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Optimal active yaw control for a wind turbine

Control de guiñada activo óptimo para un aerogenerador

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Abstract

In this work a control strategy based on the mathematical model of an active yaw system for a 20 KW horizontal axis wind turbine is proposed. It allows to increase its efficiency in the presence of changes in the intensity and direction of the wind. The inverse optimal control strategy is implemented based on the mathematical model using the equations of state that represent the dynamics of the yaw system, whose model was obtained with the FAST program, specialized software for modeling wind turbines, which allows obtaining the mathematical model of the orientation system in a more precise way. The results are presented via simulation, where the control strategy is validated in the presence of disturbances. The contribution of this work lies in the application of the optimal control strategy and the tuning parameter search strategy of the control law.

Inverse optimal control, Parameter search strategy, Yaw control

Resumen

En este trabajo se propone desarrollar una estrategia de control avanzada para el modelo matemático que representa un sistema de orientación activa de un aerogenerador de eje horizontal de 20 KW, que le permita incrementar su eficiencia en presencia de cambios en la intensidad y dirección del viento. Se implementará la estrategia de control óptimo inverso basado en el modelo matemático usando las ecuaciones de estado que representan las dinámicas del sistema de orientación, cuyo modelo fue obtenido con el programa FAST, programa especializado para el modelado de aerogeneradores, que permite obtener el modelo matemático del sistema de orientación de forma más precisa. Los resultados se presentan vía simulación, donde se valida la estrategia de control en presencia de perturbaciones. La contribución de este trabajo radica en la aplicación de la estrategia de control óptimo y la aplicación de la estrategia de búsqueda de parámetros de sintonización de la ley de control.

Control óptimo inverso, Estrategia de búsqueda de parámetros, Control de orientación

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Introduction

Due to the great environmental pollution caused by gasoline motor vehicles, nuclear plants, hydroelectric plants that use turbines activated by fossil fuels and the high costs for the installation of electrical networks in the communities, it is necessary to use clean energy obtained from the air, water, sun, as well as their optimization to make the most of the energy obtained from different sources at cheaper costs. 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 (Farag, W. et al, 2017). In the last two decades many investigations have discussed how to maximize the wind energy extracted from wind turbines. 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.

The control of the attack angle and the torque of the generator has been of greater interest on the part of the researchers, since it has a notable effect on the extraction of energy; on the other hand, yaw control of the nacelle is of lower interest due to its lesser effect on small and medium size turbines (few hundred KW). However, the trend in the industry is to use turbines with megawatt capacities and sophisticated control systems for the nacelle, which are necessary for energy extraction and protection of internal components (Farag, W. et al, 2017).

The kind of orientation system for low power wind turbines with the greatest application is the passive type, which has a vane at the rear of the wind turbine, which positions the rotor in the direction of the wind, the active orientation system is made up of mechanical, electrical, and hydraulic elements.

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 (Rodríguez-Solano A. et al, 2018). The normal function of the active guidance system is to follow the direction of the wind. Also, in extreme conditions like a storm, the rotor is positioned 90° out of the wind (De Zutter, S. et al, 2017). In this work, it is proposed to develop an advanced control strategy for the mathematical model that represents an active orientation system of a 20 KW horizontal axis wind turbine, which allows it to increase its efficiency in the presence of changes in the intensity and direction of the wind.

Justification

This project originated from the need to increase the efficiency of horizontal axis wind turbines, implementing an advanced control technique, making the most of the force of the wind to generate energy. The contribution of this project lies in developing a control strategy to optimize the energy produced by adjusting the orientation angle of the wind turbine nacelle. The content of the article is presented as follows: section 1, a brief description of the wind turbine, section 2 presents the mathematical model of the orientation system, section 3 describes the control strategy, section 4 presents the method of searching for parameters of the control law, section 5 the results, and finally the conclusions.

1. Description of the wind turbine

The wind turbine system considered in this article is a three-blade horizontal axis type. A typical wind turbine consists of 3 main components: a)- The nacelle, which contains the main components of the turbine, including the gearbox and the electric generator, b)- The tower, where the nacelle is supported, c)- Rotor and its blades which capture the energy of the wind and transfer it to the rotor shaft and then to the electric generator.

2. Mathematical model of the 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. In the literature, different expressions have been used for the turbine power in case the orientation angle γ is different from zero. Fig. 1 illustrates the definition of the orientation angle γ. It is the angle between the direction of the approaching wind speed and the rotor axis (De Zutter, S. et al, 2017).

