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Degradation of a wind-turbine drive-train under turbulent conditions : effect of the control law

Elena E. Romero¹, John J. Martinez¹ and Christophe Bérenguer¹

Abstract—This work compares the simulated degradation produced at the drive-train of a given wind turbine when it is functioning at optimal and sub-optimal operating points. The simulation considers different classes of wind conditions and supposes the use of the same Maximum Power Point Tracking (MPPT) algorithm but calibrated with different feedback gains. The dissipation at the drive-train is modeled using contact mechanics principles, and it is intended for modeling the mechanical fatigue due to changes in wind speed and turbulence. The paper presents the proposed model for the drive-train degradation and the obtained power curves for a simulated variable-speed 2MW (100m rotor diameter) wind turbine, with fixed gear box and horizontal-axis.

I. INTRODUCTION

Nowadays, the growing interest in the renewable energy market has driven research in wind turbines. This sector grew up near 53% in 2020, installing more than 93 GW of wind power, and some experts expect that over 469 GW of new wind capacity will be installed in the next five years. Nevertheless, some disbelief is still associated with the numerous random factors that can affect the profitability of this technology [1]. The nature of the wind can be the origin of unexpected fatigue damage by the aerodynamic loads that create deformations of the drive-train, reducing the useful life of the turbine and raising the cost of the energy [2].

The wind turbine drive-train is a complex mechanical system where many load modes can induce different problems. Among all the faults of wind turbines, the transmission faults occur more frequently and usually lead to the most extended maintenance works and excessive maintenance cost [3]. In this regard, the analysis of these parts of the system has been the high interest for the industry and the academia, providing numerous methods to know the torsional loads and fatigue behaviors [4],[5]. Nevertheless, many designed models may result in unstable mechanical modes, because they ignore the dynamics of the flexible shaft [6], resulting in inaccurate estimation. The dissipated energy has been suggested as an indicator of damage produced by tower top displacements [7]. A similar degradation principle could be used to model degradation on other wind turbine components.

On the other hand, steady wind speed can cause less vibration on a wind turbine shaft compared to the case with

the same average but high turbulence intensity wind speed. The latter may cause sudden overloads to the shaft leading to its degradation. Therefore, to obtain a complete image of the effects of wind conditions on the shaft degradation, the automatic control system must be taken into account [8].

This paper presents a novel shaft model, for Variable-Speed Fixed-Pitch wind turbines, to simulate the drive-train degradation produced by the system's operation at points below and above optimal feedback control. Different wind speeds and turbulence intensities are taken into account to illustrate the obtained degradation due to the random effect of the wind conditions. The proposed simulation relies on a wind speed model estimated from real data measurements of a laminar wind speed and two classes of turbulent wind speed data obtained from stochastic differential equations. Furthermore, a mechanical contact principle is used for modeling the transmission damping, which is leveraged to estimate the power and the energy dissipated at the shaft and consequently to estimate an image of the fatigue in the drive-train.

II. WIND TURBINE DYNAMICAL MODEL

A. Mechanical model

For modeling the degradation phenomena that have a significant influence on the lifetime of the drive-train in a wind turbine, we consider a simplified drive-train representation shown in Fig. 1. The nomenclature is presented in Table I. It is possible to represent the drive-train system as two rigid bodies linked by a flexible shaft that is being deformed with an angle θ_s when the rotor speed ω_r is slightly different to the generator speed ω_g . The rigid bodies are an image of all mechanical devices located at each side of the effective shaft.

