Pitching System for Small Scale Wind Turbine

EE432 Final Project

Lily Goldman

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Summary

The Cal Poly Wind Power(CPWP) club is competing in the 2023 Collegiate Wind Competition. For the turbine development portion of the competition, each team is required to create a small scale wind turbine to test in a wind tunnel to be compared on how well they produce a powercurve. CPWP club will use a PI controller for their pitching mechanism to best optimize the power output of the system. The pitching mechanism, in Figure 1, includes a PWM controlled linear actuator that when extended to different lengths, will vary the pitch of the blades from 10 to 20 degrees. The controller uses data from a voltage and current sensor to digitally control the system with an Arduino Uno.

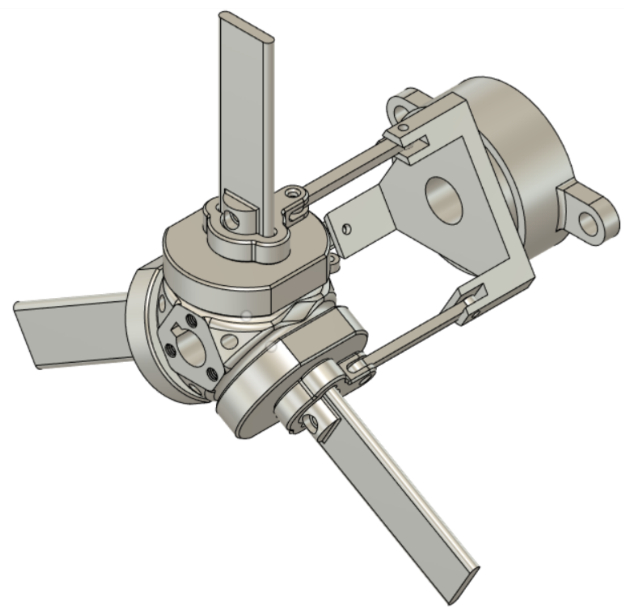


Figure 1. CAD model of four bar linkage pitching mechanism

Problem Statement

The competition requires that the turbine can optimize RPM while maintaining a stable power production from wind speeds between 5-11m/s. This stability has to be automated by the turbine while in the wind tunnel. Our team has decided that a digital PI controller can achieve this stability with zero steady state error, overshoot less than 25%, settling time less than 2 seconds, and rise time less than a second.

Literature Review

CPWP has never implemented a control system for their wind turbine. Most teams use state diagrams that use previous data gained by testing to control the system. Before the turbine goes into the competition wind tunnel, the best pitch for each wind speed would typically be found experimentally. This solution is more complicated for our club to achieve because we do not have a wind tunnel they can easily test in. These unknown conditions delt by CPWP closely reflect how full scale turbines respond to unknown wind speeds. They use dynamic equations to change the pitch and torque of the system to get peak power of the system. The aim of this work is the control of the aerodynamic rotor torque to give the maximum mechanical power and the control of the electromagnetic torque to give the maximum electrical power. [1]

Controlling the pitch angle of the turbine is the easiest way to exploit the aerodynamic power of the wind. “When wind speed exceeds the rated wind speed, in order to limit the output power of wind turbine around the rated value, we can adjust the pitch angle of wind turbine to realize, pitch controller will be activated at this time” .[2] Power of the wind is found in equation 1 and then manipulated in equation 2 to incorporate the power coefficient (C_p). The power coefficient is a function of the pitch angle and the tip speed. Equation 3 proves that as the pitch angle increases, the power coefficient reduces. Pitch control can be done by using one of three inputs: wind speed, generator speed, and generator power.

