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

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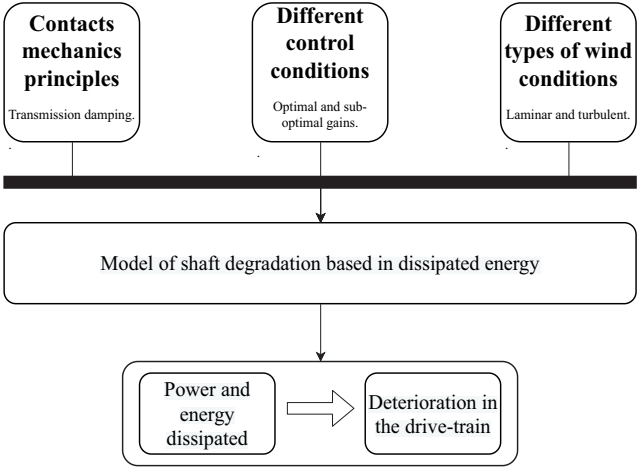
Overview

Problem Statement

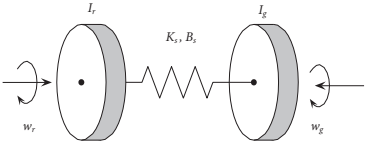
Problems

- Environmental factors can affect the profitability of wind turbines technologies.
- Unexpected **fatigue damage** can create **deformations** of the drive-train.
- The functioning on **non-optimal control** conditions, affects the **efficiency** of the turbine.
- Transmission faults **decrease lifetime** of wind turbines, which increase maintenance and energy costs.

Proposed Solution



Drive-train with a flexible shaft model (Bianchi et al. 2007 [1])



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

Variables of the system

K_s: Stiffness of the transmission $[kg/s^2]$

I_r: Inertia of the rotor $[kgm^2]$

τ_r: Aerodynamic torque $[Nm]$

ω_r: Rotor speed $[rad/s]$

B_s: Damping of the transmission $[kg/s]$

I_g: Inertia of the generator

τ_c: Generator torque $[Nm]$

ω_g: Generator speed $[rad/s]$

Wind turbine dynamical model (Aerodynamic torque)

The aerodynamic torque [Nm], produced by the wind speed, will be:

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

with λ (the tip-speed ratio) defined as:

$$\lambda = \frac{\omega_r R}{V} \tag{3}$$

And, the model of the Power Coefficient $C_p(\lambda,\beta)$ (Saint Drenan et al. 2020 [2])

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

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

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

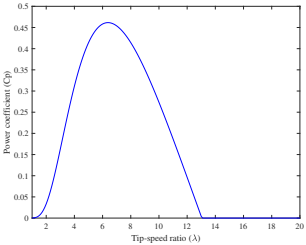
Wind turbine dynamical model (Optimal control law)

Description

The optimal control law, of VS-FP turbines, considers the generator torque τ_c as a function of the rotor speed:

$$\tau_c = K_c(\omega_r)^2 \tag{6}$$

To maximize the conversion efficiency it is necessary that the rotational speed be adjusted in proportion to the wind speed to maintain an optimum tip-speed-ratio λ_0.



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

$$P_g = \tau_c \omega_r \tag{8}$$

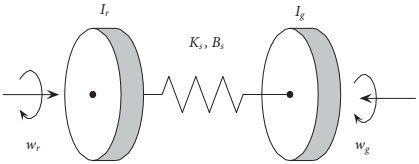
$$E_g = \int_0^t P_g \, dt \tag{9}$$

Proposed Degradation Model

Description

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:

$$E_d = \int_0^t P_d dt \tag{10}$$



$$P_d = \tau_d(\omega_g - \omega_r) \tag{11}$$

$$\tau_d = B_s(\theta_s)(\omega_g - \omega_r) \tag{12}$$

$$B_s(\theta_s) = \frac{3}{2}\theta_s \alpha K_s \tag{13}$$

(Hunt et al. 2020 [3])

Wind Speed Simulation

Simulation Objective

The variations of wind speeds, along the time, can affect the **efficiency** and **durability** of the mechanical parts of the turbine. Different wind speeds and turbulence intensities are used to illustrate the obtained degradation due to the random effect of the wind conditions.

Wind Speed Generation Model (Ma et al. 2018 [4])

$$V(t) = \overline{V}(t) + v(t) \tag{14}$$

$$dV(t) = -\hat{a}(V(t) - \hat{u})dt + \hat{b}\, dW(t) \tag{15}$$

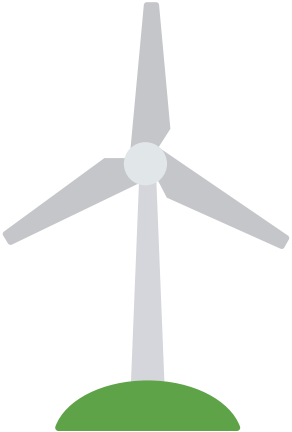
Low Variance:

$$dV(t) = -0.0314(V(t) - 10.0245)dt + 0.2517\, dW(t) \tag{16}$$

High Variance:

$$dV(t) = -(V(t) - 10.0245)dt + 0.6459\, dW(t) \tag{17}$$

Simulation Settings: 2MW wind turbine



Technical Specifications

- Rated power: 2MW
- Rotor diameter: 100 m
- Variable-speed Fixed-pitch Wind Turbine
- K_s: 1e8 kg/s^2