TABLE I: Nomenclature

Symbol	Units	Physical meaning
K_s	[kg/s ²]	Stiffness of the transmission
B_s	[kg/s]	Damping of the transmission
I_r	[kgm ²]	Inertia of the rotor
I_g	[kgm ²]	Inertia of the generator
τ_r	[Nm]	Aerodynamic torque
τ_c	[Nm]	Generator torque
ω_r	[rad/s]	Rotor speed
ω_g	[rad/s]	Generator speed

The considered system corresponds to a Variable-Speed

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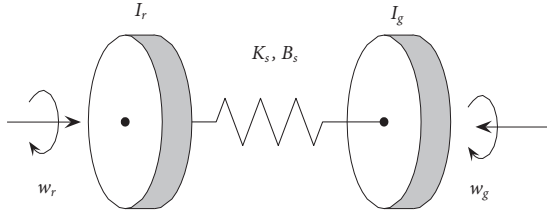


Fig. 1: Drive-train with a flexible shaft representation.

Fixed-Pitch turbine (VS-FP); in this type of turbine, it is common to use a reduced model of the wind energy conversion system taking into account the resonance mode of the drive-train, and the simplified system can thus be described by the following equations, as presented in [2] :

$$\begin{pmatrix} \dot{\theta}_s \\ \dot{\omega}_r \\ \dot{\omega}_g \end{pmatrix} = \begin{pmatrix} 0 & 1 & -1 \\ -\frac{K_s}{I_r} & -\frac{B_s}{I_r} & \frac{B_s}{I_r} \\ \frac{K_s}{I_g} & \frac{B_s}{I_g} & -\frac{B_s}{I_g} \end{pmatrix} \begin{pmatrix} \theta_s \\ \omega_r \\ \omega_g \end{pmatrix} + \begin{pmatrix} 0 & 0 \\ \frac{1}{I_r} & 0 \\ 0 & -\frac{1}{I_g} \end{pmatrix} \begin{pmatrix} \tau_r \\ \tau_c \end{pmatrix} \quad (1)$$

where τ_r is the aerodynamic torque applied to the rotor by the wind, and can be calculated as:

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

with V the wind speed, ρ the air density and R the rotor radius, $C_p(\lambda, \beta)$ is the power coefficient, β is the pitch angle and λ the tip speed ratio, defined as:

$$\lambda = \frac{\omega_r R}{V} \quad (3)$$

The power coefficient C_p is an indicator of the useful power in the wind flow and it is a function of the pitch angle β and λ . The power coefficient can be defined using different methods, including the theory of aerodynamics, blade element momentum (BEM) theory, computational fluid dynamics (CFD), fuzzy logic, or generalized dynamic wake (GDW) models [9], [10], [11]. Nevertheless, a numerical approximation of the aerodynamic power coefficient is often accepted for achieving enough simplicity and accuracy [12], [13]. This type of model has the form:

$$C_p(\lambda, \beta) = c_1 \left(\frac{c_2}{\lambda_i} - \frac{c_3}{\beta} - c_4 \lambda_i \beta - c_5 \beta^x - c_6 \right) e^{-\frac{c_7}{\lambda_i}} + c_8 \lambda \quad (4)$$

In [14], Eq.(4) was optimized, obtaining the parameter λ_i and the different constants as:

$$\lambda_i^{-1} = (\lambda + c_9 \beta)^{-1} - c_{10} (\beta^3 + 1)^{-1} \quad (5)$$

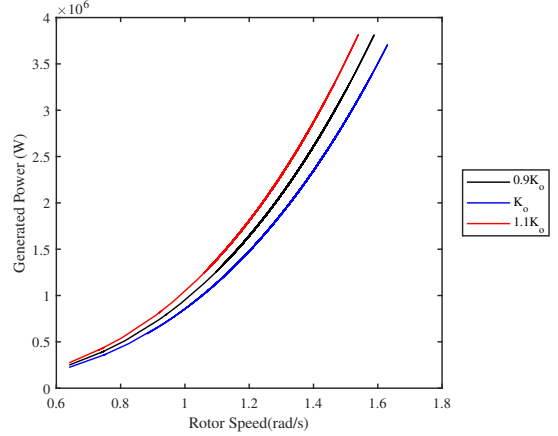


Fig. 2: Generated power with respect to rotor speed produced by optimal and sub-optimal torque controllers.

with $c_1 = 0.22$; $c_2 = 120$; $c_3 = 0.4$; $c_4 = 0$; $c_5 = 0$; $c_6 = 5$; $c_7 = 12.5$; $c_8 = 0$; $c_9 = 0.08$; $c_{10} = 0.035$; $x = 0$.

