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Gain-scheduling wind-turbine control to mitigate the effects of weather conditions on the drive-train degradation

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Abstract: This paper presents a gain-scheduling wind-turbine control strategy to mitigate the effects of adverse weather conditions on the degradation of the drive-train. By choosing a suitable control gain according to the wind class, it is possible to establish a trade-off between generated energy and drive-train degradation. The dissipated energy in the mechanical transmission is used as an indicator of degradation. The drive-train is modeled as a flexible shaft using non-linear dynamics of a mass-spring-damper system. Simulations consider a variable speed-fixed pitch turbine of 2 MW (100 m rotor diameter), with a horizontal axis and fixed gearbox. The results show that the proposed gain-scheduling control strategy maintains the desired turbine efficiency by adequately managing the drive-train degradation according to the wind turbulence conditions.

Keywords: Wind Turbine Control, Gain-Scheduling control, Degradation Management, Wind Conditions.

1. INTRODUCTION

The development of renewable energy technologies has been strongly encouraged with the progression of the environmental crisis. Thus, wind power generation plays a central role, covering 13% of the electricity demand in Europe with 220 GW and 8.44% in the United States with 123 MW. Moreover, it should continue to grow to cover 25% of Europe's electricity demand in 2030. Therefore, optimizing wind turbines operation is of high interest to the industry. (American Clean Power Association (2021); Komusanac et al. (2021); Lee and Zhao (2021)).

However, different factors affect the profitability of this technology. The random nature of wind speed conditions represents a challenge in optimizing the lifetime of wind turbines. In particular, if we consider that high wind speed variations are one of the principal factors of increasing degradation rate. (Romero et al. (2021); Ma et al. (2018); Bianchi et al. (2007)). The uncontrolled weather conditions (e.g., wind turbulence intensity) can deteriorate the mechanical transmission in a wind turbine. This could be due to persistent variations in the radial and angular shaft deflections when the system is submitted to wind speed with high variances. Besides, the shaft deterioration increases the maintenance and energy costs. (Romero et al. (2021); Bianchi et al. (2007); Ma et al. (2018)).

Motivated by the benefits of the improvement of this technology, numerous control approaches to reduce the loads by the wind variation in the wind turbine have been proposed in the literature (Li et al. (2020); Pan et al. (2021)). Nevertheless, most of the scientific efforts are focused on the deterioration of individual components of the turbine (Sanchez et al. (2020); Castro and Branner (2021)). However, changes in the wind conditions and their interactions with the control system are not yet considered to analyze the drive-train deterioration.

Thus, considering the effect of the random nature of wind speed represents a challenge in developing future control strategies. Besides, it is expected that wind turbines are operated under a not well-adapted control strategy during significant periods, affecting the efficiency of the turbine (Romero et al. (2021)).

This paper aims to present a gain-scheduling wind-turbine control strategy that can mitigate the effects of adverse weather conditions by choosing a suitable feedback control gain depending on the wind turbulence conditions. The approach allows establishing a trade-off between generated and dissipated energy to maximize the efficiency of a wind turbine by taking into account the actual wind conditions. The drive-train is simulated as a flexible shaft by considering a nonlinear mass-spring-damper model. Furthermore, the dissipated energy in the mechanical transmission is used to model the degradation of the shaft. Finally, the performance of the proposed strategy is illustrated through several numerical experiments by considering different wind turbulence scenarios.

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2. MODELLING OF DRIVE-TRAIN DEGRADATION

2.1 Wind Turbine Dynamical Model

The representation of the drive-train in a variable speed-fixed pitch (VS-FP) wind turbine can be made in a simplified model that considers the flexible transmission that connects two rigid bodies as presented in Bianchi et al. (2007). Considering the dynamic of the drive-train system: the shaft is deformed with an angle θ_s due to the difference between the generator speed ω_g and the rotor angular speed ω_r . The representation of two rigid bodies allows us to embrace the parts and mechanical devices on each side of the shaft, including terms such as the rotor inertia I_r , generator inertia I_g , the damping of the transmission B_s and the stiffness of the transmission K_s .