Time simulation

- t: 30 minutes (1800s)

Type Wind Conditions

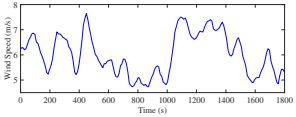
- Laminar: Real Data
- Turbulent with high and low variance: Simulated

Optimal Conditions

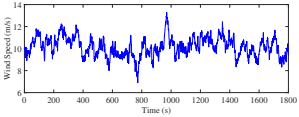
- α: 0.5
- $C_{p_{max}}$: 0.4615
- λ_0: 6.4
- K_c: 9.5065e5

Wind Speed Simulation and Effects on the Torsion shaft angle

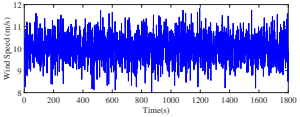
For different wind conditions, (a) Laminar (b)Turbulent flow with low variance, (c) Turbulent flow with high variance:



(a)

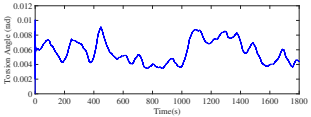


(b)

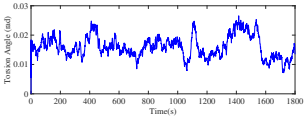


(c)

Figure: **Wind speed (m/s)**



(a)



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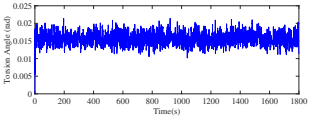
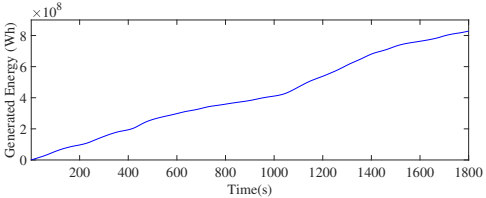


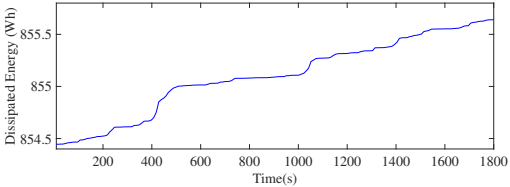
(c)

Figure: **Torsion shaft angle (rad)**.

Performance of the wind turbine optimal control



(a) Generated energy



(b) Dissipated energy

Figure: (a) Generated energy and (b) dissipated energy for optimal feedback control laminar wind conditions.

Performance of the wind turbine with optimal and sub-optimal torque controllers

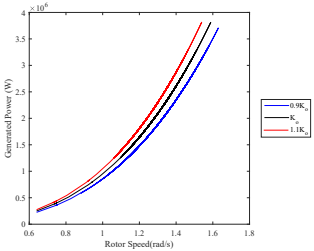


Figure: Generated power with respect to rotor speed produced by optimal and sub-optimal torque controllers.

The generated power is a cubic function of the rotor speed. In 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.

Comparison of dissipated and generated energy with optimal and sub-optimal conditions

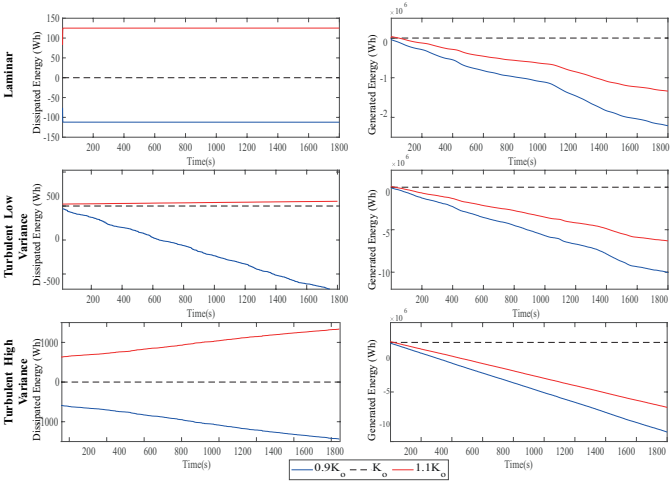


Figure: Dissipated and Generated energy at the flexible shaft versus time for different wind taking as reference optimal conditions.

Conclusions

- The results illustrate the impact of persistent variations in the shaft angle when the system is submitted to wind speed with high variances.
- When the system works in sub-optimal control conditions, the results showed two possible situations:
  - More generated energy but more degradation.
  - Less degradation, but less generated energy.
- This work is the 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.

Thanks for your attention

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References

- F. D. Bianchi, R. J. Mantz, and H. D. Battista, *Wind Turbine Control Systems*. Springer, 2007.
- Y.-M. Saint-Drenan, R. Besseau, M. Jansen, I. Staffell, A. Troccoli, L. Dubus, J. Schmidt, K. Gruber, S. G. Simões, and S. Heier, "A parametric model for wind turbine power curves incorporating environmental conditions," *Renewable Energy*, vol. 157, pp. 754–768, Sept. 2020.
- K. Hunt and E. Crossley, "Coefficient of restitution interpreted as damping in vibroimpact," *Journal of Applied Mechanics*, vol. 42, 1975.
- J. Ma, M. Fouladirad, and A. Grall, "Flexible wind speed generation model: Markov chain with an embedded diffusion process," *Energy*, vol. 164, pp. 316–328, Dec. 2018.