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Title: OPTIMAL CONTROL OF THE ACTIVE YAW SYSTEM FOR A WIND TURBINE

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Introduction

The electrical energy generated by wind turbines has advantages to satisfy the demand for energy worldwide, for example: a)- it is energy that does not produce toxic gases such as CO_2 that increase global warming, b)- the energy source is constantly renewed. To reduce the cost of energy produced by wind turbines and make them competitive for conventional power plants, power generation can be optimized (Wael Farag, Manal El-Hosary, Ahmed Kamel, Khaled El-Metwally, 2017).

Local control systems in wind turbines are responsible for controlling each element of the wind turbine individually, such as: attack angle control system, yaw control, and generator torque control.

Mechanical power

In the literature, different expressions have been used for the turbine power in case the orientation angle γ is different from zero (Simon De Zutter, Jeroen D. M. De kooning, 2017). The power is multiplied by the cosine of the orientation angle:

$$Pt=1/2\,\rho\pi\,R^2V^3Cp\cos\gamma \tag{1}$$

This equation is based on the fact that the wind mass flux across the rotor surface decreases by cos γ when the rotor surface normal has an angle γ with the wind direction. The energy extracted from the wind is proportional to the mass flux of the wind, and consequently the power also decreases by cos γ.

However, this reasoning does not take into account the fact that blade efficiency decreases under oriented inflow conditions. When the orientation angle γ is different from zero, the wind does not hit the blade leading edge orthogonally (Simon De Zutter, Jeroen D. M. De kooning, 2017). Therefore, the blade does not generate the same lift forces as it would with an orthogonal inlet flow, that is the lift forces decrease. Therefore, it is argued that only the orthogonal component of the wind should be used to compute the power. Therefore, the turbine power becomes:

$$Pt=1/2\,\rho\pi\,R^2V^3Cp\cos^3\gamma \tag{2}$$

Pasive orientation system

The kind of orientation system for low power wind turbines with the greatest application is the passive type.

The disadvantage of this kind of passive orientation system is that the wind rotor always remains oriented in the predominant direction of the wind, consequently, it is not possible to regulate the output power of the electric generator in the face of different magnitudes of wind speed (Benjayil Rodríguez-Solano, Alfredo Reyna-Gomez, 2018).

Figure 1. Pasive orientation system. Source: https://www.enair.es/es/aerogeneradores/e70pro

Active yaw system

The active orientation system consists of a planetary gear coupled with one or more DC or AC motors depending on the torque required to move the wind turbine nacelle, the control system is responsible for activating the motor coupled with the gear to rotate the nacelle towards the direction of the wind.

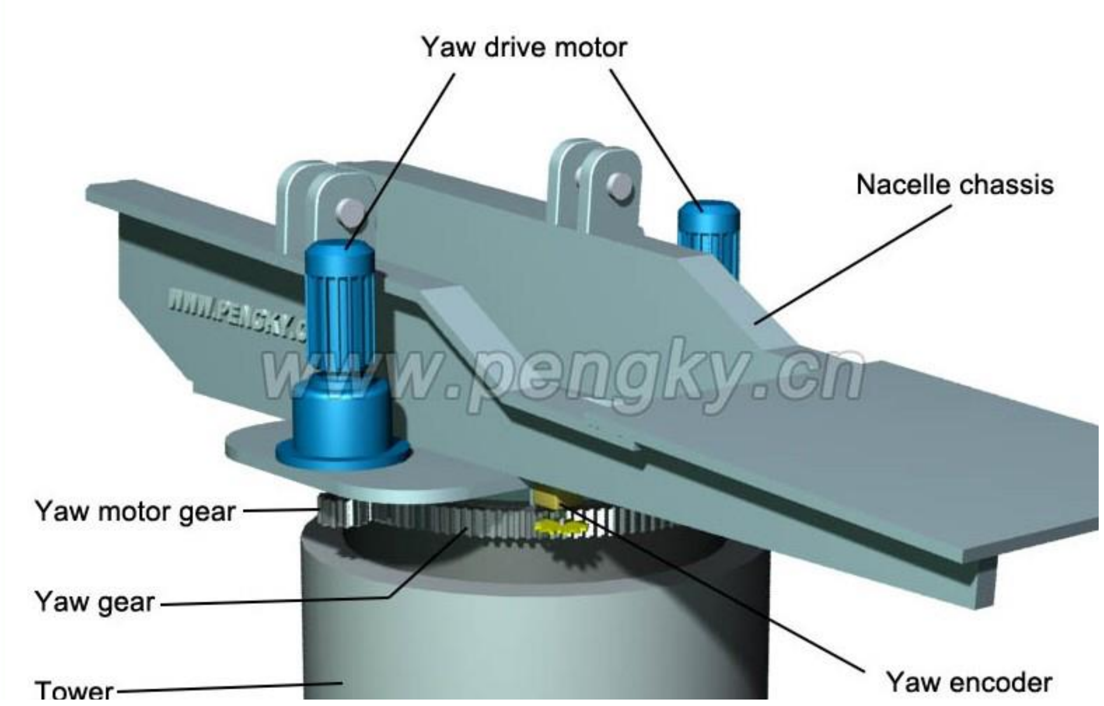

Figure 2. Active yaw system. Source: https://www.pengky.cn/zz-horizontal-axis-turbine/07-wind-turbine-yaw-device/wind-turbine-yaw.mp4