$$P_w = \frac{1}{2}\rho A V_w^3 \tag{1}$$

$$P_m = \frac{1}{2}\rho A V_w^3 C_p(\lambda, \beta) \tag{2}$$

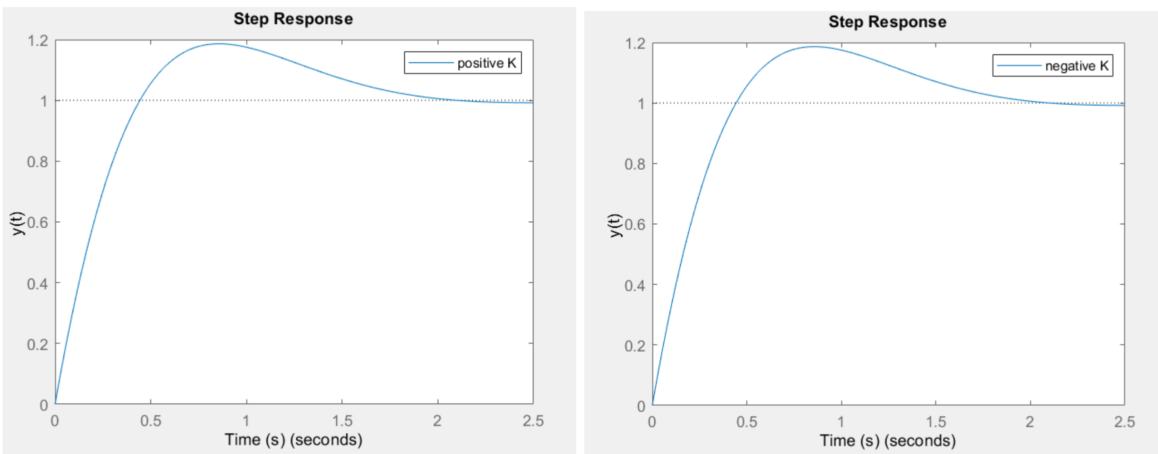
$$C_p = 0.5176\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right)e^{\frac{-21}{\lambda_i}} + 0.0068\lambda \tag{3}$$

In the textbook, Modern Control Systems, there is an example titled "Wind turbine speed control" that uses the transfer function in equation 4 and a PI controller to stabilize the system. All K values found in this example were negative. A further analysis of the system is done in figure 2 to better understand why the negative values would result in a stable system in equation

5. When switching the Kp and K values from negative to positive, it resulted in the same system response. I will continue my analysis by closely following the book's example, but with positive K values.

$$G_p(s) = \frac{K}{\tau s + 1} \qquad (4)$$

$$G_c(s) = K_P + \frac{K_I}{s} = -0.0025[\frac{s+2}{s}] \qquad (5)$$



Figures 2 & 3. Step response of G_p * G_c[left: K = 7200; Kp = 0.0025 and right: K = -7200; Kp = -0.0025]

System Design

The control system studied in this paper is a PI controller used to stabilize the system response of the first order transfer function in equation 6. The block diagram of this system is in figure 4.

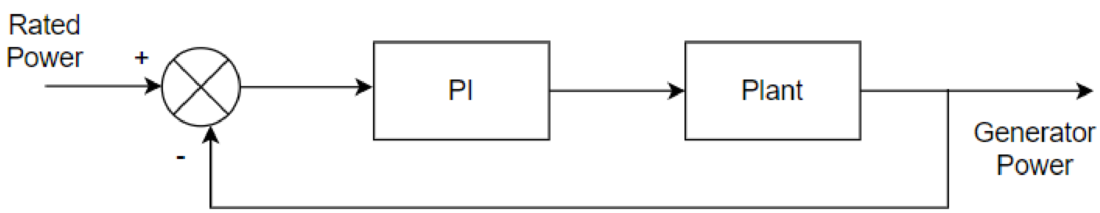


Figure 4. Continuous time block diagram of pitching system

The dynamic equation (4) from the textbook is used as the plant transfer function and the PI equation (5) in the system controller. The values are updated in this analysis to reflect the CPWP competition wind turbine. The tau in equation 4 is 2 seconds because of the weight on the servo and the stroke speed of 3.3mm/sec.