The torque and power coefficients are of special interest for control purposes. The power coefficient C_p has its maximum at (λ_0, β_0) , with β_0 being a very small angle, ideally zero, and maximum conversion efficiency is accomplished at λ_0 . To realise the potential benefits of the variable-speed operation, the rotational speed must be adjusted initially in proportion to the wind speed to maintain an optimum tip-speed-ratio, [2].

An optimal control law, of VS-FP turbines, considers the generator torque control τ_c as a function of the rotor speed, see [15], as :

$$\tau_c = K_c (\omega_r)^2 \quad (6)$$

where K_c is an optimal feedback control gain given by:

$$K_c = \frac{1}{2} A R^3 \frac{C_{p_{max}}}{\lambda_0^3} \quad (7)$$

where A is the rotor swept area, $C_{p_{max}}$ is the maximum power coefficient and λ_0 is the corresponding tip-speed ratio when $C_{p_{max}}$ occurs.

Thus, the generator power will be:

$$P_g = \tau_c \omega_r \quad (8)$$

and, by consequence the generated energy will be:

$$E_g = \int_0^t P_g dt \quad (9)$$

B. Proposed Degradation Model

This section aims to present a novel drive-train model that considers contact mechanics principles to simulate the degradation in the system, using dissipated energy at the turbine shaft, denoted E_d , as an indicator of deterioration.

A two-mass model usually represents the drive train of a wind turbine. Fig. 1 shows a system of this type, where the low-speed mass of the turbine is connected to the high-speed mass of the generator through a flexible shaft modeled as a spring and damper. Here, we consider that the drive train system is subject to various phenomena producing fatigue, as fatigue by vibration, by friction, by impacts, and by other aerodynamics factors that have to be considered in the deterioration model. In addition, cyclic torque fluctuations potentially reduce the useful life of the drive-train [2], [6], [16]. For this reason, we consider a flexible shaft modeled as a spring and damper based on contact mechanics, adopting the contact model proposed in [17]. Thus, we consider here a damping coefficient that can be modeled as a nonlinear function of the angular deformations.

In this work, the damping coefficient B_s is considered to be a function of the torsion angle θ_s , of the constant stiffness of the transmission K_s , and of a constant parameter α that depends of the material. That is,

$$B_s(\theta_s) = \frac{3}{2}\theta_s\alpha K_s \quad (10)$$

Therefore, the damping torque can be obtained as:

$$\tau_d = B_s(\theta_s)(\omega_g - \omega_r) \quad (11)$$

hence providing the following dissipated power:

$$P_d = \tau_d(\omega_g - \omega_r) \quad (12)$$

Consequently, the amount of energy that is dissipated by the drive-train will be:

$$E_d = \int_0^t P_d dt \quad (13)$$

which is considered here as an image of the drive-train deterioration. Remark that this dissipated energy is a function of both the amplitude of the angular shaft torsion and the square of the relative velocity ($\omega_g - \omega_r$).

III. SIMULATION PROCESS

This section illustrates the behavior of a wind turbine for different wind conditions. In particular, we present the obtained levels of dissipated energy at the turbine shaft that are compared to that actually generated by optimal and sub-optimal control feedback gains.

A. Wind Speed Generation Model

To obtain a complete analysis of a wind turbine, it is necessary to consider the variations of wind speeds, along the time, that can affect the efficiency and durability of the mechanical parts of the turbine.