Methodology

Mathematical model of the active yaw system

Since the main objective of this work is the design of the controller, an existing mathematical model was taken, which was obtained with a specialized software for modeling wind turbines called FAST, since it allows obtaining a more precise model of the orientation system, the transfer function which represents the mathematical model of the wind turbine yaw system to control only the position is represented as (J.M. Jonkman, M.L. Buhl Jr., 2005):

$$G(s) = \frac{Yawsprint}{(YawIner(s^2) + YawDamp(s) + Yawsprint)} \tag{3}$$

where *Yawsprint* is the linear equivalent spring constant of the yaw actuator, *YawIner* is the inertia of the nacelle about the yaw axis, and *YawDamp* is the equivalent linear damping constant of the nacellee yaw actuator.

To implement the optimal control strategy, the representation in the state space of the system is obtained:

$$\begin{aligned} &x1=x2 \\ &x2=-10x1-7.3x2+10u \\ &y=x1 \end{aligned} \tag{4}$$

where x_1 is the angular position of the nacelle, x_2 is the displacement speed, *u* is the input voltage to the system and *y* is the controlled variable of the system.

Table 1 . *Nacelle features. Source of own elaboration .*

Parameter	Value
Nacelle mass	960 Kg
Yawsprint	75,392 N•m/rad
YawIner	7,532.9 kg•m^2
YawDamp	55,336.7 N•m/(rad/s)
Rated speed of nacelle orientation	0.3 ° /s

In (Ornelas-Tellez, F., Sánchez, E. N., Loukianov, A. G., 2011), the optimal control law for discrete-time control is obtained:

$$u_k^* = -1/2\left(R(x_k) + \cdots .. + 1/2\, g^T(x_k)P_k g(x_k)\right)^{-1} g^T(x_k)P_k f_d(x_k) \tag{5}$$

P_k and R are symmetric and positive definite matrices; thus the existence of the inverse in (5) is assured. The control law (5) depends on the P_k matrix at each time step.

Searching method of tuning parameters

In (Villegas-Ruvalcaba, et al. 2021) a new method is proposed to adjust the parameters of the optimal control law. Equation (5) is replaced by the following:

$$u_k^* = -K\left(R(x_k) + \cdots .. + 1/2\, g^T(x_k)P_k g(x_k)\right)^{-1} g^T(x_k)P_k f_d(x_k) \tag{6}$$

The goal is to find the gain K that adjusts the control u^*_k, with control law parameters P_k and R fixed. The following methodology for this purpose is described below:

1. Select the values of P and R fixed heuristically.

2. Give values to the input variables and the system parameters to properly analyze which ranges of those variables generate an error ξ greater than the tolerance ε.

3. Find a K value for each desired reference variable in the ranges or values of the previous point that best fit.

4. Construct a function with the K gains found that depend on the input variable or parameter which destabilized the system.

5. In case an appropriate value of gain K is not found, adjust the parameters P and R to obtain a better convergence.

In this work, ξ is taken as the percentage error when the system falls into a steady state error, that is, when the error converges to a point close to the desired reference. The error tolerance with respect to the desired reference is $\varepsilon = 1\%$, consequently, there will be different gains K that satisfy $\xi < \varepsilon$.

Results

In order to evaluate the performance of the optimal control scheme, different operating points are proposed. The scheme is implemented in MATLAB/Simulink and the parameters for simulation are given in Table 1 and equations (7)-(9).

Figures 3 and 4 show the historical data of the wind speed and direction from January to May 2022 taken from the meteorological station of the international airport of Guadalajara, Jalisco (wunderground, 2022). The wind direction is in degrees respect north.