In this paper, the description of the wind turbine will be limited to the dynamics of the drive-train, reducing the dynamical equations as those presented in Bianchi et al. (2007) in a first-order LPV system. That is:

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

where τ_r is the aerodynamic torque, which captures the torque produced from the wind observed in the mechanical shaft. τ_r can be calculated by considering the wind speed (V), the air density (ρ), the rotor radius (R), as follows:

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

The parameter $C_p(\lambda, \beta)$ corresponds to the power coefficient, which allows knowing a wind turbine's ability to capture the useful wind power. In general, C_p is modeled using numerical approximations, taking into account the pitch angle β and the tip speed ratio λ . See for instance (Dai et al. (2016), Saint-Drenan et al. (2020)).

The tip speed ratio λ is defined in term of ω_r , R and V . In addition, it is possible to calculate a maximum power coefficient $C_{p_{max}}$ that concerns with the maximum conversion efficiency, achieved at the optimal operation point $\lambda = \lambda_0$ (the optimal λ value) and optimal pitch angle (e.g. $\beta \approx 0$).

The variable-speed wind turbines can work with maximum efficiency over a wide wind speed range of rated power. The benefits of the operation in the VS-FP turbines can be achieved if ω_r is modified in proportion to the wind speed to maintain an optimum tip-speed ratio (Bianchi et al. (2007)). For control purposes, the generator torque control τ_c can be considered as a function of the rotor speed, (see for instance Johnson et al. (2006)), as :

$$\tau_c = K_c^{opt} (\omega_r)^2 \quad (3)$$

where K_c^{opt} is the theoretical optimal feedback control gain calculated as a function of $C_{p_{max}}$, λ_0 , and the rotor swept area, denoted A , as follows:

$$K_c^{opt} = \frac{1}{2} A R^3 \frac{C_{p_{max}}}{\lambda_0^3} \quad (4)$$

and, the generated energy during the time t will be:

$$E_g = \int_0^t P_g dt = \int_0^t \tau_c \omega_r dt \quad (5)$$

2.2 Degradation Model

During the wind turbine operation, the drive-train is one system that suffers the impact of changing loads that can increment its failure rate. It is commonly accepted that torsional vibrations, bearing friction and impacts, or radial and angular torque fluctuations contribute to the degradation of the drive-train and, consequently, they reduce the useful life of the wind turbine (Rahimi (2016), Bianchi et al. (2007), Cetrini et al. (2019)).

Here we consider a degradation model of the drive-train presented in Romero et al. (2021). The model is based on contact mechanics principles, and it has been used to simulate degradation in the transmission by using dissipated energy E_d as an indicator.

The simplified model of a drive-train shown in Fig.1 was used, considering that the two rigid bodies represent the rotor components (low-speed mass) and the generator components (high-speed mass) connected by a flexible shaft modeled as a spring and damper. Thus, based on contact mechanics, the damping coefficient, denoted B_s , can be modeled as a nonlinear function of the angular deformation and can be written as a function of the torsion angle θ_s as follows:

$$B_s(\theta_s) = \frac{3}{2} \theta_s \alpha K_s \quad (6)$$

where K_s is the constant stiffness of the transmission, and α is a constant parameter that depends on the material.

For computing the damping torque, it is necessary to consider the rotational speed difference between both rotational devices. It can be obtained as:

$$\tau_d = B_s(\theta_s) (\omega_g - \omega_r) \quad (7)$$

Therefore, the dissipated power due to angular deformations will be:

$$P_d = \tau_d (\omega_g - \omega_r) \quad (8)$$

Taken together, (7) and (8) show that the power dissipated by the drive-train is a function of the angular shaft torsion and the square of the relative velocity. The amount of dissipated energy is then:

$$E_d = \int_0^t P_d dt = \int_0^t B_s(\theta_s) (\omega_g - \omega_r)^2 dt \quad (9)$$

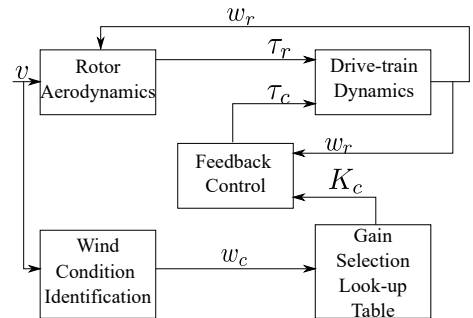


Fig. 1. Architecture of the proposed gain-scheduling control strategy.

