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UFSC Universidade Federal de Santa Catarina

Parametric estimation and control of a wind turbine

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Leonardo Gobbi Lopez

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Resumo

Um aerogerador é um tipo de gerador de energia elétrica que utiliza como fonte o vento. Sendo assim, uma fonte renovável de energia é, por isso, capaz de responder às necessidades do presente sem comprometer os recursos das gerações futuras. Isso faz da turbina eólica uma opção pertinente para gerar a energia elétrica do hoje e do amanhã.

A participação da energia eólica na produção mundial tem aumentado constantemente, assim como a quantidade de estudos feitos no setor. Turbinas eólicas são atualmente um competidor de porte como solução para geração de energia graças ao seu preço cada vez menor e à sua alta eficiência.

Gipsa-Lab, situado na "École nationale supérieure de l'énergie, de l'eau et de l'environnement"(Escola nacional superior de energia, água e meio ambiente) do "Institut National Polytechnique de Grenoble"(Instituto Nacional Politécnico de Grenoble), decidiu, portanto, ampliar o ensino feito na universidade abrangendo aerogeradores, buscando, então, aumentar os conhecimentos dos estudantes e facilitar a pesquisa no assunto. Para isso, com a ajuda de estudantes, o laboratório construiu um modelo reduzido de uma turbina para ser estudado antes da construção de outras três maquetes.

O objetivo do trabalho desenvolvido foi de compreender e estudar a fundo o modelo em escala menor, obtendo informações quanto ao funcionamento da eólica para estimar o sistema e desenvolver uma lei de controle. Além disso, a turbina deve servir como trabalho prático para os alunos de engenharia e facilitar os estudos das próximas maquetes a serem construídas. Este relatório deve ser visto de duas maneiras: como relatório acadêmico e manual para os próximos utilizadores da maquete.

O trabalho do estagiário Leonardo Gobbi Lopez começou a partir desse ponto. Já havia uma maquete construída da turbina, então sua primeira tarefa foi validar a construção. Ele realizou mudanças desta com a ajuda do corpo de trabalhadores do laboratório para melhorar a dinâmica do vento.

A maquete é constituída de um túnel de vento, onde de um lado há um ventilador e do outro há duas hélices de um helicóptero miniatura acopladas a um gerador de corrente contínua. Quando o ventilador começa a girar, o vento é criado, fazendo a turbina se movimentar.É possível agir sobre o sistema mudando a corrente que entra no gerador e permite a geração de energia. Tal corrente funciona como freio na turbina reduzindo a velocidade angular.

O estagiário começou adquirindo conhecimento dos coeficientes importantes para uma turbina eólica como a constante de força eletromotriz. Depois, ele calibrou as medidas e preparou a simulação com parâmetros mais relevantes fisicamente como o ângulo de pitch (ângulo da hélice da turbina em relação à direção do vento) e a velocidade do vento criada no túnel. Tudo isso foi feito baseando-se nas prováveis equações do sistema.

Com os bons valores obtidos, Leonardo mediu diversas curvas de análise importantes a uma turbina eólica, como o coeficiente de potência em função da relação da velocidade de ponta para diferentes velocidades do vento e do ângulo de pitch.

Após o fim das análises, o estagiário concentrou-se em obter uma lei de controle. Para isso, ele estimou o sistema utilizando como entrada de corrente uma sequência binária pseudoaleatória, que é mais robusta para medições. Depois ele utilizou minimos quadrados para estimar os parâmetros do sistema.

Para o controle em si, foi obtida uma lei que não utiliza a medida de velocidade do vento. Para tal, foi calculado um observador de estados para estimar essa velocidade, baseando-a na velocidade angular da turbina e na corrente aplicada ao sistema.

Depois se foi obtido um controle por realimentação de estados que busca manter o sistema em um ponto ótimo de geração de energia.

Após a validação completa da lei de controle proposta por via de simulações, foi-se implementada tal lógica diretamente na turbina utilizando o software Simulink®em tempo real. Esse teste direto na planta permitiu concluir que a lei de controle obteve resultados satisfatórios, mantendo o sistema dentro de uma região ótima de geração de energia com uma boa estimação da velocidade do vento.