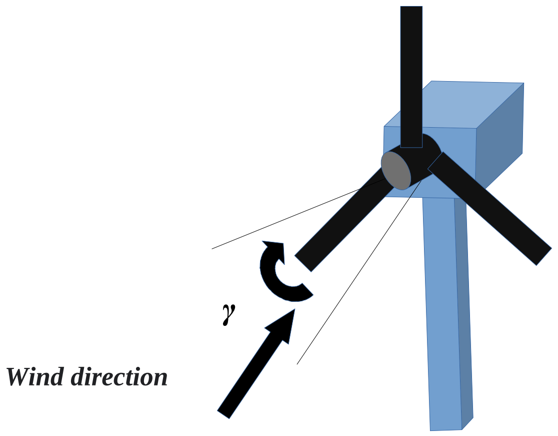

Figure 1 Definition of the orientation angle
Source of Own Elaboration

The power is multiplied by the cosine of the orientation angle:

$$Pt=1/2\,\rho\pi R^2V^3Cp\cos\gamma \qquad (1)$$

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 (De Zutter, S. et al, 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:

$$Pt=1/2\,\rho\pi R^2V^3Cp\cos^3\gamma \qquad (2)$$

Wind tunnel tests were performed on a turbine rotor under oriented inlet conditions. Pressure distributions over the blade section were measured to calculate forces and power (De Zutter, S. et al, 2017). The measurements were shown to be close to the cos3 γ curve, ie equation (2). To accurately obtain the real power produced by the rotor, a detailed study using computational fluid dynamics (CFD) must be carried out, which is outside the scope of this work.

Fig. 2 shows the variation of the mechanical power produced from the orientation angle of the wind generator. It is observed that if the rotor faces the wind direction (yaw = 0°), the wind turbine will obtain the maximum efficiency in power generation. Otherwise, when there is a misalignment between the rotor axis and the wind direction (yaw ≠ 0 °), it implies a decrease in the capture of wind energy.

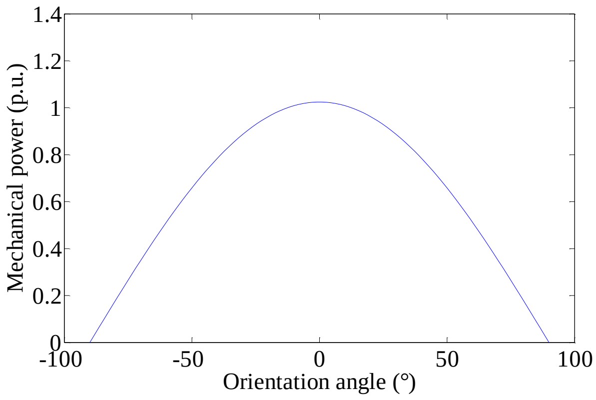

Figure 2 Mechanical power as a function of orientation angle
Source of own elaboration, Matlab 2013B.

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 (Jonkman, J. M., et al 2005):

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

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 nacelle yaw actuator.

Parameter	Value
Nacelle mass	960 Kg
Yawsprint	75,392 N•m/rad
YawIner	7,532.9 kg•m²
YawDamp	55,336.7 N•m/(rad/s)
Rated speed of nacelle orientation	0.3 ° /s

Table 1 Nacelle features

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

$$\begin{aligned} \dot{x_1} &= x_2 \\ \dot{x_2} &= -10x_1 - 7.3x_2 + 10u \quad (4) \\ y &= x_1 \end{aligned}$$

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.

3. Optimal control strategy for the active yaw system

Consider a nonlinear system in discrete time:

$$x_{k+1} = f(x_k) + g(x_k)u_k \quad (5)$$

where $x_k \in R^n$ is the state of the system at time $k \in Z_+$, $u \in R_m$ is the control input, f: $R^n \rightarrow R^n$, g: $R^n \rightarrow R^{nxm}$ are smooth mapping functions. Assume f(0)= 0 and $g(x_k) \neq 0$, $\forall\, x_k$. The control law is inverse optimal in the sense that it minimizes the functional variety given as:

$$J(x_k) = \sum_{n=k}^{\infty}(l(x_n) + u_n^T R(x_n) u_n)\text{, k=0, 1, 2, ...} \quad (6)$$

