{p_{opt}} \frac{1}{\lambda_{opt}^3}$$

However, a steady state error remains, particularly in presence of disturbances. An additional drawback of this technique is that it assumes the wind turbine operating near the optimal rotor speed, from which by setting, $\hat{T}_a = T_{a_{opt}}$ with

$$T_{a_{opt}} = \frac{1}{2}\rho\pi R^2 C_{p_{opt}} v^3 \tag{15}$$

the ω_{ref} expression comes out [15]. The difference between ω_{opt} and ω_{ref} will induces significant power losses during the transitions. Therefore, a more precise value of ω_{ref} is needed.

In [16], it is shown that a wind turbine is stable around any point of the optimal aerodynamic efficiency curve. One can maintain T_a on this curve by choosing a control torque T_g that tracks the same value instead of wind speed variations. The T_g expression is then deduced

$$T_g = k_t\omega_r^2 - K_t\omega_r \tag{16}$$

This method is known as the Indirect Speed Control (ISC) technique. Nevertheless, the transitions during fast wind speed variations are followed by power losses. Add to this, the control strategy is not robust with respect to measurement noise and disturbances.

In a summary, the control techniques presented above show two main drawbacks : on the one hand, they do not take into consideration the dynamical aspect of the wind and the turbine, on the other hand, they are not robust with respect to measurement noise and disturbances. In order to go over these drawbacks, a nonlinear dynamic state feedback will be presented, it will be used with a wind speed estimator in the aim of taking into consideration its dynamical aspect. Furthermore, this structure allows the rejection of disturbances acting on the control torque T_g.

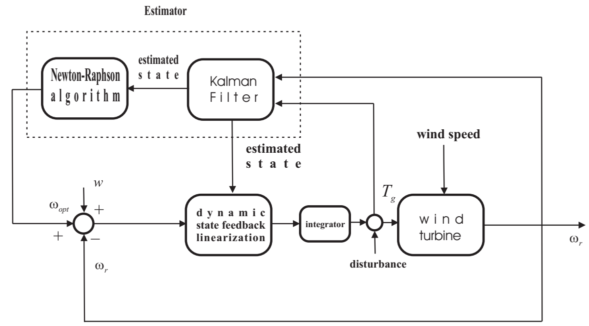


Fig. 4. Nonlinear Dynamic State Feedback with estimator controller scheme

A. aerodynamic torque estimation

The wind speed varies over the disc swept by the rotor [2], consequently, it is impossible to represent the rotor wind speed by a unique measure. The wind speed measured by the turbine anemometer is an approximation of the one that appears in the aerodynamic torque expression (3), and that is called *rotor effective wind speed*, it is defined as a single point wind speed signal which will causes wind torque variations through rotor power and thrust coefficients, that will be stochastically equivalent to those calculated through blade element theory in turbulent wind field [17]. In the aim of obtaining a more coherent value of v and to control the wind turbine without using anemometer, one can use the wind turbine as a measurement device. For this, one can proceed in two steps : aerodynamic torque estimation and wind speed deduction.

The Kalman filter has been used in the literature for aerodynamic torque estimation [4], [14]. The basic principle is herein to include T_a as an extended state of which dynamics are driven by a white noise.

$$\begin{aligned}
\begin{bmatrix} \dot{\omega}_r \\ \dot{T}_a \end{bmatrix} &= \begin{bmatrix} -\frac{K_t}{J_t} & \frac{1}{J_t} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \omega_r \\ T_a \end{bmatrix} + \begin{bmatrix} -\frac{1}{J_t} \\ 0 \end{bmatrix} T_g + \begin{bmatrix} 0 \\ 1 \end{bmatrix} \xi \\
y &= \omega_r + w
\end{aligned} \tag{17}$$

ξ is the process noise and w the measurement noise.

In the approaches using Kalman filter, the estimated state is not exploited to deduce the optimal reference speed ω_{opt}.

In this work, the estimated state $\left[\hat{\omega}_r\ ,\ \hat{T}_a\right]^t$ is used to obtain an estimate of the effective wind speed $\hat{v}$ from which the optimal rotor speed is derived.