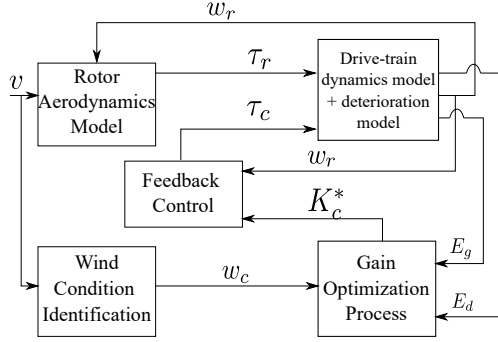


Fig. 2. Scheme of the off-line optimization process for designing feedback control gains.

3. PROPOSED GAIN-SCHEDULING CONTROL STRATEGY

In a wind turbine, the control gain of the generator is usually adjusted without considering the changes in the wind flow conditions. However, in Romero et al. (2021), it has been shown that when the control system ignores wind conditions, the efficiency and the degradation of the turbine are significantly affected. As stated in Romero et al. (2021), the four following observations can be made:

- The dissipated energy increases when the wind conditions are of high turbulence ;
- In addition, the chosen control gain impacts the degradation (which is considered here to be proportional to the dissipated energy E_d), for instance:

$$E_d = \begin{cases} \text{Increases when } K_c > K_c^{opt} \\ \text{Decreases when } K_c < K_c^{opt} \end{cases}$$

where K_c stands for the chosen control gain and K_c^{opt} is the theoretical optimal feedback control gain ;

- A control gain chosen higher than the optimal one leads to a greater energy production than a control gain smaller than the optimal one, i.e consider two possible control gain choices K_c^a and K_c^b , around the optimal one, such that

$$K_c^a < K_c^{opt} < K_c^b, \quad (10)$$

then, choosing K_c^b leads to a higher energy production than choosing K_c^a ;

- However, even if the choice of a higher gain K_c^b leads to a higher energy production, in the case of high turbulent flow, this increase in the energy production is not that significant.

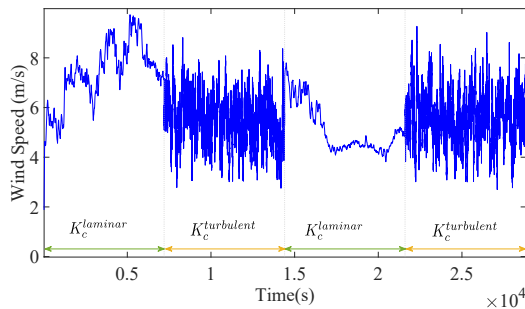


Fig. 3. Example of gain-scheduling depending on two wind conditions.

Considering these observations, a trade-off can be found between the dissipated and the generated energy by a proper choice of K_c , and the problem is thus to design a control strategy which allows the selection of a suitable control gain according to the wind conditions. Here, we will assume that those wind conditions are identified, online, by a given algorithm that is outside of the scope of this paper.

This work proposes a gain-scheduling wind-turbine control strategy to manage the degradation and to optimize the lifetime of the mechanical transmission components while maintaining an acceptable efficiency of a wind turbine under varying weather conditions. In the next section, the proposed control architecture will be presented.

3.1 Gain-Scheduling Control Architecture

The proposed control architecture is shown in Fig.1. That architecture uses the wind speed information for identifying the wind speed conditions w_c (laminar or turbulent flow, for instance), as follows:

$$w_c = \begin{cases} 1 & \text{if } v \text{ corresponds to turbulent flow} \\ 0 & \text{if } v \text{ corresponds to laminar flow} \end{cases}$$

the index w_c can be considered as a gain-scheduling variable. The feedback gains K_c , stored into a previously designed look-up table, will be selected according to the wind conditions w_c as it is illustrated in Fig.3. Thus, the control torque τ_c is then obtained by using (3).

Remark that the dynamics (1), the varying parameter (6) and the control law (3), can be rewritten as a Linear Parametric Varying (LPV) control system. Then, stability guarantees of the proposed control architecture can be obtained by using today available LPV and polytopic analysis tools, see for instance Apkarian et al. (1995).

The values of the control gains K_c can be obtained off-line by solving an optimization problem as it is explained in the next section.

3.2 Optimization for gain-scheduling control design

The interest of adopting a gain-scheduling control approach is the possibility to select suitable control gains K_c^s for each wind condition, which allows to reach a trade-off between dissipated and generated energy. Hence, those gains can be obtained as the solution of an optimisation problem.