O trabalho feito pelo estagiário chegou ao fim após esse ponto, mas com muitas outras opções a serem desenvolvidas na turbina, agora em aberto, graças aos esforços empreendidos durante este estágio. Outras técnicas podem ser utilizadas no futuro como controle preditivo ou robusto, por exemplo. O sistema é não linear, o que permite outro tipo de análise.

O legado deste período de trabalho desenvolvido por Leonardo Gobbi Lopez pôde ser validado com um relatório completo que vai ajudar os próximos trabalhadores da maquete e os futuros aplicadores do pequeno aerogerador como ferramenta de ensino.

Abstract

Wind turbines are a fast growing niche of clean energy production throughout the world mainly because of their reduction of price and increase of efficiency. Based on this, much research and development is being made to further consolidate their market and their importance around the world. Given it can be used virtually anywhere there is enough wind, this kind of technology deserves to be more discussed and taught on undergraduate level.

Gipsa-Lab's close relation to the teachings done at ENSE3 of Grenoble Institute of Technology allowed the laboratory to be seen as a means to introduce students into the field of wind turbines. With that in mind, the Gipsa-Lab with the auxiliary help from students made the effort to build a small wind turbine pilot model to be studied prior to building more robust ones for practical work for future students.

The work described in this paper starts from here onwards, where intern Leonardo Gobbi Lopez thoroughly studied the small wind turbine model while preparing it for measurements.

After preparing the wind turbine the intern moved on to measuring important information from it such as commonly analyzed curves for wind turbines and coefficients to later advance over model estimation in order to pursue the development of a control law. A series of trials were made before reaching good system estimation, all steps described in detail in the course of the text.

With the wind turbine model completely uncovered a control law was extracted, which achieved the objective of maintaining the wind turbine at a good efficiency peak and thus finalizing the interns task.

This paper not only serves academic purposes but it can also be read as a manual for future workers with the small wind turbine model.

Contents

Chapter 1

Introduction

This chapter presents the motivation, contextualization and the objectives of the work done during the internship at Gipsa-Lab situated in Grenoble, France.

1.1 Global contextualization

Wind turbines convert kinetic energy from wind into electrical power [1]. This type of generation is growing fast throughout the world mainly because of its cleanness with regard to the environment and extensive demands, which renders it more efficient and less expensive to produce [2]. Figure 1.1 and Figure 1.2 shows these results.

Figure 1.1: Worldwide installed wind power capacity forecast [3]

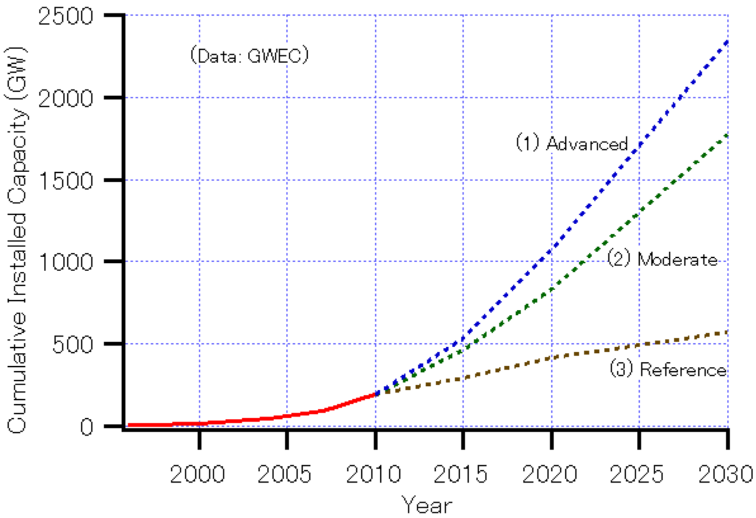
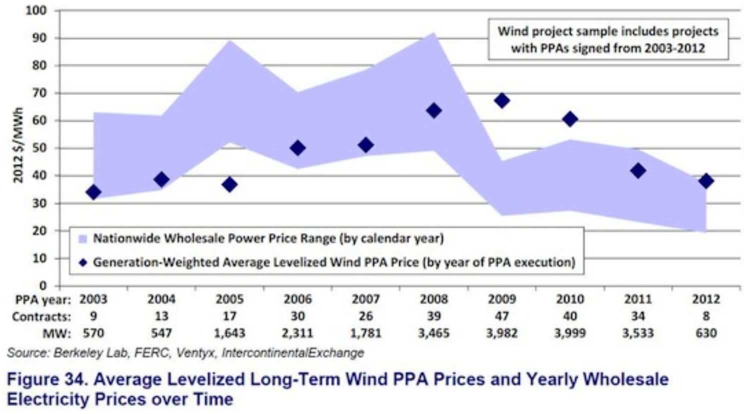


