Pitch variable Wind Turbine Control

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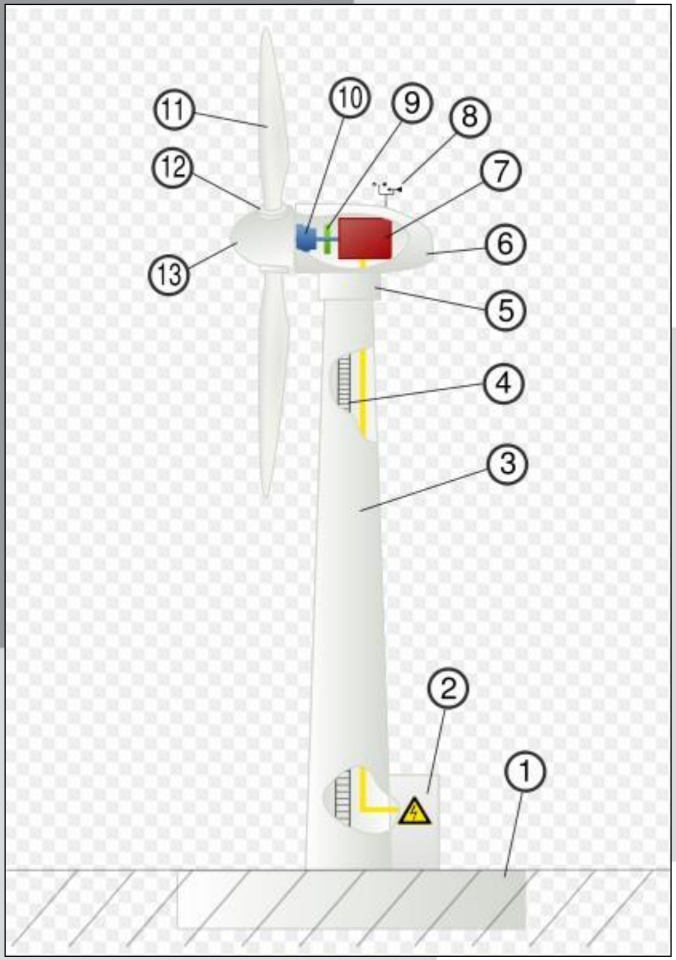
Wind Turbine Structure



1. Base
2. Electrical network connection
3. Tower
4. Stairs
5. Variable Yaw system
6. Nacelle
7. Generator
8. Anemometer
9. Brake
10. GearBox
11. Blade
12. Variable pitch system
13. Hub