Using the optimal value function $J^*(x_k)$ for Equation (5) in terms of the Lyapunov function $V(x_k)$, Equation (6) can be rewritten as:

$$V(x_k) = l(x_k) + u_k^T R u_k + \sum_{n=k+1}^{\infty} (l(x_n) + u_n^T R u_n) \quad (7)$$

$$V(x_k) = l(x_k) + u_k^T R u_k + V(x_{(k+1)}) \quad (8)$$

where the boundary condition V(0)= 0 is required for $V(x_k)$ to become a Lyapunov function. We define the discrete-time Hamiltonian $H(x_k,u_k)$ as:

$$H(x_k, u_k) = l(x_k) + u_k^T R u_k + V(x_{(k+1)}) - V(x_k) (9)$$

In (Ornelas-Tellez, F., et al, 2011), a Lyapunov function for discrete-time control is proposed to solve equation (9), in the form:

$$V_c(X_k) = 1/2\, x_k^T P_k x_k, P_k = P_k^T > 0 \quad (10)$$

Substituting (10) in (9) and solving, the optimal control law is obtained:

$$u_k^* = -1/2\left(R(x_k) + \cdots. + 1/2\, g^T(x_k) P_k g(x_k)\right)^{-1} g^T(x_k) P_k f_d(x_k) \quad (11)$$

P_k and R are symmetric and positive definite matrices. Then the existence of the inverse in (11) is guaranteed. The control law (11) depends on the P_k matrix at each time step.

4. Searching method of tuning parameters

In (Villegas-Ruvalcaba, et al. 2021) a new method is given for adjusting parameters of the optimal control law. Equation (11) is replaced by:

$$u_k^* = -K\left(R(x_k) + \cdots + 1/2\, g^T(x_k) P_k g(x_k)\right)^{-1} g^T(x_k) P_k f_d(x_k) \quad (12)$$

The goal is to find the gain K that adjusts the control u^*_k, with control law parameters P_k and R fixed. To achieve this goal, we purpose the next methodology:

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

5. 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 (13)-(15).

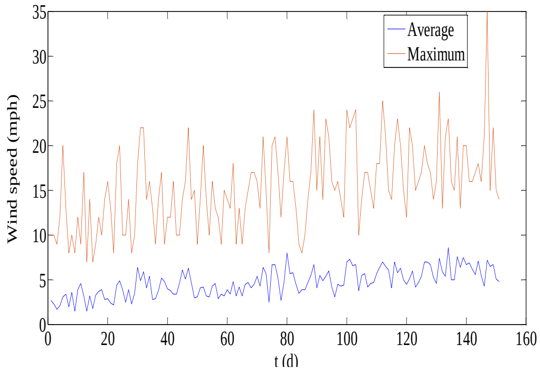

Figure 3 Wind speed.
Source of own elaboration, Matlab 2013B.

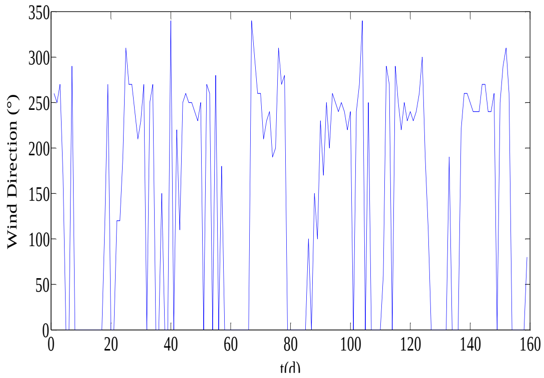

Figure 4 Wind direction
Source of own elaboration, Matlab 2013B

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.

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:

$$K = -(0.2)\text{Pref} + 2.12 \tag{13}$$

where P_{ref} is the reference of the wind direction,the gains P and R were calculated heuristically as:

$$P = \begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix} \tag{14}$$

$$R = 0.8 \tag{15}$$

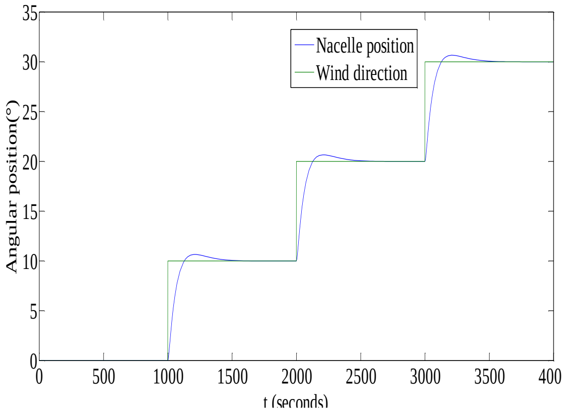

Figure 5 Wind direction tracking
Source of own elaboration, Matlab 2013B

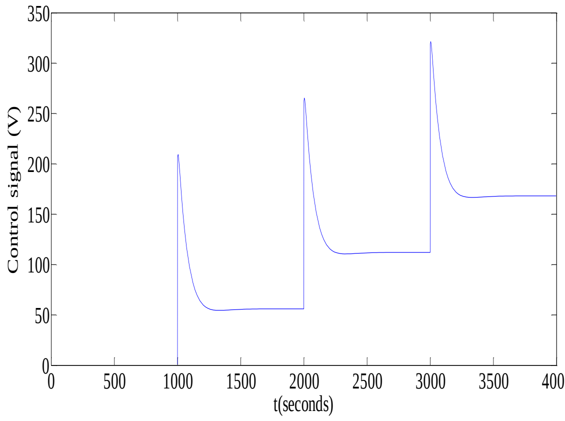

Figure 6 Actuator control signal

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).

Fig. 5 shows the orientation tracking in the face of changes in wind direction, the optimal control keeps the wind turbine in the desired position in a stable manner, guaranteeing that the power generated by the system is maximum. 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.

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.

References

[1] Haro, A., Young, H., & Pavez, B. (2021). Fuzzy Logic Active Yaw Control of a Low-Power Wind Generator. *IEEE Latin America Transactions*, *19*(11), 1941-1948. https://ieeexplore.ieee.org/abstract/document/9475848
DOI= 10.1109/tla.2021.9475848
Last visited on 08/26/2022

[2] De Zutter, S., De Kooning, J. D., Samani, A. E., Baetens, J., & Vandevelde, L. (2017, August). Modeling of active yaw systems for small and medium wind turbines. In *2017 52nd International Universities Power Engineering Conference (UPEC)* (pp. 1-6). IEEE. https://ieeexplore.ieee.org/abstract/document/8231885
DOI= 10.1109/upec.2017.8231885
Last visited on 08/26/2022

[3] Farag, W., El-Hosary, M., Kamel, A., & El-Metwally, K. (2017, November). A comparative study and analysis of different yaw control strategies for large wind turbines. In *2017 Intl Conf on Advanced Control Circuits Systems (ACCS) Systems & 2017 Intl Conf on New Paradigms in Electronics & Information Technology (PEIT)* (pp. 132-139). IEEE. https://ieeexplore.ieee.org/abstract/document/8303031
DOI= 10.1109/accs-peit.2017.8303031
Last visited on 08/26/2022

[4] Jonkman, J. M., & Buhl, M. L. (2005). *FAST user's guide* (Vol. 365, p. 366). Golden, CO, USA: National Renewable Energy Laboratory.
https://openfast.readthedocs.io/en/main/_downloads/d8bd014121d6505cb25cf49bee5eaa80/Old_FAST6_UsersGuide.pdf
DOI= 10.2172/15020796
Last visited on 08/26/2022

[5] Ornelas-Tellez, F., Sanchez, E. N., Loukianov, A. G., & Navarro-López, E. M. (2011, December). Speed-gradient inverse optimal control for discrete-time nonlinear systems. In *2011 50th IEEE Conference on Decision and Control and European Control Conference* (pp. 290-295). IEEE. https://ieeexplore.ieee.org/abstract/document/6160374
DOI= 10.1109/cdc.2011.6160374
Last visited on 08/26/2022

[6] Villegas-Ruvalcaba, M., Gurubel-Tun, K. J., & Coronado-Mendoza, A. (2021). Robust Inverse Optimal Control for a Boost Converter. *Energies*, *14*(9), 2507. https://www.mdpi.com/1996-1073/14/9/2507
DOI= 10.3390/en14092507
Last visited on 08/26/2022

[7] Rodríguez-SolanoA, B., Reyna-GómezA, A., Avilés-ÁlvarezB, J. A., Campos-MercadoC, E., & García-SalazarD, O. (2018). Control de orientación de un aerogenerador de baja potencia para regular el voltaje de salida. *Ingenierías*, *21*(81), 5. http://ingenierias2.uanl.mx/81/documentos/A21_N81_control_del_sistema.pdf
Last visited on 08/26/2022

[8] Weather Underground (Mayo 2022). https://www.wunderground.com Last visited on 08/26/2022