For each case (laminar or turbulent, for instance), the value of the gain is obtained as the one that minimizes the ratio of the dissipated energy E_d over the generated energy E_g under the considered wind conditions:

$$K_c^* = \arg \min_{K_c} \left(\frac{E_d(K_c, w_r)}{E_g(K_c, w_r)} \right) \quad (11)$$

All the gains obtained for each possible situation are stored into a look-up table. The control system will recover these gains, online, to implement the control loop.

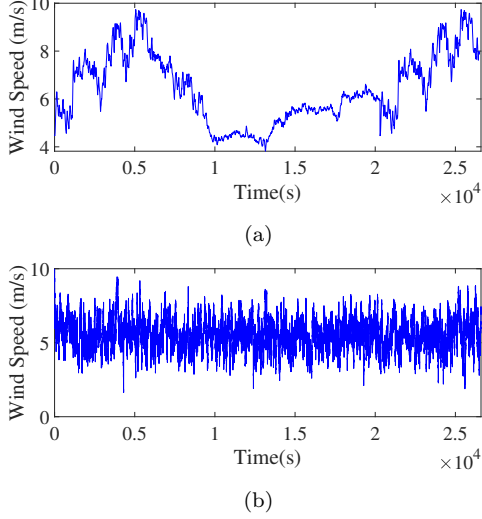


Fig. 4. Considered wind speed conditions: (a) laminar and (b) turbulent

4. SIMULATION OF THE PROPOSED APPROACH

4.1 Simulation Setting

For VS-FP turbines, a reduced model is regularly used, where the drive-train system is represented by two rigid masses connected by a flexible shaft. In this work, we simulate a VS-FP turbine with a horizontal-axis and fixed gearbox. The rated power of the turbine is 2 MW and 100 m rotor diameter.

For the case of the chosen turbine, the power coefficient curve, C_p versus λ : the value of $C_{p_{max}}$ is 0.4615 at λ_0 equal to 6.4. Therefore, using (4), the theoretical optimal feedback control gain, will be $K_c^{opt} = 9.5065e5$.

4.2 Wind Speed Generation

Uncontrolled weather conditions such as the wind speed increase the deterioration of the drive-train in a wind turbine. It is thus necessary to obtain a model to reproduce wind speed under different flow conditions (laminar and turbulent), in order to simulate the wind turbine degradation.

For the laminar wind speed case, the real measurement of the wind speed over a period of approximately 7 hours (27000s) was used to feed the model (Fig.4a).

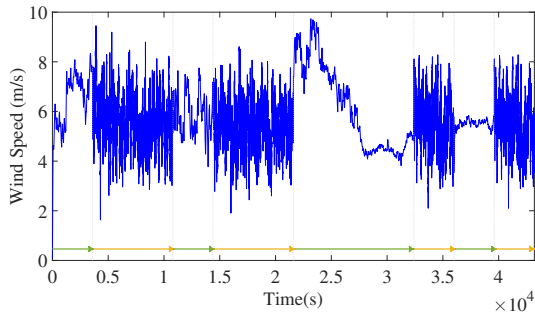


Fig. 5. Simulated wind speed.

In the turbulent case, different types of models exist to predict wind speed (Hanifi et al. (2020); Manwell et al. (2009); Liu et al. (2020)). However, the approach proposed in Ma et al. (2018) allows generating different classes of wind speed by using a stochastic equation (12). In this work, this latter model was used to simulate a data set of turbulent wind speed:

$$dV(t) = -\hat{a}(V(t) - \hat{u})dt + \hat{b} dW(t) \quad (12)$$

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

The parameters \hat{a} , \hat{b} , and \hat{u} were chosen from real wind speed records for periods as presented in Ma et al. (2018). Thus, the equation for reproducing turbulent wind speed is:

$$dV(t) = -0.0314(V(t) - 5.5135)dt + 0.2517 dW(t) \quad (13)$$

For the turbulent wind speed, the simulation was performed during the same period length as in the laminar case (27000s) and is presented in Fig.4b.

However, this works aims to evaluate how an suitable control gain can mitigate the effects of adverse weather conditions. For this purpose, a third data set was reproduced for 12 hours ($t = 43200s$), with periods in laminar flow conditions and others in turbulence, organized randomly, during a minimum of 1 hour. In Fig. 5 the alternation between laminar and turbulent periods are represented with lines to identify each flow regimen.