Wind Turbine Structure

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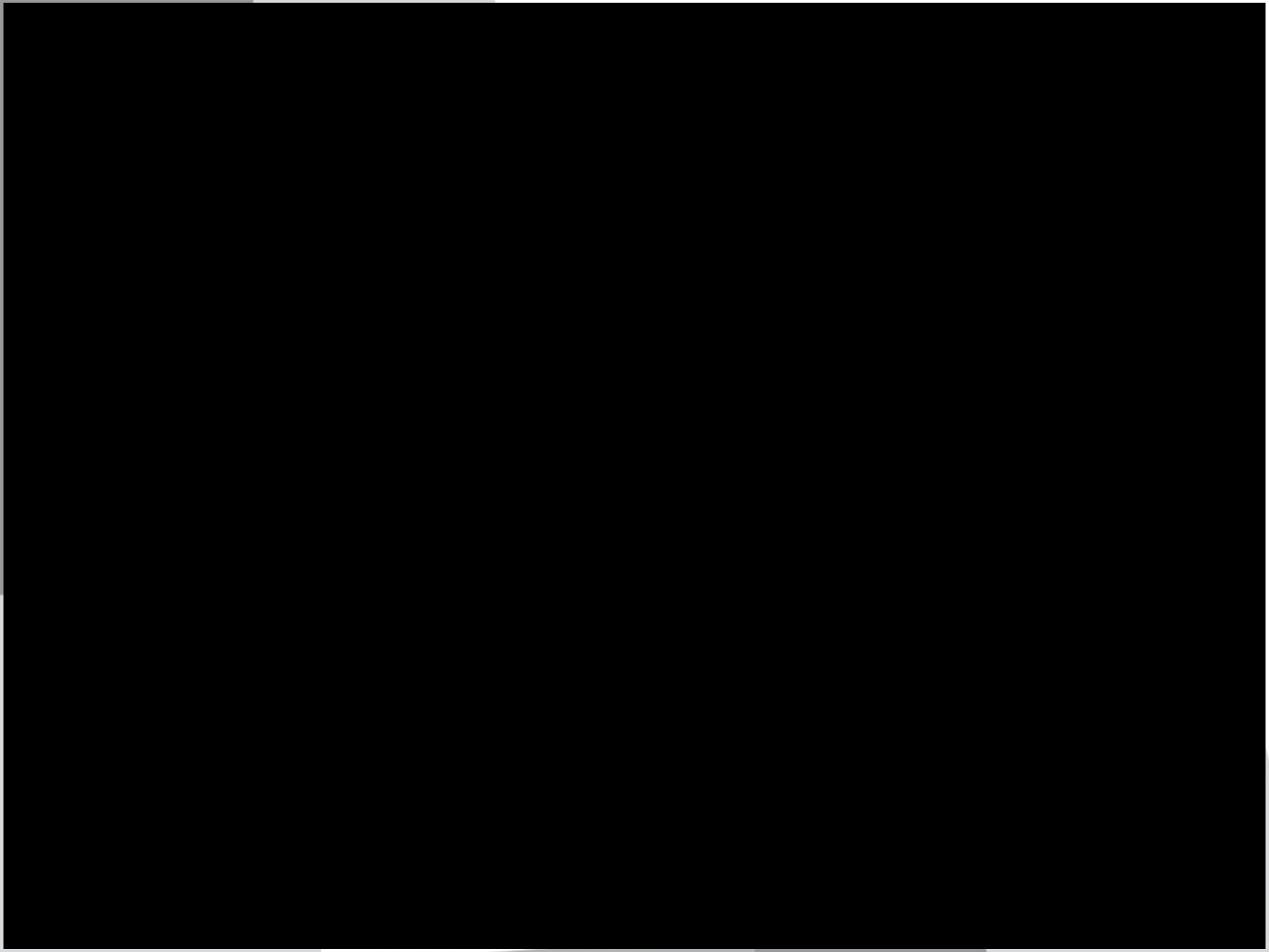
ARGOLABE
WIND TURBINE
GRUPO
PIEROLA

Wind Turbine Structure



Wind Turbine Model

- Wind Turbine Control Main objectives:
  - Maximize the Annual Energy Production.
  - Reduce the mechanical loads (fatigue).
  - Avoid resonant frequencies.

Wind Turbine Model

- Wind Turbine Aerodynamics.
- Power train Model.
- Electrical machine and power electronics stage Model.