Figure 1.2: Wind turbine prices per MWh [2]



Looking to Brazil, the installed capacity is of 1 GW (gigawatt) while it is estimated that there could be 140 GW installed throughout the country [4]. Wind turbines has a grow rate of 20% a year [5] and based on the Brazilian energy matrix (based mainly on hydroelectric power plants) it is expected to shift investments to the wind energy sector.

Based on this continuing growth in importance of wind turbines, it is important to keep researching and studying even further and hence develop ways to tests new techniques and promote stronger familiarization between this source of energy and undergraduate students, primarily in the field of engineering.

The present paper seeks to understand and modify a small wind turbine model by developing a consistent measuring methodology and control design aiming to facilitate further works on the field.

1.2 Motivation

Gipsa-Lab is a research laboratory based in the "École nationale supérieure de l'énergie, l'eau et l'environnement" (National Superior School of Energy, Water, and the Environment) which is one of the engineering schools of the "Institut National Polytechnique de Grenoble" (Grenoble Institute of Technology). So it is a laboratory that has a stronger connection with engineering undergraduates and teachers/researchers and, therefore, seeks improvements in both domains: teaching and researching.

Most of the lectures and practical work done by the undergraduates on wind turbines have been based purely on simulations lacking a more physical point of view. This was the reason why the small wind turbine model was crafted. It was an attempt to develop 3 more models that could be used for practical work for future students. In addition, the Gipsa-Lab can also profit from the models to develop their own techniques regarding wind energy generation.

1.3 Objective

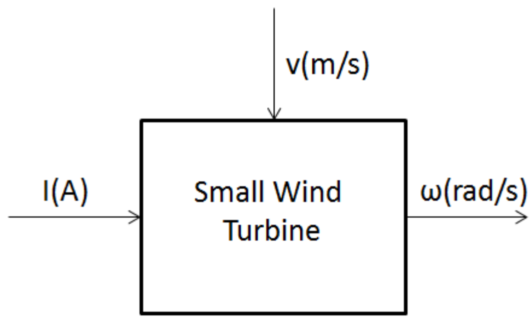
The wind turbine model had already been built by students and the staff of Gipsa-Lab prior to the start of the internship that led to this paper; so the contribution of the intern started from this point.

The idea was to validate the model construction by a series of measures and tests and afterwards gather relevant information about the wind turbine generation capabilities and important curves to be analyzed.

With the model validated, the intern had to pursue the direction of creating a control law for the small turbine. That was to be acquired by estimating the system through measures and estimation techniques. With an estimated system a simple control law should come more naturally, opening space for more advanced ones.

In terms of control the main objective was to achieve control without the knowledge of the wind speed, which is relevant but not necessary for a proper operation of the wind turbine and the sensor itself is not completely reliable. The scheme ahead, Figure 1.3, shows the input current (I) to the wind turbine, the wind (v) that works like a disturbance and our output the angular velocity (ω).

Figure 1.3: Open loop system scheme for control



The wind turbine will generate electricity if there is current applied to it and enough wind to make it turn and, therefore, generate. The current applied will break the turbine while the wind will accelerate it. Depending on the wind speed there is a value of angular velocity that is the optimal point of energy generation.

Our control objective was to define a control strategy to manipulate the current to keep the wind turbine in an optimal point of energy generation.

To summarize, the main point of the project was to acquire good methodology for each of the objectives above making it easier to redo them for the new models that are to be craft.