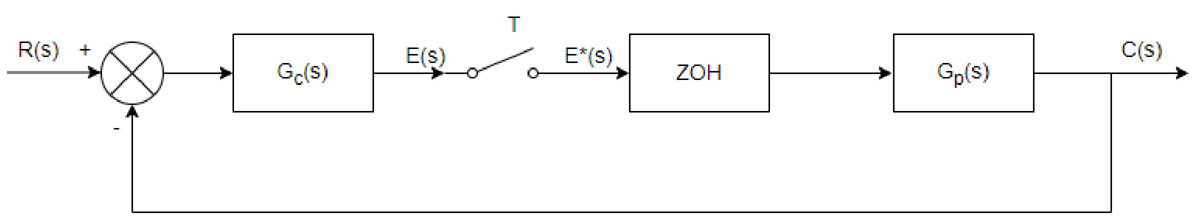


Figure 5. Discrete time block diagram of pitching system

To then discretize the system, a sampler and a ZOH is added in between the controller and the plant as seen in Figure 5. The sampler will trigger every 0.05 seconds.

Computer Simulations

G(s) was first simulated in matlab to verify the system's stability. Figure 6 illustrates a stable system that has a very slow rise time.

$$G(s) = \frac{1}{2s+1} \qquad (6)$$

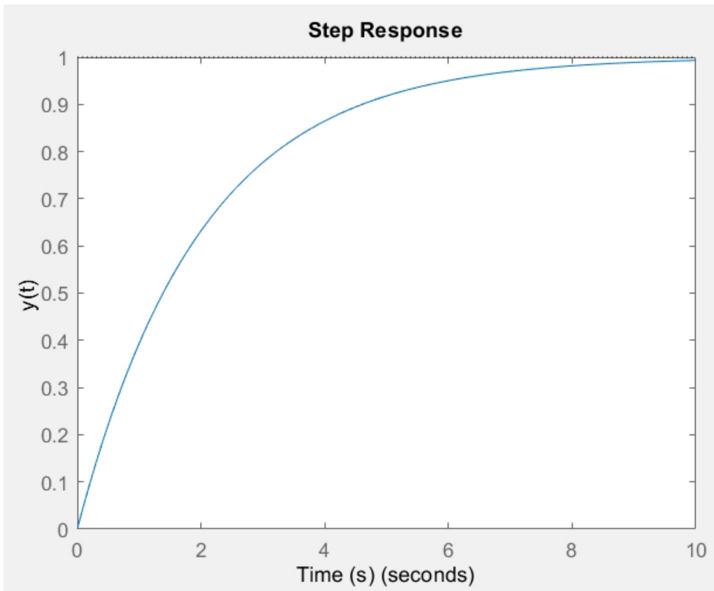


Figure 6. Step response of equation 6

A zero order hold is applied to equation 6 to convert it from continuous time to discrete time.

$$G(s) = \frac{1-e^{-Ts}}{s}\frac{1}{2s+1}$$

$$G(z) = (1 - z^{-1})\sum_{\lambda=\frac{-1}{2},0}\left(\frac{1}{s(2s+1)}\right)\left(\frac{1}{1-z^{-1}e^{T\lambda}}\right)\Big|_{T=0.05s}$$

$$G(z) = (1-z^{-1})\left[\frac{1}{(2\lambda+1)}\cdot\frac{1}{(1-z^{-1}e^{T\lambda})}\Big|_{\lambda=0} + \left(\frac{1}{s(1-z^{-1}e^{T\lambda})}\right)\Big|_{\lambda=-\frac{1}{2}}\right]$$

$$G(z) = \frac{(1-z^{-1})}{(1-z^{-1})} + \frac{(1-z^{-1})}{\left(-\frac{1}{2}\right)(1-0.98z^{-1})} = 1 + \frac{z-1}{-\frac{z}{2}+0.488}$$