Wind Turbine Model

- Wind Turbine Aerodynamics

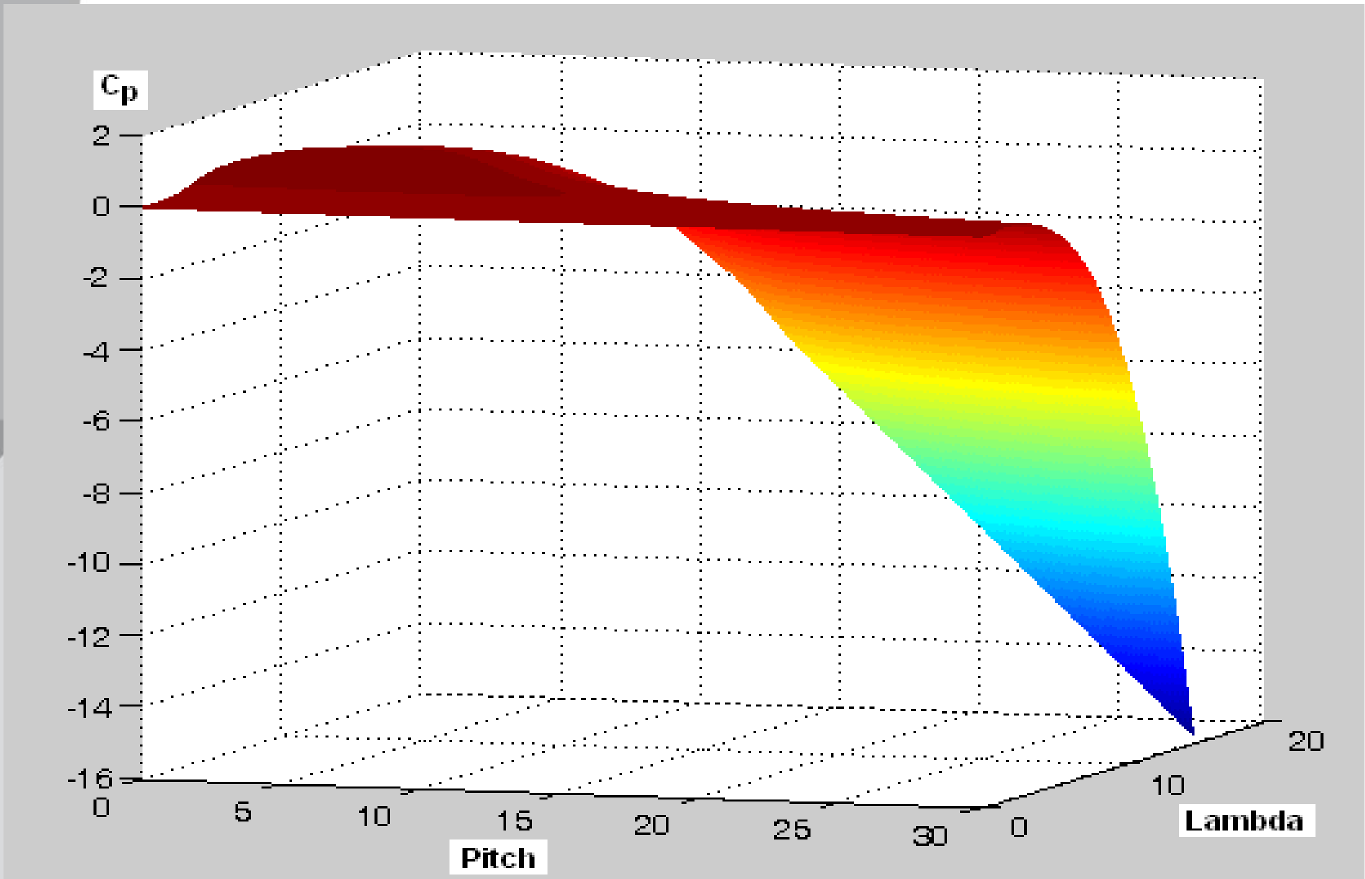
$$P = C_P \cdot \frac{\pi \cdot v^3 \cdot \rho_{air} \cdot R^2}{2}$$

P = Captured power [W]
V = Wind Speed [m/s]
R = Radius [m]
ρ_{air} = Air density [kg/m^3]

Wind Turbine Model

•Cp: Power coefficient:

• TSR $\lambda = \dfrac{\omega \cdot R}{v}$



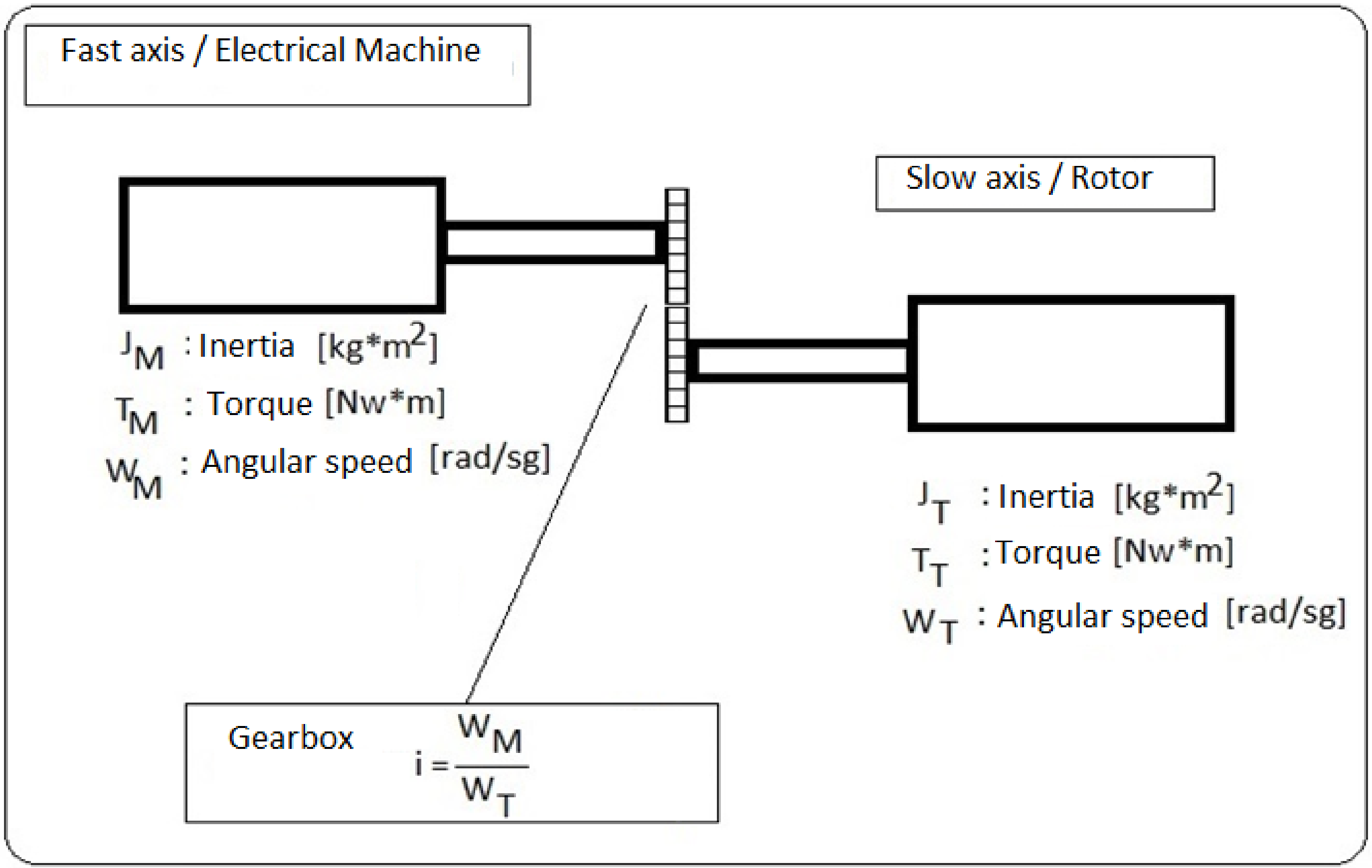
Wind Turbine Model

- Aerodynamical torque:

$$T_T = \frac{P}{w} = \frac{C_P \cdot \pi \cdot v^3 \cdot \rho_{\text{aire}} \cdot R^2}{2 \cdot w}$$

Wind Turbine Model

- Power train modeling:



Wind Turbine Model

- Power train dynamical model

$$\frac{J_T}{i}\cdot\frac{dw_M}{dt}=T_T-i\cdot\left[J_M\cdot\frac{dw_M}{dt}+T_M\right]$$

$$\frac{J_T}{i^2}\cdot\frac{dw_M}{dt}=\frac{T_T}{i}-J_M\cdot\frac{dw_M}{dt}+T_M$$

$$\left[\frac{J_T}{i^2}+J_M\right]\cdot\frac{dw_M}{dt}=\frac{T_T}{i}-T_M$$

$$\frac{dw_M}{dt}=\frac{\frac{T_T}{i}-T_M}{\frac{J_T}{i^2}+J_M}$$

Wind Turbine Model

- Simple model of the electrical machine + Power stage:

$$\frac{dT_M}{dt} = \tau_{PE} \cdot (T_M^{\ *} - T_M)$$

$T_M^{\ *}$: Torque Set Point (N.m)

T_M : Real Torque Set Point (N.m)

τ_{PE} : Power Electronics time constant [seg^{-1}]

Wind Turbine Control

- Objectives:
  - Power, fatigue, mechanical resonance avoidance
- Control inputs:
  - Wind Turbine Speed w
- Control outputs:
  - Electrical machine torque
  - Blade pitch angle
  - Wind Turbine yaw angle.

Wind Turbine Control

- At low rotor speed, pitch=0

$$T_{T,optim} = \frac{P_{optim}}{w} = \frac{C_{P,optim} \cdot \pi \cdot v^3 \cdot \rho_{\text{air}} \cdot R^2}{2 \cdot w}$$

$$\lambda = \frac{w \cdot R}{v} \rightarrow v^3 = \frac{w^3 \cdot R^3}{\lambda^3}$$

$$T_{T,optim} = \frac{C_{P,optim} \cdot \pi \cdot \rho_{\text{air}} \cdot R^5}{2 \cdot \lambda_{optim}^3} \cdot w^2$$