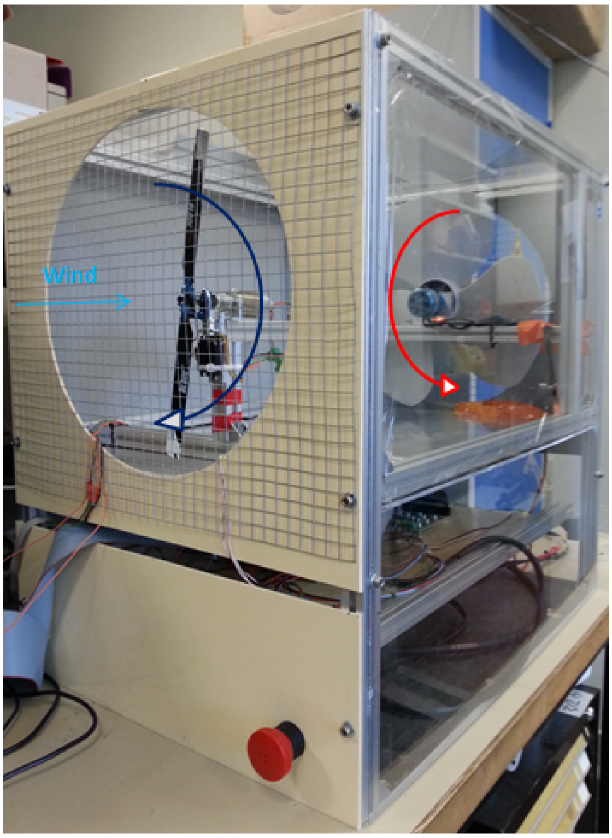
Chapter 2

Understanding the wind turbine model

For a thorough understanding of the present work an explanation about the wind turbine model at hand is necessary.

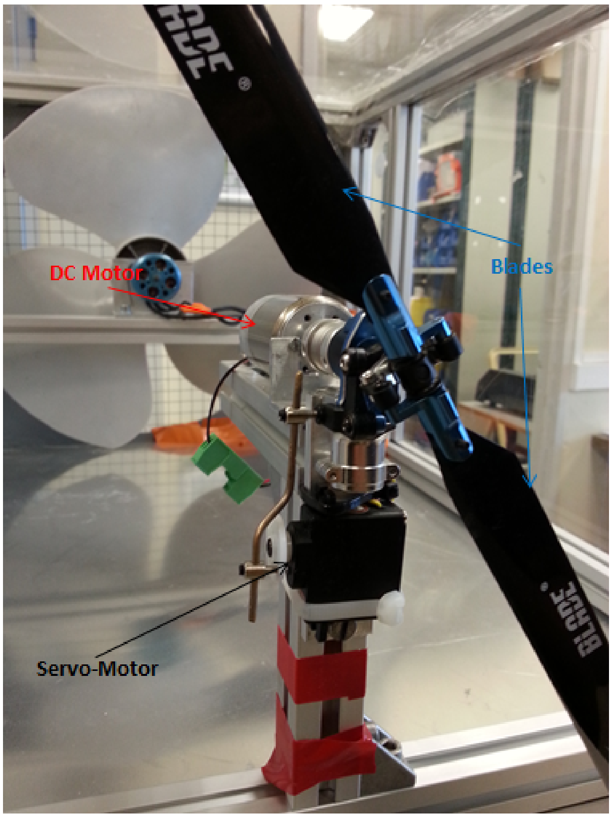
To begin with, we have a small wind turbine inside a box with only two opposite sides open. One end has the wind turbine and the other a fan helix attached to a motor. The idea is that by turning on the motor, the air will come from the wind turbine's end and go out through the fan making, therefore, the turbine generate electricity. Figure 2.1 shows a photo of the model.

Figure 2.1: Photo of the wind turbine box. Left: the wind turbine. Right: the fan



The turbine itself is made with two small helix from aero models that are attached to a servo-motor for pitch control (the angle in which the helix will face the incoming wind). The main axis of the turbine is parallel to the winds direction and is connected to a DC motor responsible for the energy generation. Figure 2.2 demonstrates the parts of the wind turbine

Figure 2.2: Wind turbine model



For measurements and real time information of the model we dispose of a tachometer to obtain the current angular speed of the turbine's helixes and of the measured tension value from the DC motor. As for inputs to the model we can demand an angle for the pitch, an electrical current for the DC motor (this will work as a break to the wind turbine and will trigger the energy generation) and the wind speed created by the fan. The interface we are using to manipulate these inputs and check the outputs is via a real time Simulink®application that will allow an easy and simple manipulation of the variables.

This summarizes everything at hand and helps us explain the equations of interest and measurements made.

2.1 System equations

A wind turbine has a few important equations that we are required to understand before going any further. We have two types of equations, one that comes from the DC motor and another one that explains the movement behavior.