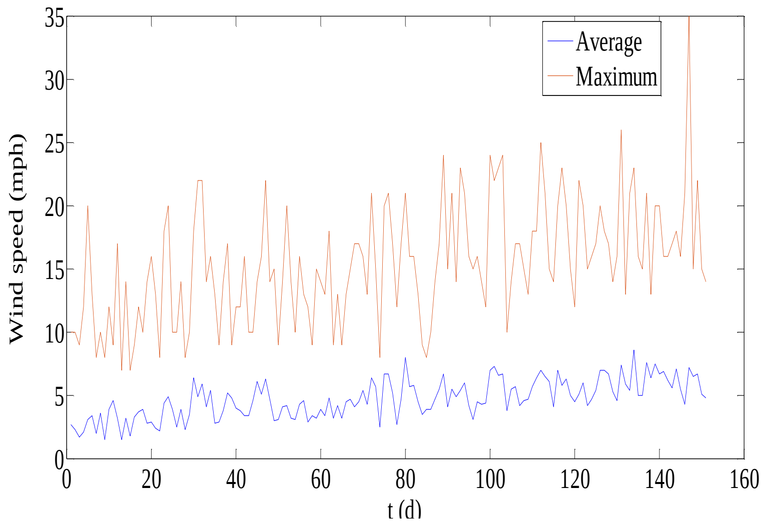

Figure 3. *Wind speed. Source of own elaboration, Matlab 2013B.*

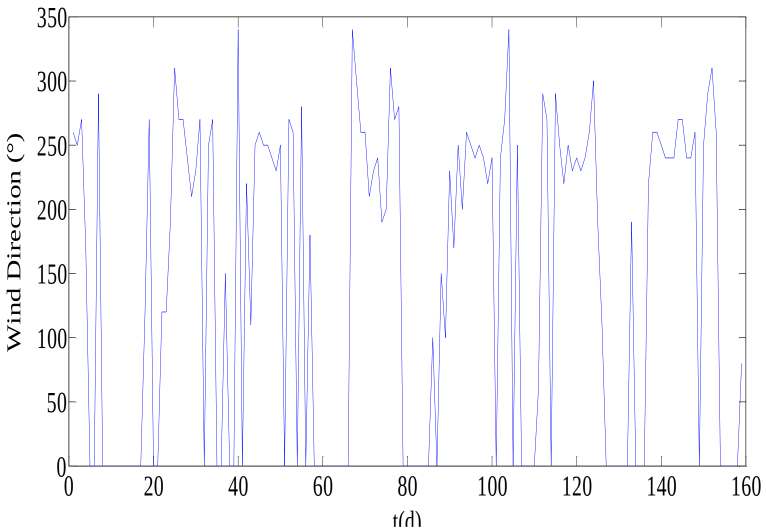

Figure 4. *Wind direction. Source of own elaboration, Matlab 2013B.*

Fig. 5 describes the behavior of the wind turbine in the presence of different wind directions and at a constant speed. Different trajectory tracking tests were performed with different optimal control tunings, as a result the dynamic gain K for the control law parameter search is:

$$K = -(0.2)\mathrm{Pref} + 2.12 \tag{7}$$

where P_{ref} is the reference of the wind direction, the gains P y R were calculated heuristically resulting in:

$$P = \begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix} \tag{8}$$

$$R = 0.8 \tag{9}$$

The optimal control strategy is subjected to three stepwise changes in wind direction: 0° to 10°, 10° to 20°, and 20° to 30°. The wind speed remains constant at 20 mph since at that value the wind turbine is capable of generating electricity at its nominal power (Haro et al., 2021).

Figure 6 shows the control signal of the actuator that drives the orientation of the wind turbine, dosing the necessary voltage in such a way that it represents energy savings.

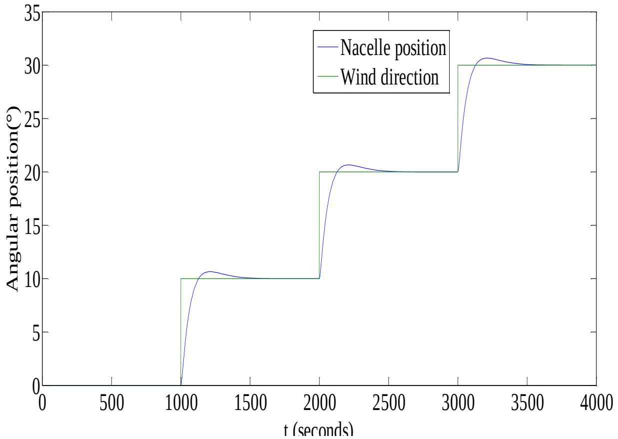

Figure 5. *Wind direction tracking. Source of own elaboration, Matlab 2013B.*

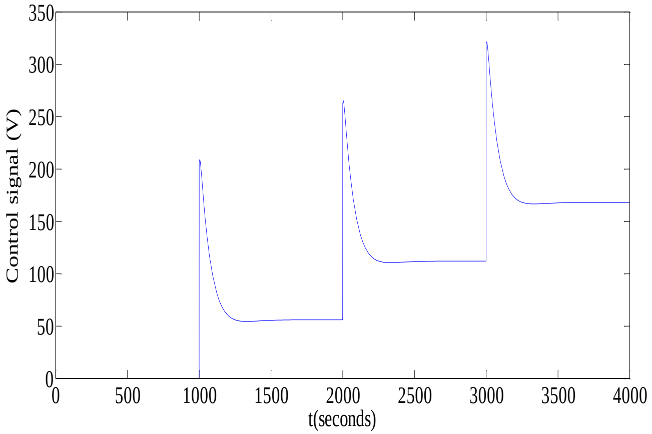

Figure 6. *Actuator control signal. Source of own elaboration, Matlab 2013B.*

Conclusions

This work presents an optimal orientation control strategy for a small-scale wind turbine (20kW). The control strategy is based on the system model and the tuning of its parameters is performed with a search method that depends on a function based on the desired references of the system. The proposed strategy allows regulating the power generated by the orientation of the wind turbine nacelle under different conditions of wind direction. The results obtained demonstrate the effectiveness of the proposed method to take advantage of the available wind potential in the event of unforeseen changes in the direction of the wind. Future work includes the validation of the control strategy in a scale wind turbine.

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