Different types of models have been developed in the literature to reproduce or predict wind speed in short-term periods, see for instance [18], [19]. By considering the description of relative motion on fluids proposed by Reynolds [20], equation (14) allows modeling the wind speed $V(t)$, at

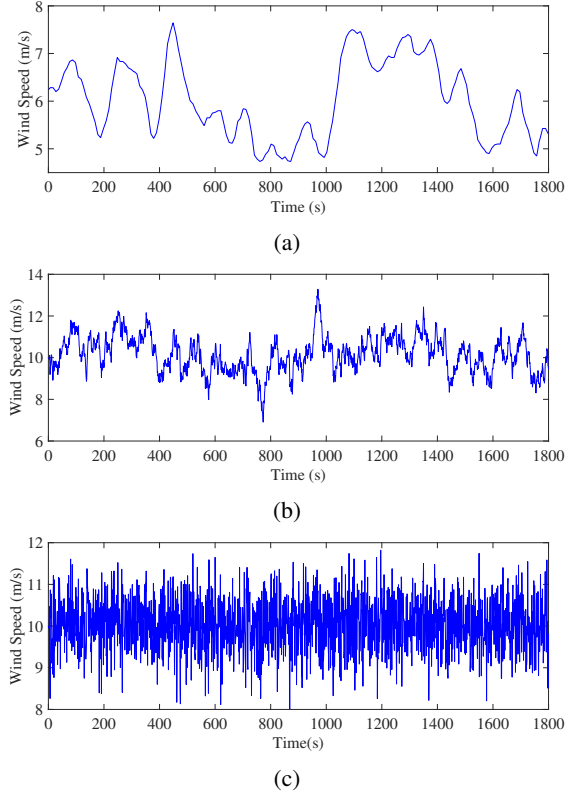


Fig. 3: Considered wind speed conditions: (a) laminar and (b), (c) turbulent ones.

any instant t , by taking into account its mean value $\bar{V}(t)$ and its fluctuation $v(t)$:

$$V(t) = \bar{V}(t) + v(t) \quad (14)$$

The term $\bar{V}(t)$ is often considered as an output of a simple low-pass filter corresponding to the daily, monthly, season or annual mean behavior, and the fluctuation $v(t)$ can be considered as an output of a high-pass filter, see for instance [21].

In [8], a modelling approach is proposed, which considers that the wind speed dynamics can be modelled as a diffusion process following a stochastic differential equation, defining a so-called Ornstein-Uhlenbeck (OU) process:

$$dV(t) = a(V(t), t)dt + b(V(t), t)dW \quad (15)$$

where $a(V(t), t)$ and $b(V(t), t)$ are the drift and diffusion terms, while dW is the standard Wiener process (or standard Brownian motion, a continuous process whose increments are normally distributed).

Turbulence can be classified into three different classes, where the first two include 99% of the wind speed sequences [21], [22]. The method presented in [8] allows generating different classes of wind speed, by using the stochastic equation (16) as a particular case of model (15), by suitably choosing the model parameters \hat{a} , \hat{b} , and \hat{u} .

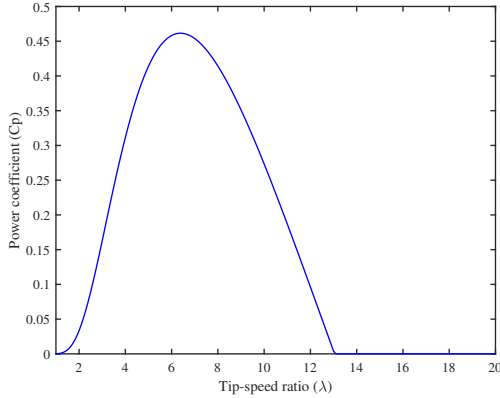


Fig. 4: Considered power coefficient C_p versus tip-speed ratio λ .

$$dV(t) = -\hat{a}(V(t) - \hat{u})dt + \hat{b} dW(t) \quad (16)$$

In our experiment, we used the parameters \hat{a} , \hat{b} , and \hat{u} estimated from real wind speed records on a specific period and presented in [8].