B. wind speed estimation

The effective wind speed v is related to T_a by the aerodynamic torque expression

$$T_a = \frac{1}{2}\rho\pi R^3 C_q(\lambda)v^2 \tag{18}$$

where

$$C_q(\lambda) = C_q(\lambda, \beta_{opt})$$

$C_q(\lambda)$ is defined using a look-up table. Nevertheless, to solve equation (18) for v, using numerical algorithms, an analytic expression of $C_q(\lambda)$ is needed. It is then approximated using a polynomial in λ.

$$C_q(\lambda) = \sum_{i=0}^{n} a_i \lambda^i$$

the estimate of the wind speed $\hat{v}$ is obtained by solving the following algebraic equation

$$\hat{T}_a - \frac{1}{2}\rho\pi R^3 C_q\left(\frac{\hat{\omega}_r R}{\hat{v}}\right)\hat{v}^2 = 0 \tag{19}$$

The Newton-Raphson algorithm is then used to solve equation (19). As this equation has a unique solution, that is contained in the below rated wind speed range, the convergence of the algorithm is obtained after a few iterations only. $\hat{v}$ is used to obtain $\hat{\omega}_{opt}$

$$\hat{\omega}_{opt} = \frac{\lambda_{opt}\hat{v}}{R} \tag{20}$$

C. nonlinear static state feedback control with estimator

From the estimate of the optimal rotor speed and the aerodynamic torque, a static state feedback linearization control technique with asymptotic rotor speed reference tracking is used. A chosen dynamics is then imposed to the rotor speed tracking error $\hat{\varepsilon}$.

$$\dot{\hat{\varepsilon}} + a_0\hat{\varepsilon} = 0 \tag{21}$$

where

$$\hat{\varepsilon} = \hat{\omega}_{opt} - \hat{\omega}_r \tag{22}$$

from equations (9) and (21), the obtained control torque is

$$T_g = \hat{T}_a - K_t\hat{\omega}_r - J_t a_0\hat{\varepsilon} - J_t\dot{\hat{\omega}}_{opt} \tag{23}$$

D. nonlinear dynamic state feedback control with estimator

The static state feedback linearization control technique is not so robust with respect to perturbations [18].
Even if the system can be linearized by a static state feedback, one can impose a higher order dynamics to the tracking error for getting a dynamic state feedback. Let us chose a second order dynamics, the tracking error $\hat{\varepsilon}$ is governed by the following differential equation

$$\ddot{\hat{\varepsilon}} + b_1\dot{\hat{\varepsilon}} + b_0\hat{\varepsilon} = 0 \tag{24}$$

From (9) and (24), it comes out

$$\dot{T}_g = \dot{\hat{T}}_a - K_t\dot{\hat{\omega}}_r - J_t\ddot{\hat{\omega}}_{opt} - J_t b_1\dot{\hat{\varepsilon}} - J_t b_0\hat{\varepsilon} \tag{25}$$

A very fast dynamics will lead to the tracking of the wind speed turbulence and also to large control loads. The choice of this dynamics must lead to track the average wind speed above small time intervals. The scheme of the dynamic state feedback controller, without wind speed measurement is given in Fig. 4. All the derivatives that appear in the generator torque expression (23) and (25) are obtained using an approximated filtered derivatives.

TABLE I

WIND TURBINE CHARACTERISTICS

Rotor diameter	43.3 m
gearbox ratio	43.165
Hub height	36.6 m
Generator system electrical power	650 KW
Maximum rotor torque	162 KN.m

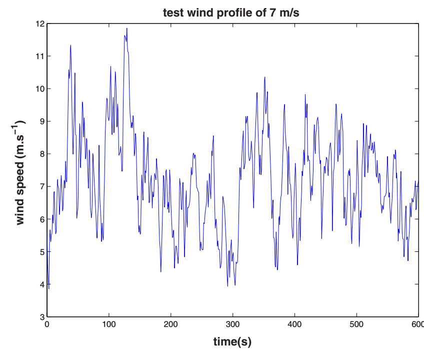


Fig. 5. Wind speed profile of 7 m.s^{-1} mean value

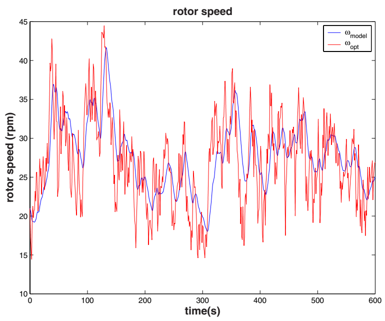
IV. VALIDATION RESULTS

As already mentioned, the wind turbine considered in this study is variable speed, variable pitch one. It consists of two blades rotor coupled with a gearbox. The high speed shaft drives an induction generator connected to the grid via a power electronics device. The numerical simulations have been performed using a wind turbine whose characteristics are given in TABLE I. The validation tests have been performed using a wind turbine simulator.[1]. The applied input wind speed profile of 7 m.s^{-1} mean value is shown in Fig. 5