$$G(z) = \frac{0.02469}{z-0.9753}$$

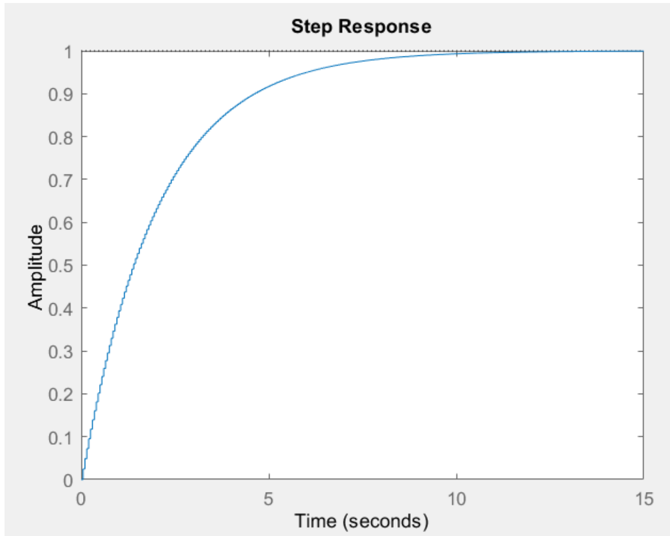


Figure 7. Step response of G(z)

The system is modeled in figure 7 to verify that the discrete response matches the continuous response. Figure 8 then illustrates the block diagram of the closed loop transfer function with a new parameter, K, introduced.

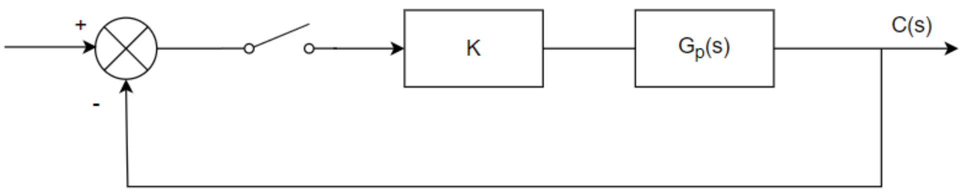


Figure 8. Block diagram of the discrete plant transfer function

$$T(z) = \frac{C(z)}{R(z)} = \frac{KG(z)}{1 + KG(z)}$$

$$= \frac{K\left(\frac{0.02469}{z - 0.9753}\right)}{1 + K\left(\frac{0.02469}{z - 0.9753}\right)}$$

$$= \frac{K(0.02469)}{z - 0.9753 + 0.9753K}$$

Using Bilinear transform and Routh-Hurwitz criterion, the range of K for a stable system is found.

$$z(T=0.05)=\frac{1+\frac{T}{2}w}{1-\frac{T}{2}w}=\frac{1+0.025w}{1-0.025w}=\frac{40+w}{40-w}$$

$$\left(\frac{40+w}{40-w}\right)+(0.02469K-0.9753)=0$$

$$(0.0247-0.02469)w+(-6368+0.02469K)=0$$

$$0.0247-0.02469K>0$$

$$1.0041>K>0$$

A PI controller is then added to the system to speed up the response of the system.