The wind speed simulation has thus been performed using parameters presented in [8] providing the following models:

$$dV(t) = -0.0314(V(t) - 10.0245)dt + 0.2517 dW(t) \quad (17)$$

$$dV(t) = -(V(t) - 10.0245)dt + 0.6459 dW(t) \quad (18)$$

During the simulation process, it was considered different wind speed scenarios with an air density of 1.1 kg/m^3 :

- The first scenario corresponds to laminar wind flow where real measurements of wind speed were used to feed the model, see Fig. 3a).

In addition, turbulent regimen was also simulated, as it was mentioned before, with two classes of turbulent wind:

- Equation (17) was used to generate wind flow with a low variance, see Fig. 3b)
- Equation (18) was used to generate wind flow with a high variance, see Fig. 3c).

Using these three types of wind conditions makes it possible to complete the different situations that a turbine may be subjected to in a more realistic environment.

B. Simulation Setting

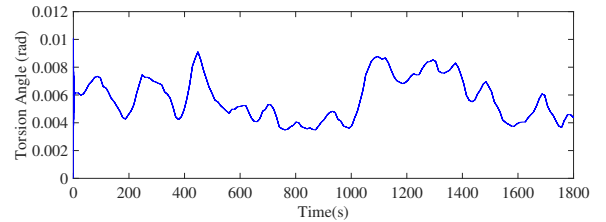
As was mentioned before, it is common to use a simplified representation for the VS-FP turbines, as shown in Fig. 1, where whole transmission system is considered as a system of two rigid bodies connected by a flexible shaft. In this simulation, we consider a VS-FP turbine of 2 MW with a 100 m rotor diameter, with fixed gear box and horizontal-axis. The simulation is performed to obtain a degradation process in the transmission shaft in a short period of 30 minutes ($t = 1800s$), where K_s has a value of $1e8$ and α was

arbitrarily chosen considering the suggested range presented in [17] with a value of 0.5.

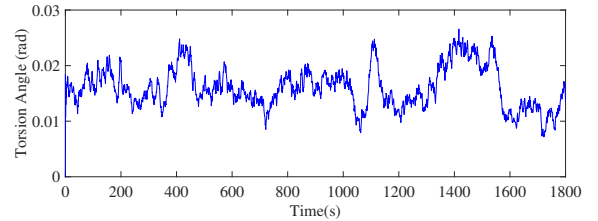
For this turbine, the power coefficient curve, C_p versus λ , is presented in Fig. 4, where the value of $C_{p_{max}}$ that can be obtained is equal to 0.4615 at λ_0 equal to 6.4.

Thus, the optimal feedback control gain (7), will be $K_c = 9.5065e5$. Nevertheless, one part of this work aims to illustrate the performance of the wind turbine sub-optimal control gains. For this reason, two additional scenarios were proposed to complete the analysis:

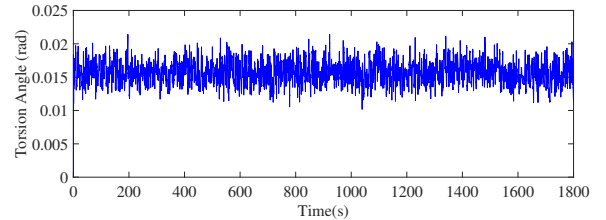
- System controlled at 10% below the optimal K_c
- System controlled at 10% above the optimal K_c .



(a) Laminar flow.



(b) Turbulent flow with low variance.



(c) Turbulent flow with high variance.

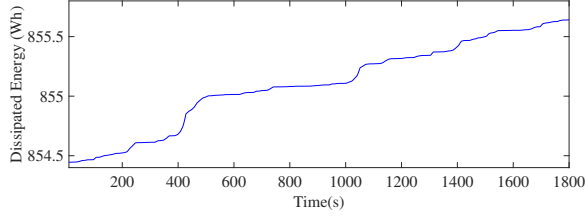
Fig. 5: Obtained torsion shaft angle for different wind conditions.