From the DC motor as generator:

$$U_{mcc} = \epsilon - RI - L\dot{I} \tag{2.1}$$

$$\epsilon = K\omega \tag{2.2}$$

$$\Gamma_{elec} = KI \tag{2.3}$$

The precedent equations (2.1) and (2.2) show how the DC motor tension (U_{mcc}) will respond to the electrical current (I) and the angular velocity (ω) taking into account the motor's electromotive force (ϵ), resistance (R) and inductance (L). Equation (2.3) shows the electrical resistant torque (Γ_{elec}) created by the current with a constant of electromotive force (K), that also appears in equation (2.2).

From the movement behavior:

$$C_p = \frac{P_g}{P_w} \tag{2.4}$$

$$P_g = U_{mcc}I \tag{2.5}$$

$$P_w = \frac{1}{2}\rho\pi r^2 v^3 \tag{2.6}$$

$$\lambda = \omega\frac{r}{v} \tag{2.7}$$

$$\Gamma_{wind} = C_p\frac{P_w}{\omega} \tag{2.8}$$

$$J\dot{\omega} = \Gamma_{wind} - \Gamma_{elec} - \Gamma_{visc}\omega - \Gamma_{dry} \tag{2.9}$$

Equations (2.4) to (2.6) represent the power factor (C_p) of the system based on the power provided by the wind (P_w) and the amount taken from it (P_g). Equation (2.7) represents the "tip speed ratio" (λ), which is highly related to the wind turbine's efficiency and compares how fast the tip of the helix turns to the wind velocity (v). The last two equations, (2.8) and (2.9), represent the true movement of the wind turbine, relating the inertia (J) with the angular velocity of the turbine, wind torque (Γ_w), electrical torque (Γ_{elec}) and a torque from viscous (Γ_{visc}) and dry friction (Γ_{dry}).

Just to keep in mind, we did not get in into this subject but the air density (ρ) is a very important value that can and will change very often since it depends on the temperature and density of the air. We considered it constant.

With all these equations we're now capable of estimating the unknown parameters through some measurements of the system.

2.2 Estimating the constant of electromotive force

The constant of the electromotive force is a very important parameter from our DC motor since it appears in more than one equation and is necessary so we can obtain all the important values.

To estimate this constant we need to increase the angular velocity of the wind turbine without adding any current to the DC motor transforming equation (2.1) into equation (2.10).

$$U_{mcc} = \epsilon = K\omega \tag{2.10}$$

Now, in order to estimate what will be needed, we have to measure the relation between the angular velocity and the tension that comes from the motor. For that reason, we increased the fan speed through various points. Which resulted in a bigger angular velocity every time and a relative tension to that velocity. An external tachometer was used to measure the speed. After this, all that remained was to make a simple linearization to estimate the constant resulting in the value in equation (2.11).

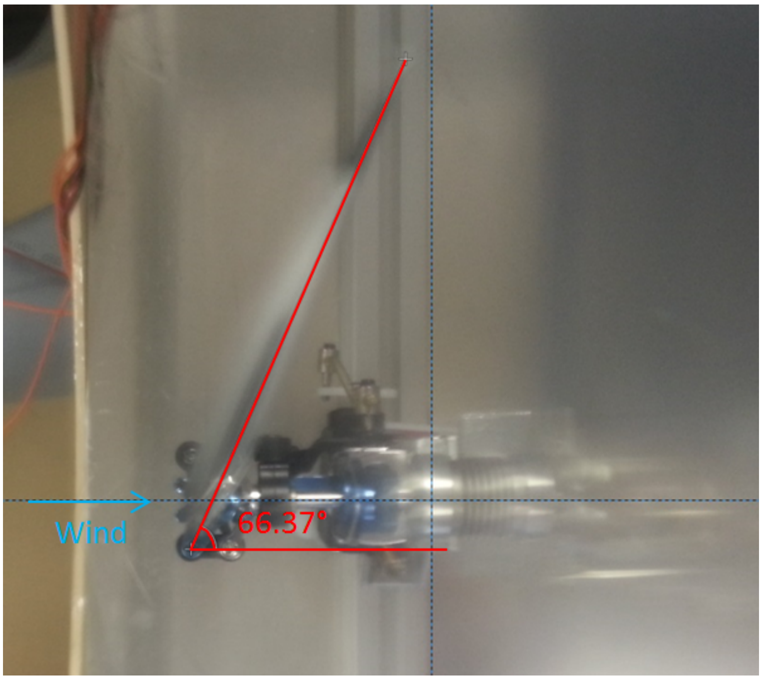
$$K = 0.0221 \frac{V}{rad/s} \tag{2.11}$$

Now we'll move on into calibrating the angle input.