Wind Turbine Control

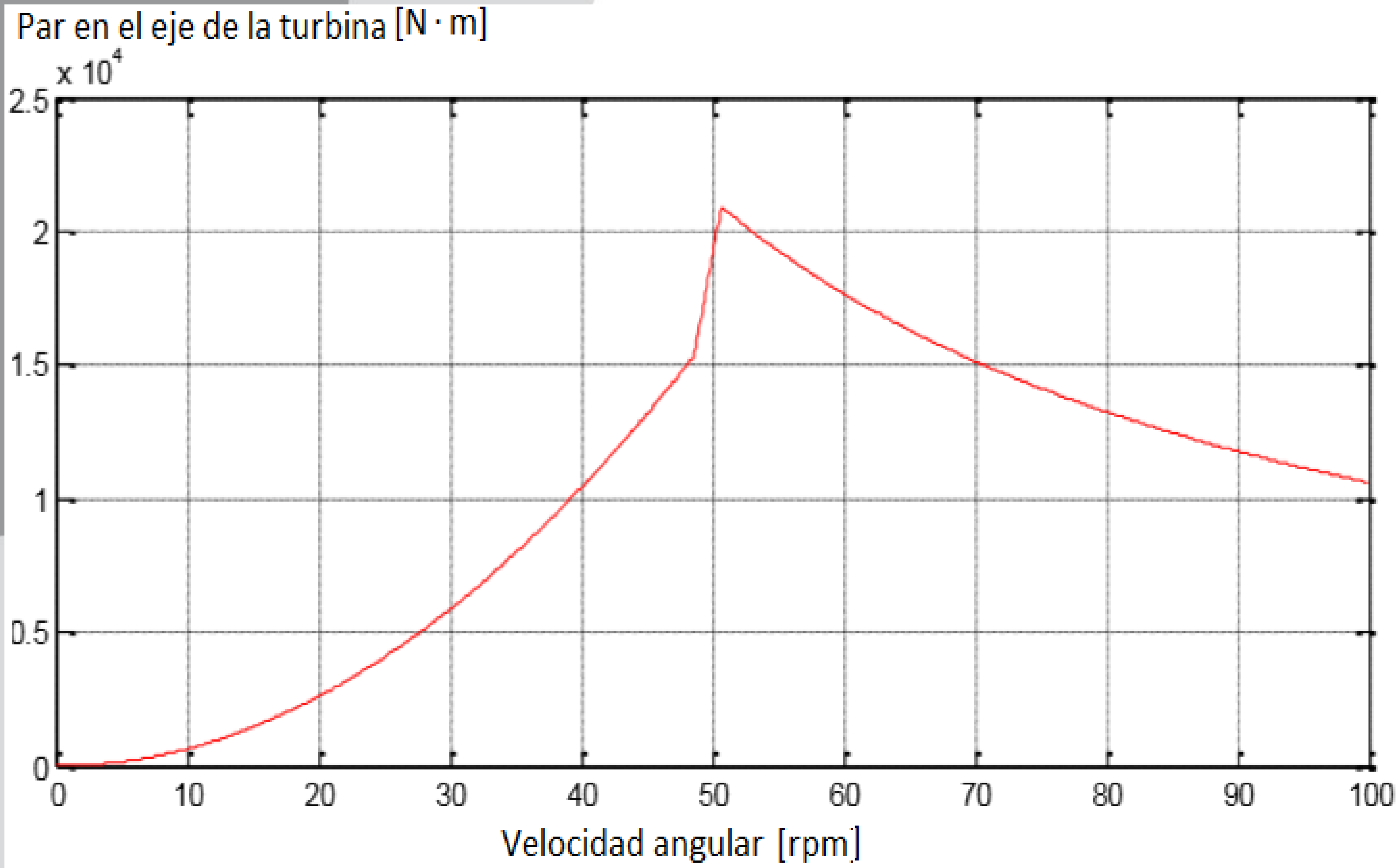
- At low rotor speed (pitch=0)

$$T_{M,optim} = \frac{C_{P,optim} \cdot \pi \cdot \rho_{\mathrm{air}} \cdot R^5}{2 \cdot i_{reduc} \cdot \lambda_{optim}^3} \cdot w^2$$

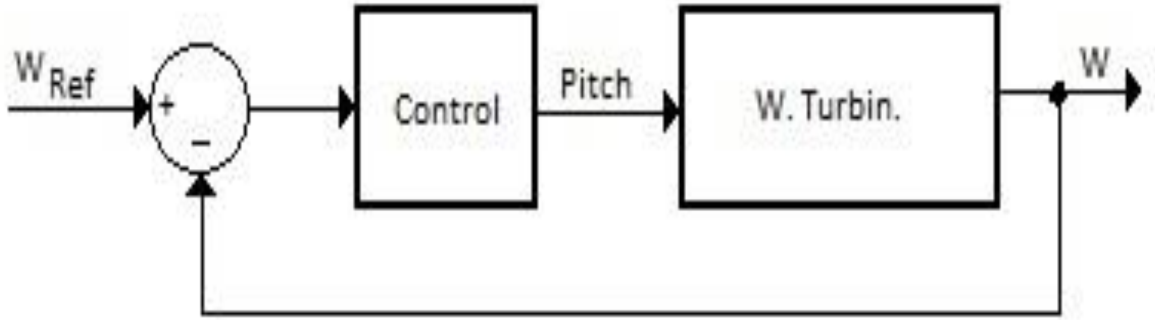
- At high rotor speed the control changes the pitch value in order to keep the rotor speed at set point value.