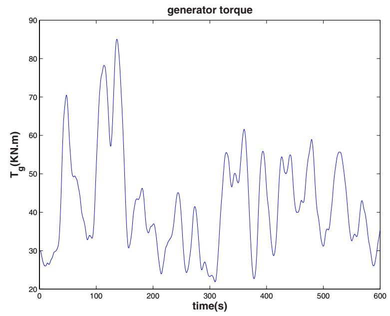
A. Using the model

First, the mathematical model is used with the proposed controllers. A measurement noise on ω_r as well as a disturbance of 10 KN.m on the control torque T_g have been introduced. The simulation results show that the required performance are reached using the nonlinear dynamic state feedback controller with estimator (NDSFE). In Fig. 6(a), one can check that the rotor speed ω_r tracks the mean tendency of the optimal rotational speed ω_{opt} without tracking the turbulent component. This led to acceptable control loads, as depicted in Fig. 6(b), that remains below the maximum value of T_g (162 KN.m).

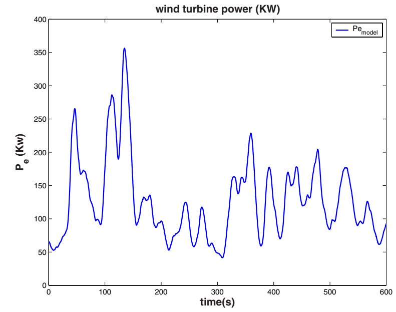
[1]developed by NREL (National Renewable Energy Laboratory), Golden, CO.



(a) rotor speed

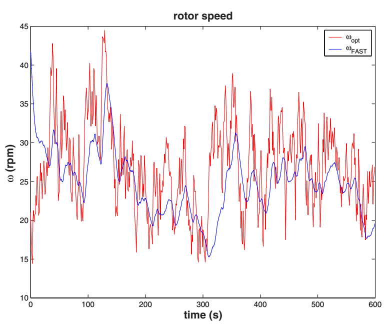


(b) generator torque

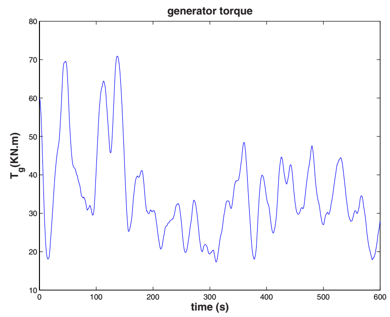


(c) generator power

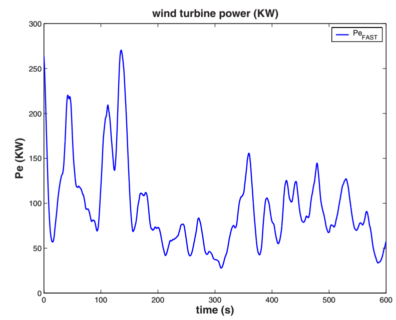
Fig. 6. Tests of the nonlinear dynamic state feedback controller, with estimator, upon the mathematical model



(a) rotor speed



(b) generator torque



(c) generator power

Fig. 7. Validation of the nonlinear dynamic state feedback controller, with estimator, by using the wind turbine simulator

B. Validation by using the wind turbine simulator

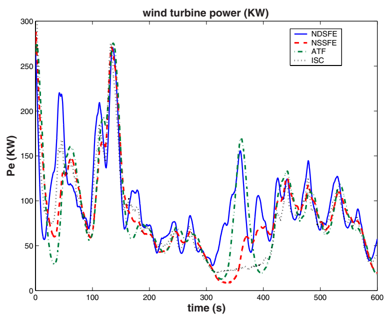
The validation of the controllers has been carried out upon the wind turbine simulator. The obtained performance are shown to be as expected using the dynamic state feedback controller with estimator. As Fig. 7(a) shows, the rotor speed variations remain smooth, without big fluctuations, while tracking the mean tendency of the optimal rotational speed. That ensures an optimal power extraction from the wind, so the oscillations will be reduced in the drive train components. The generator torque T_g with the simulator (Fig. 7(b)) , remains below the maximum acceptable value, with smooth variations. That induces low frequency variations in the generator currents, in other words, a better preservation of the electrical wind turbine devices. The Nonlinear Dynamic State Feedback Linearization, with estimator (NDSFE) controller ensures the rejection of the disturbance on the control torque. In the same way, the Kalman filter used with the Newton-Raphson algorithm provides a good estimate of the wind speed, the aerodynamic torque as well as the rotor speed from a noisy measurement of ω_r.