4.3 Gain-scheduling Control Strategy Setting

In this work, we considered two scenarios of wind speed conditions (laminar and turbulent) to validate the proposed Gain-scheduling control strategy. Each case was evaluated, separately, in order to obtain two possible suitable control gains, as is show below:

$$K_c^s = \begin{cases} K_c^{turbulent} \text{ optimal } K_c \text{ for turbulent flow} \\ K_c^{laminar} \text{ optimal } K_c \text{ for laminar flow} \end{cases}$$

The values of $K_c^{laminar}$ and $K_c^{turbulent}$ are solution of an off-line optimisation problem as it is illustrated in Fig.2. As result the optimal control gains are:

- $K_c^{laminar}$ which can take values until 11% above K_c^{opt} . This gain is optimal for laminar wind conditions.

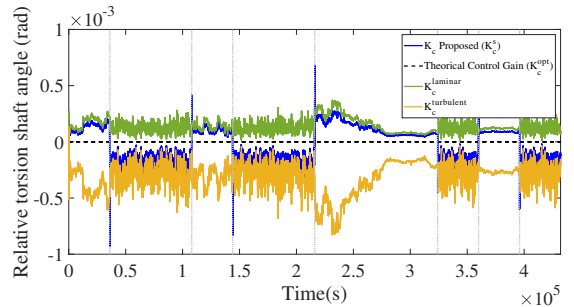


Fig. 6. Comparison of the relative torsion shaft angle for different feedback gains K_c .

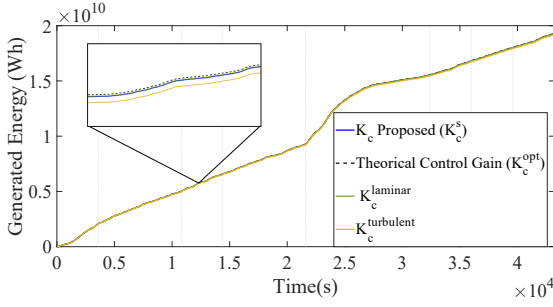


Fig. 7. Generated energy for different feedback gains K_c .

- $K_c^{turbulent}$ which can take values until 15% below K_c^{opt} . This gain is optimal for turbulent wind conditions.

Besides, we consider that the wind conditions are identified and the change of flow regimen is made every hour (3600 seconds) as is indicated in Fig.5.

For validation of the proposed gain-scheduling control strategy, the same changing wind condition scenario was used for testing and comparing four different choices of the control gain:

- Case with the proposed gain-scheduling K_c^s : during all the simulation, K_c is switched between $K_c^{laminar}$ and $K_c^{turbulent}$ depending on the wind conditions;
- Case with the theoretical optimal control gain K_c^{opt} : during all the simulation, K_c is set at the value of $K_c^{opt} = 9.5065e5$, computed using (4);
- Case with $K_c^{laminar}$: during all the simulation, K_c is set at a value obtained as optimal under laminar conditions, determined using (11);
- Case with $K_c^{turbulent}$: during all the simulation, K_c is set at a value obtained as optimal under turbulent conditions, determined using (11).

4.4 Results and discussion

This work used the dynamical system presented in (1) to simulate the generated energy and the dissipated energy (i.e. degradation) in the transmission shaft by considering the necessity to adapt the control gain depending on the variations in the wind nature. During all the simulations, the wind speed used as an input to the model is presented in Fig. 5. The change of flow regimen between laminar and turbulent is indicated in all figures by dotted vertical gray lines.

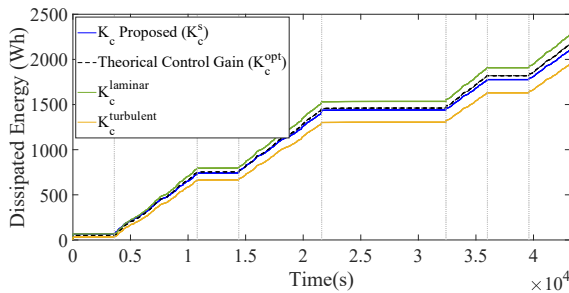


Fig. 8. Dissipated energy for different feedback gains K_c .

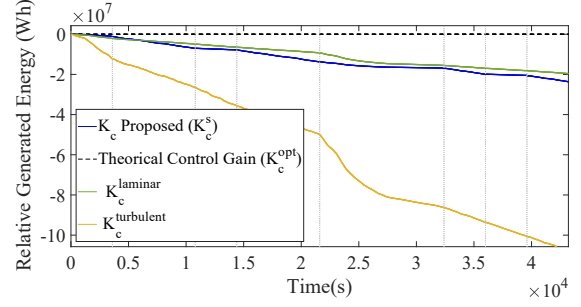


Fig. 9. Comparison of the relative generated energy with respect to the optimal case.