C. Results and discussions

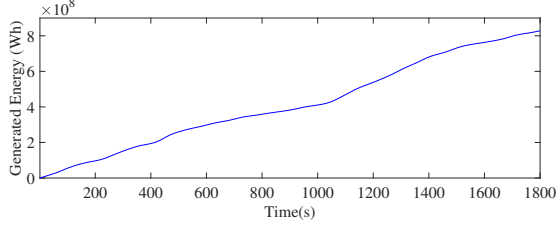
The dynamical system (1) was used to simulate the variations in the torsion angle in the transmission shaft by considering an optimal control for three wind speed cases, see Fig. 5. The obtained torsion angles have a small magnitudes but depending of the wind conditions, the speed of the fluctuations are more or less important.

Figure 6a shows the dissipated energy for laminar flow with optimal control gain and it can be compared to the generated one, see Fig. 6b.

Figure 2 shows the generated power versus rotational speed curves for different control gains. As expected, the generated power is a cubic function of the rotor speed. In

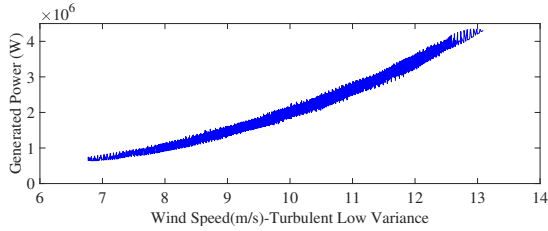


(a) Dissipated energy.

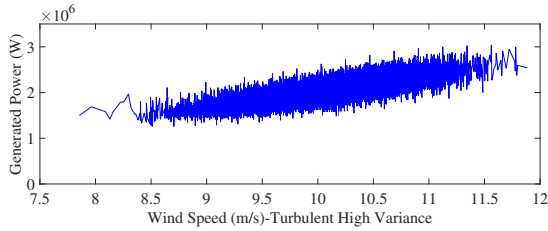


(b) Generated energy.

Fig. 6: Generated and dissipated shaft energies for optimal feedback control.



(a) Turbulent with low variance.



(b) Turbulent with high variance.

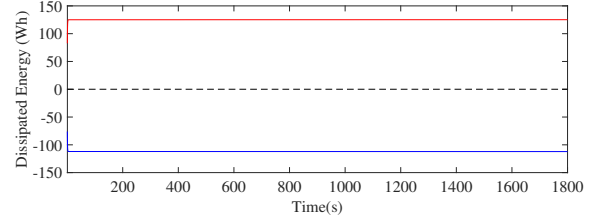
Fig. 7: Generated power with a sub-optimal control gain for turbulent wind conditions.

the case that the control gain is $1.1K_c$, the produced power is greater than that produced by the optimal one and for $0.9K_c$, at same rotor speeds.

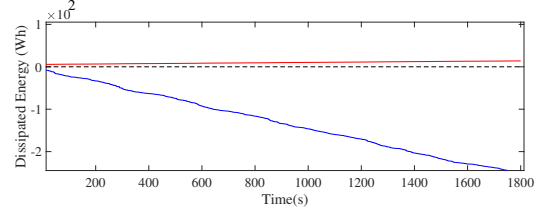
Figure 7 illustrates the effect of the turbulence in the produced energy. When the turbine is submitted to a lower wind turbulence it can produce more power than in the case of wind turbulence with greater variance.