In order to evaluate the contribution level of the proposed controller, a comparison is made between the different controllers. The simulations have been carried out using the wind turbine simulator, under the same operating conditions on disturbance and measurement noise. The obtained performance with the different controllers are shown in Fig. 8 and summarized in TABLE II. One can observe in Fig 8(a) that the produced electric power using the NDSFE is a little bit more significant. The low speed shaft torque oscillations are also shown to be reduced using the NDSFE strategy, as depicted in Fig. 8(b). One notice that the performance of the three first controllers remain close. On the other hand, one can note that the dynamic state feedback controller with estimator allows an improvement of 10% of the efficiency compared to the indirect speed controller with a decrease of 1.18 KN.m on the standard deviation of the low speed shaft torsional torque T_{ls}.

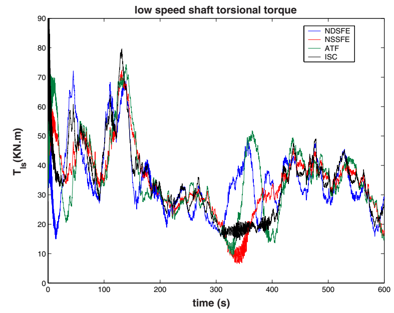
V. CONCLUSION

Nonlinear feedback controllers, with wind speed estimator have been developed for wind turbine control. The objectives are to synthesize robust controllers that maximize the energy extracted from the wind while reducing mechanical loads.

It has been proposed, herein, controllers based on dynamic state feedback linearization technique, with asymptotic rotor speed reference tracking, combined with an aerodynamic torque and wind speed estimator. The dynamic aspects of the wind and the turbine were taken into account leading to good performance. The control strategy has been validated with an aeroelastic wind turbine simulator and has led to satisfactory results, which indeed points out the efficiency level of the developed controllers in comparison with those presented in the existing literature.



(a) electrical power



(b) low speed shaft torque

Fig. 8. Electrical power and low speed shaft torque using the different control strategies

TABLE II

COMPARISON OF THE DIFFERENT CONTROL STRATEGIES

	Efficiency [%]	T_{hs} standard deviation [KN.m]
ISC	59.01	12.77
NSSFE	61.28	11.87
ATF	63.49	13.19
NDSFE	70.01	11.59

NOTATION AND SYMBOLS

v	wind speed $(\mathrm{m}\cdot\mathrm{s}^{-1})$.
ρ	air density $(\mathrm{kg}\cdot\mathrm{m}^{-3})$.
R	rotor radius (m).
P_a	aerodynamic power (W).
T_a	aerodynamic torque $(\mathrm{N}\cdot\mathrm{m})$.
λ	tip speed ratio.
β	pitch angle (deg).
$C_p(\lambda,\beta)$	power coefficient.
$C_q(\lambda,\beta)$	torque coefficient.
ω_r	rotor speed $(\mathrm{rad}\cdot\mathrm{s}^{-1})$.
ω_g	generator speed $(\mathrm{rad}\cdot\mathrm{s}^{-1})$.
T_{em}	generator (electromagnetic) torque $(\mathrm{N}\cdot\mathrm{m})$.
T_g	generator torque in the rotor side $(\mathrm{N}\cdot\mathrm{m})$.
T_{ls}	low speed shaft $(\mathrm{N}\cdot\mathrm{m})$.
T_{hs}	high speed shaft $(\mathrm{N}\cdot\mathrm{m})$.
J_r	rotor inertia $(\mathrm{kg}\cdot\mathrm{m}^2)$.
J_g	generator inertia $(\mathrm{kg}\cdot\mathrm{m}^2)$.
J_t	turbine total inertia $(\mathrm{kg}\cdot\mathrm{m}^2)$.
K_r	rotor external damping $(\mathrm{Nm}\cdot\mathrm{rad}^{-1}\cdot\mathrm{s}^{-1})$.
K_g	generator external damping $(\mathrm{Nm}\cdot\mathrm{rad}^{-1}\cdot\mathrm{s}^{-1})$.
K_t	turbine total external damping $(\mathrm{Nm}\cdot\mathrm{rad}^{-1}\cdot\mathrm{s}^{-1})$.
K_{ls}	low speed shaft damping $(\mathrm{Nm}\cdot\mathrm{rad}^{-1}\cdot\mathrm{s}^{-1})$.
B_{ls}	low speed shaft stiffness $(\mathrm{Nm}\cdot\mathrm{rad}^{-1})$.

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