Nevertheless, to find the optimal $K_c^{laminar}$ and $K_c^{turbulent}$, the evaluation was made using the wind speed data presented in Fig. 4, giving, as a result, a value for each case. In this work, the values of $K_c^{laminar}$ and $K_c^{turbulent}$ are $1.0552e06$ and $1.4260e5$ respectively.

The dynamical system presented in (1) was used to validate the gain-scheduling control strategy, simulating the variations in θ_s , switching the K_c according to the wind conditions. Fig. 6 shows a comparison of the behavior in the variation of θ_s using the optimal case as a reference. The results show that the wind conditions affect the variation of the torsion angle, and it is possible to minimize the impact if a suitable control gain is used.

Fig. 7 shows the generated energy for different K_c : with K_c^{opt} it is possible to generate more energy, followed by the case where $K_c^{laminar}$ is used, because a greater K_c leads to a higher generation of energy. Nevertheless, the gain-scheduling control strategy allows improving energy generation when the wind exhibits periods of turbulent conditions. Fig. 8 illustrates the dissipated energy for the period of evaluation. The case with $K_c^{laminar}$ dissipated a higher amount of energy. Moreover, in the case of $K_c^{turbulent}$, a K_c lower than the optimal leads to minor degradation. Nevertheless, it can be seen that the gain-scheduling control strategy allows to follow the behavior of the case with K_c^{opt} in terms of energy dissipation.

To further discuss these results, let consider the generated and dissipated energy and compare with the K_c^{opt} scenario:

- Generated energy: The optimal case always leads to a significant amount of generated energy, and greater K_c increases the energy generation. However, if the control gain is switched according to the wind

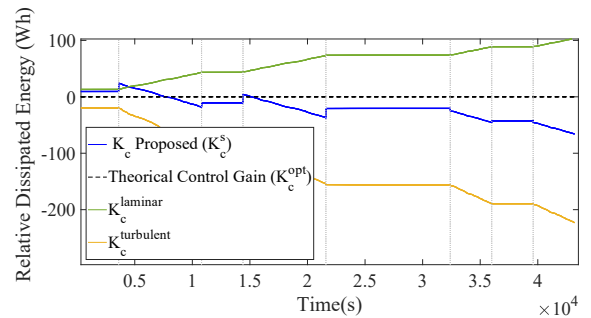


Fig. 10. Comparison of the relative dissipated energy with respect to the optimal case.

conditions (K_c^s), it is still possible to increase the generation of energy almost at the level reached under laminar ideal conditions, see Fig.9.

- Dissipated energy: regarding the generated energy, a higher generation leads at the same time to a significant level of dissipated energy, and hence degradation. For this reason, the dissipated energy in the case with $K_c^{laminar}$ is above the optimal ones. However, the $K_c^{turbulent}$ is below the other cases with a significant difference, while the case with suitable control gain K_c^s allows to keep a low level of dissipated energy, dissipating less energy than in the cases with $K_c^{laminar}$ and even with K_c^{opt} , see Fig.10.

We can thus conclude that the proposed control adaptation strategy allows to increase energy generation in turbulent cases and decreases dissipated energy in the drive-train system (when compared to situation where K_c is higher than optimal). As a consequence, the system can profit of both a higher generation of energy and a lower dissipated energy.

5. CONCLUSIONS

This paper proposes a gain-scheduling control strategy to optimize the efficiency of a wind turbine under varying weather conditions, finding an optimal trade-off between the generated energy and degradation (due to dissipated energy) in the drive-train. The proposed strategy considers the variation of the wind conditions to alternate between different suitable control gains, maximizing the generated energy and decreasing the dissipated energy.

The proposed strategy was tested using different wind speed scenarios to consider a more complete panorama about the possible wind conditions affecting the turbine. Real data measurement was used to simulate the wind conditions for laminar flow, while for turbulent wind conditions, a stochastic model was used to simulate it.

The results show that it is possible to maximize the generated energy and decrease the dissipated energy by switching the control gains depending on wind flow conditions, decreasing the variations in the shaft angle, and getting closest to the theoretical optimal behavior.

Stability conditions of the proposed control scheme can be obtained by expressing the whole dynamical control system as a Linear Parametric Varying system and, by using suitable available tools in this area. This aspect will be treated in a future work.

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