$$T_{M,HighSpeed} = \frac{P_{no\min al}}{i_{reduc} \cdot w}$$

Wind Turbine Control



Wind Turbine Control



Wind Turbine Control

- PI controller equations + power train model equations:

$$J_{Total} \cdot \frac{dw}{dt} = \frac{C_P \cdot \pi \cdot v^3 \cdot \rho_{\text{aire}} \cdot R^2}{2 \cdot w} - \frac{P_N}{w} = f(w, v, \beta)$$

$$\beta = K_P \cdot (w^* - w) + K_I \cdot \int (w^* - w) dt$$

Wind Turbine Control

•Linearization around a working point:

$$v = cte.$$

$$w = w^* + \Delta w$$

$$\beta = \beta^* + \Delta\beta$$

$$J_{Total} \cdot \frac{d\Delta w}{dt} = \frac{\partial f}{\partial w} \cdot \Delta w + \frac{\partial f}{\partial \beta} \cdot \Delta\beta + \frac{\partial f}{\partial v} \cdot \Delta v$$

Wind Turbine Control

- Linearization around a working point:

$$\frac{\partial f}{\partial w} = \frac{P_N - P_T}{w^{*2}}$$

$$\frac{\partial f}{\partial \beta} = \frac{1}{w^*} \cdot \frac{\partial P_T}{\partial \beta}$$

$$\frac{\partial f}{\partial v} = 0$$

Wind Turbine Control

•Linearization around a working point:

$$J_{Total} \cdot \frac{d\Delta w}{dt} = \frac{P_N - P_T}{w^{*2}} \cdot \Delta w + \frac{1}{w^*} \cdot \frac{\partial P_T}{\partial \beta} \cdot \Delta \beta$$

$$J_{Total} \cdot \Delta w = \frac{P_N - P_T}{w^{*2}} \cdot \Delta w + \frac{1}{w^*} \cdot \frac{\partial P_T}{\partial \beta} \cdot \Delta \beta$$

$$J_{Total} \cdot \Delta w = \frac{P_N - P_T}{w^{*2}} \cdot \Delta w + \frac{1}{w^*} \cdot \frac{\partial P_T}{\partial \beta} \cdot (K_P \cdot \Delta w + K_I \cdot \Delta w)$$

Wind Turbine Control

•Linearization around a working point:

$$\ddot{\Delta w} + \frac{\frac{P_N - P_T}{w^{*2}} - \frac{K_P}{w^*} \cdot \frac{\partial P_T}{\partial \beta}}{J_{Total}} \cdot \dot{\Delta w} + \frac{K_I}{J_{Total} \cdot w^*} \cdot \frac{\partial P_T}{\partial \beta} = 0$$

$So:$

$$2\xi w_n = \frac{\frac{P_N - P_T}{w^{*2}} - \frac{K_P}{w^*} \cdot \frac{\partial P_T}{\partial \beta}}{J_{Total}}$$

$$W_n{}^2 = \frac{K_I}{J_{Total} \cdot w^*} \cdot \frac{\partial P_T}{\partial \beta}$$