2.3 Calibrating angle input

To retrieve a better perception of the real angle we wanted the pitch to be, we took some pictures of the wind turbine helix on various inputs for angles and calculated the real value. With that done we could use as input an angle and not just an arbitrary entry number to the servo-motor. To get the pitch angle we used "GIMP 2", an image editing software that has a tool that calculates angles, as shown in Figure 2.3.

Figure 2.3: Measuring of pitch angle with GIMP2



After a few measurements we obtained Table 2.1:

Table 2.1: Input to angle measurements

Input	Angle(°)
-40	90
-50	87.92
-60	84.15
-70	80.48
-80	75.71
-90	71.15
-100	66.37

With the data acquired and a linear approximation of the values done we could now send an angle as input to the pitch value of the helices.

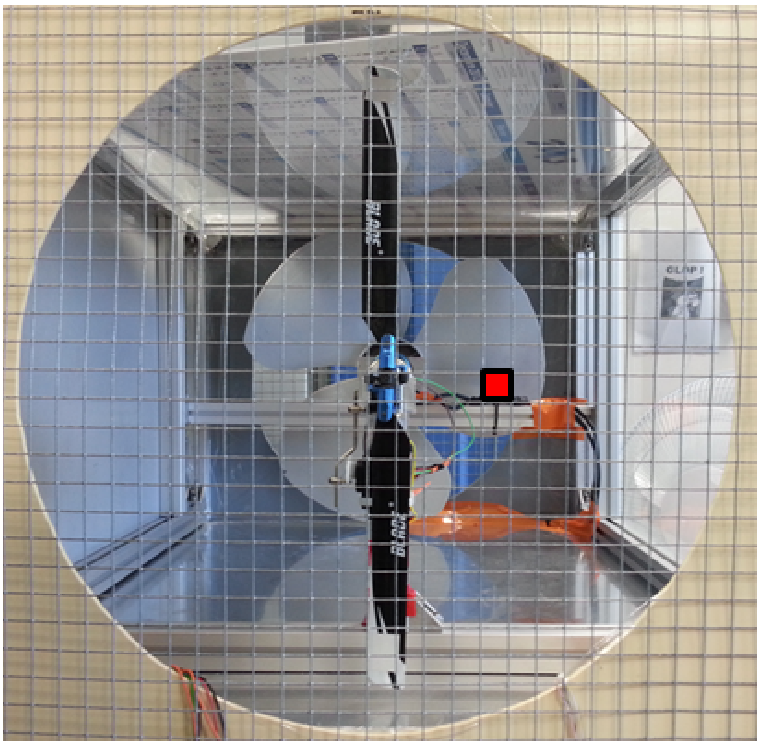
The next step from here was to obtain a good notion of the wind speed created by the fan.

2.4 Measuring created wind

Since we did not dispose of a real time value of the wind speed we needed to correlate the input to the motor of the fan to its generated wind so we could use this information in equations (2.6) and (2.7).

For the purpose, we used an anemometer to obtain the wind speed for various inputs to the motor fan keeping the wind turbine stopped so it would not disturb the real value of speed. Figure 2.4 below shows the measurement point that should avoid a certain amount of losses to the wind and get closer to the real value.

Figure 2.4: Wind measurement point



Another thing of importance in this case, digressing from the wind speed itself, was the amount of noise made by the fan for each input. The idea was to create enough wind to stimulate the turbine's motion and at the same time make as less noise as possible. For that measurement we used a cellphone application that measures noise on decibels. With that said, Table 2.2 shows the results.

Table 2.2: Relation between input to fan and the generated wind speed and noise

Input to fan	Wind Speed(m/s)	Noise(dB)
13	2.1	55.5
14	2.3	57.8
15	2.6	59.4
16	3	60.1
17	3.2	61.3
18	3.6	64.2
19	3.8	69.5
20	4	73.5

Considering that a regular conversation between two people reaches values around 60 dB and that this small wind turbine works well for wind speeds bigger than 2 m/s we were to assume that using a value ranging from 13 to 15 as an input to the turbine would be viable. In this present paper most of the measurements will be made with input to fan equal to 14 so we could have a little more working area and at the same time a harmless amount of noise that won't be disturbing.