A complete analysis can be made by considering both the dissipated and generated energy, and comparing with respect to the optimal control scenario:

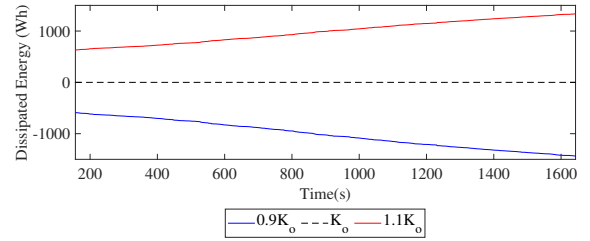
- Concerning the dissipated energy, note that if the control gain is below the optimal point, the magnitude is smaller than the other two cases. Nevertheless, when the wind flow has a more significant variance (turbulent), the



(a) Laminar flow



(b) Turbulent flow with low variance



(c) Turbulent flow with high variance.

Fig. 8: Dissipated energy at the flexible shaft versus time for different wind conditions.

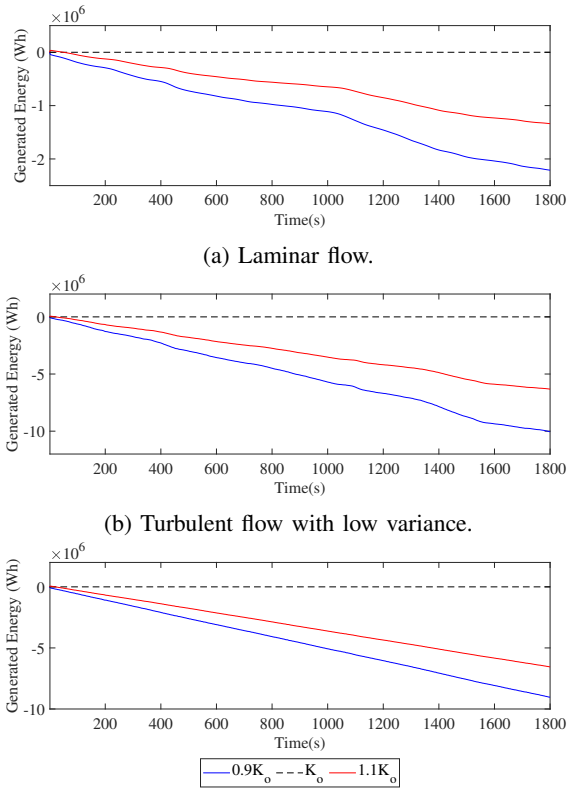
dissipated energy increases notably for a higher gain and decreases considerably for a smaller gain, see Fig. 8.

- Regarding the generated energy, as expected, the amount of generated energy is lower than the optimal one in all cases of wind conditions. Nevertheless, a control gain higher than the optimal one always leads to an energy production higher than a control gain smaller than the optimal one. Note that the difference in the energy production between the tuning $0.9K_c$ and $1.1K_c$ is reduced when the flow is more turbulent, see Fig. 9.

Note that the amount of energy that can be dissipated in a short period when the wind conditions are in high turbulence is significant. As a result, the degradation in the system can be accelerated, increasing the probability of a failure in the transmission.

IV. CONCLUSIONS

This paper proposes a novel model of shaft degradation based on dissipated energy. The proposed model is based on contact mechanics and allows us to estimate through simulation the dissipated energy at the shaft for different



(c) Turbulent flow with high variance.

Fig. 9: Generated energy versus time for different wind conditions.

wind conditions and different control gains (optimal and sub-optimal).

The proposed model was tested using real data of wind speed measurements concerning laminar flow, but also using simulated data of turbulent wind conditions obtained from stochastic differential wind models. The presented simulation provides a complete panoramic result about the possible situations affecting the turbine degradation.

The simulation results illustrate the impact of persistent variations in the shaft angle when the system is submitted to wind speed with high variances. Additionally, if the system works in sub-optimal control conditions, the results shown two possible situations: more generated energy but paying the price of more degradation, or less dissipation energy (in by consequence less degradation), but providing less generated energy. In all the cases, the optimal control gain always provide the maximum generation power, with a "nominal" degradation. This work is a first step towards a degradation-aware control approach that would allow to find dynamically the optimal trade-off between the generated energy and the turbine degradation (dissipated energy) taking into account the actual wind conditions.

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