Wind Turbine Control

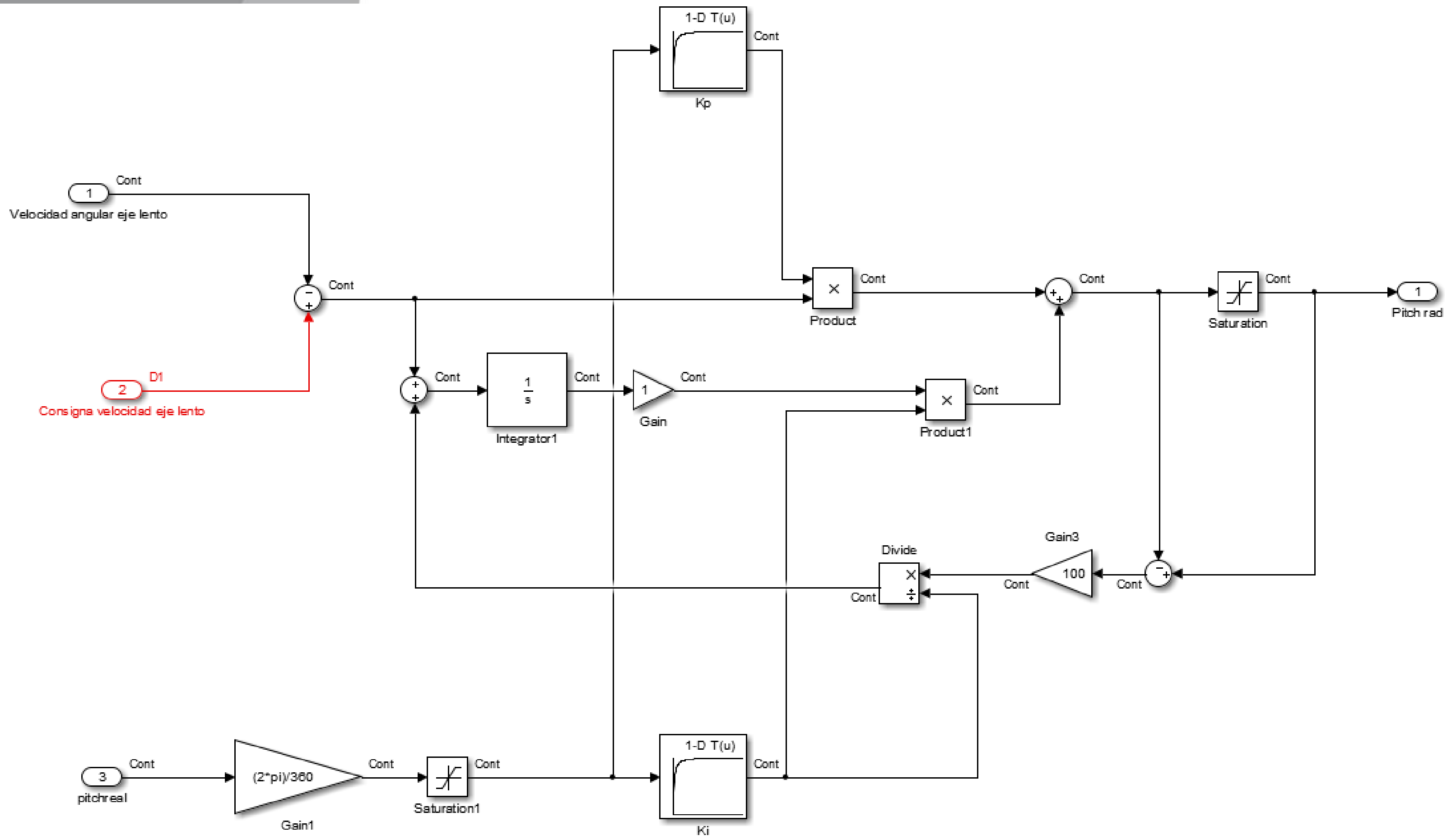
- PI controllers' parameters

$$\boxed{K_P = -\frac{W_n^{\,2} \cdot J_{Total} \cdot w^*}{\dfrac{\partial P_T}{\partial \beta}}}$$

$$\boxed{K_I = \left[-2 \cdot \xi \cdot W_n \cdot J_{Total} + \frac{P_N - P_T}{w^{*2}}\right] \cdot \frac{w^*}{\dfrac{\partial P_T}{\partial \beta}}}$$

Wind Turbine Control

- PI Controller (AntiReset Windup)



Questions

- Thanks for paying attetion
- Relates journals
  - Energies
  - Wind Energy
  - RIAI
  - IEEE on Renewable Energies
  - IEEE on Power Electronics
- Good SW: NREL, Fast, Matlab&Simulink