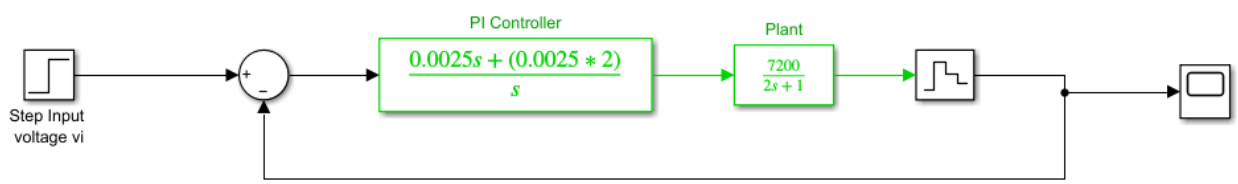


Figure 8. Simulink block diagram of the PI controller

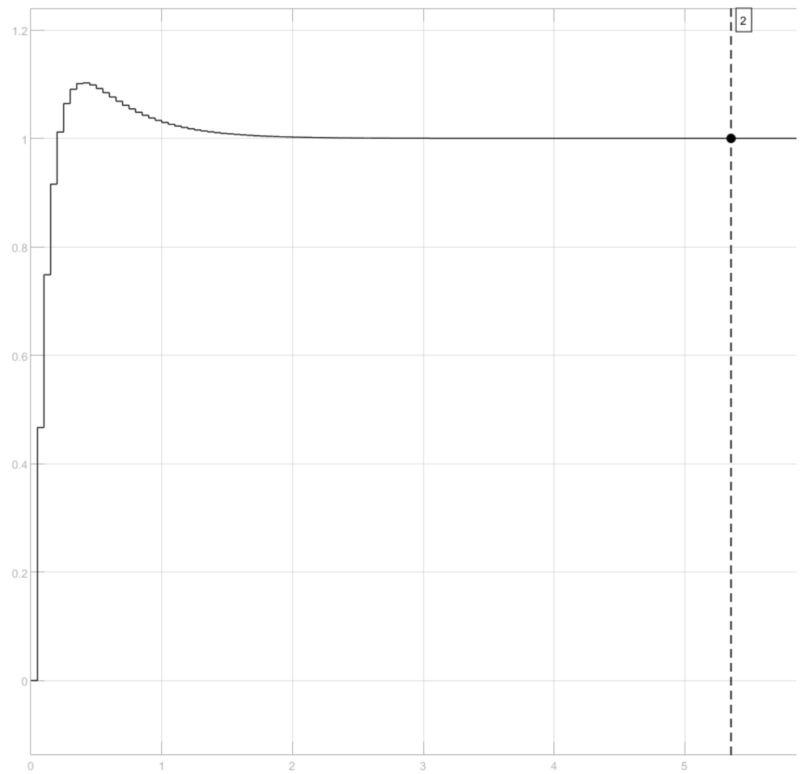


Figure 9. Step response of PI controller

Table 1. PI controller parameters and system response in figure 9

Config	K_P	K_I	K_D	Tr[sec]	Ts[sec]	MP[%]
PI	0.0025	0.005	0	0.134	2.676	10.6%

The PI controller was able to prove a much faster response time. It went from around 10 seconds to get to steady state to 2.676 seconds. The rise time will also be helpful for implementation to the actual prototyped turbine.

Conclusion and Future Plans

This project will continue to develop as the competition is not until the end of May 2023. Having a way for the turbine to have a stable rpm at any wind speed is integral to doing well in the competition. Implementing the PI controller analyzed in this paper is a good start in creating a robust control system. The first step is to get the microcontroller coded so that it interfaces properly with the linear actuator and the power sensor. The system will hopefully be tested by the end of winter quarter and then integrated testing with the entire turbine by the end of spring quarter. Finally, Cal Poly wins the Collegiate Wind Competition.

The modeling of the turbine can expand to include the torque of the generator, noise, disturbance, and other inputs such as the rpm of the generator. I am uncertain of what is used to change the torque of the system, but most of the reference papers go into depth on how it works, so it is possible. Most sources also found that the PI controller was not the most effective controller for pitch. The best one I have found is the fuzzy controller. I have already downloaded the fuzzy controller toolbox on simulink, so that will be researched over the winter break. I am excited to continue to work on this project and to finally have a unique turbine controller.

References

[1] Z. R. Labidi, H. Schulte and A. Mami, "Modeling and optimal torque control of small wind turbines with permanent magnet synchronous generators," 2017 International Conference on Green Energy Conversion Systems (GECS), 2017, pp. 1-6, doi: 10.1109/GECS.2017.8066149.

[2] W. Xiaodong, H. Shixu, W. Shirong, L. Yingming and L. Lixia, "Multi-objective optimization torque control of wind turbine based on LQG optimal control," 2013 25th Chinese Control and Decision Conference (CCDC), 2013, pp. 405-408, doi: 10.1109/CCDC.2013.6560957.

[3] Aliprantis, D. C., et al. "Modeling and control of a variable-speed wind turbine equipped with permanent magnet synchronous generator." Proc. of ICEM. Vol. 3. 2000.

[4] Hansen, A.D. and Michalke, G. (2008), Modelling and control of variable-speed multi-pole permanent magnet synchronous generator wind turbine. Wind Energ., 11: 537-554. https://doi.org/10.1002/we.278