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References

- Abad, G., Lopez, J., Rodriguez, M., Marroyo, L. & Iwanski, G. (eds) 2011, *Doubly Fed Induction Machine: Modeling and Control for Wind Energy Generation*, 1st edn, Wiley-IEEE Press: Hoboken, NJ USA.
- Bianchi, F.D., de Battista, H. & Mantz, R.J. 2007, "Wind Turbine Control Systems. Principles, Modelling and Gain Scheduling Design" in Springer, , pp. 49-79.
- Bir, G. 2013, 26/6/2013-last update*, NWTC Design Codes . .* Available: http://wind.nrel.gov/designcodes/preprocessors/bmodes/ [2014, 28/7/2014].
- Burton, T., Jenckins, N., Sharpe, D. & Boossanyi E. 2011, *Wind Energy Handbook,* 2ª edn, John Wiley & sons.
- Cagnina, L. & Esquivel, S.C. 18/10/2013, *Particle swarm optimization para un problema de optimización combinatoria*, Red de Universidades con Carreras en Informática (RedUNCI), X Congreso Argentino de Ciencias de la Computación.
- Carta, J.A., Ramírez, P. & Velázquez, S. 2009, "A review of wind speed probability distributions used in wind energy analysis: Case studies in the Canary Islands", *Renewable and Sustainable Energy Reviews,* vol. 13, no. 5, pp. 933-955.
- J.X. & Saenz, J. 2003, "Modeling and control of a wind turbine driven doubly fed induction generator", *IEEE TRANSACTIONS ON ENERGY CONVERSION,* vol. 18, no. 2, pp. 194-204.

References

- Clerc, M. 2005, *Particle Swarm Optimization,* 1st edn, Import Diff.
- Danish Wind Industry Association 2003, 7 de Mayo de 2003-last update*, Curva de potencia de un aerogenerador*. Available: http://www.motiva.fi/myllarin_tuulivoima/windpower%20web/es/tour/wres/pwr.htm [2014, .
- Departament of Defense 1997, *MIL-HDBK-1797*, Norma edn, USA, USA.
- Eichler, M. 2008, "
En el mar y en la línea: convertidor PCS 6000 para turbinas eólicas marinas de 5 MW ", *Revista ABB,* [Online], vol. 3, , pp. 56-61.
- González-González, A., Etxeberria-Agiriano, I., Zulueta, E., Oterino-Echavarri, F. & Lopez-Guede, J. 2014, "Pitch Based Wind Turbine Intelligent Speed Setpoint Adjustment Algorithms.
  ", *Energies,* vol. 7, pp. 3793-3809.
- Hammerun, T. 2006, *A fatigue Approach to Wind Turbine Control*, Technical University of Denmark.
- Hansen, M.H., Larsen, A.J. & Poulsen, N.K. 2006, *Control design for a pitch-regulated, variable speed wind turbine*, RisØ National Laboratory, Denmark.

References

•Jonkman, J. & Jonkman, B. 2014, 9/7/2014-last update, *NWTC Computer-Aided Engineering Tools (FAST v8).* Available: http://wind.nrel.gov/designcodes/simulators/FAST8/ [2014, .

•Leidhold, R., García, G. & Valla M.I. 2002, "Control para máximo rendimiento de generadores eólicos de velocidad variable, con limitación de velocidad y potencia", , ed. XIV Congreso Brasileiro de Automática, XIV Congreso Brasileiro de Automática, , 2002, pp. 3121-3122.

•Oterino, F., Zulueta, E., Ramos, J.A., Calvo, I. & Lopez Guede, J.M. 2013, "Application of Differential Evolution as nethod of pitch control settings in a wind turbine", *Renevable Energy an Power Quality (RE&PQJ),* vol. 11.

•Oterino, F., Zulueta, E., Ramos, J.A., Lopez Guede, J.M. & Larrañaga, J.M. 2012, "Particle swarm optimization based tuning for a small wind turbine pitch control", *International Journal on "Technical and Physical Problems of Engineering",* vol. 4, no. 4, pp. 164-170.

•Price, K. & Storm, R.M. 2005, *Differential Evoluton: A prcticak Approach to global optimitation,* 1st edn, Springer, Alemania.

•Red eléctrica de España 2013, "Informe del Sistema Eléctrico español 2013" in , ed. Red eléctrica de España, 3/7/2014 edn, Red eléctrica de España, 28109 Alcobendas (Madrid), pp. 4.

•Sosa Toranzo, C. & Leguizamón, G. 2013, *Evolución diferencial como factor dse mutación dinámico*, XVIII Congreso Argentino de Ciencias de la Computación.

•Storm, R.M. & Price, K. 1997, "Differential Evolution - A simple and efficient heuristic for global optimization", *Journal of global optimization,* vol. 11, pp. 341-359.

•Tapia, A., Tapia, G., Ostolaza

- Eskerrik asko eta zuen etxean hartzeagatik!
- İlginiz ve misafirperverliği için teşekkür ederiz!
- Thanks you for your attention!