We worked with this three different wind speeds throughout the internship mainly to keep the laboratory quieter, but in the future it would be interesting to have bigger variations of wind speed.

Now we had all the necessary information to start acquiring data regarding our small wind turbine efficiency and its not yet estimated parameters.

2.5 Conclusion

We managed to comprehend our wind turbine model by a series of equations and acquired important information from it. This was necessary to continue advancing into more specific details about the wind turbine.

Now, in possession of more physically correct values like the real pitch angle applied and the created wind added with our calculation of the constant of electromotive force we can pursue into discovering an important curve in terms of wind turbines: the power factor relation to the tip speed ratio.

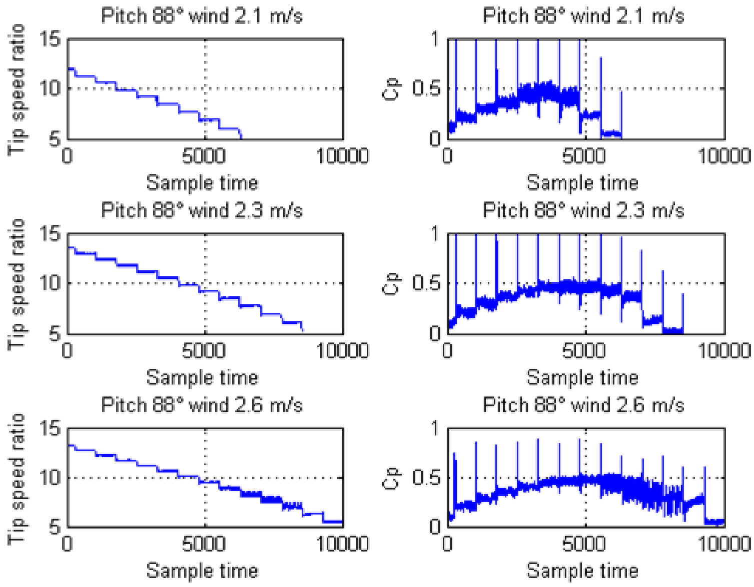
Chapter 3

Relating power factor to tip speed ratio

The most commonly analyzed curve when working with wind turbines is the one that relates the power factor (C_p) with the tip speed ratio (λ) [7]. This relation provides you the point of maximum energy generation in relation to the tip speed ratio that can be controlled. The study of the values involved is mandatory in order to achieve that knowledge

Using our real time system connected to the wind turbine we can make a series of measurements of the tip speed ratio and the resulting power factor. For that the plant was stabilized with a simple proportional controller for the angular velocity of the turbine as reference. In order to arrive at the necessary measures we decreased the speed by little steps of 10 rad/s which proportioned a different tip speed ratio while maintaining the wind speed constant and pitch at 88° (angle that got the highest angular velocity). The measures obtained for the power factor and tip speed ratio from 3 series of measurements are in Figure 3.1.

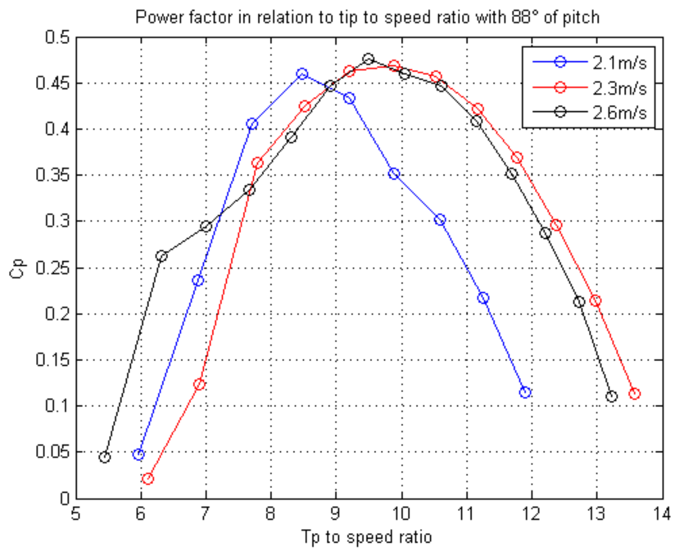
Figure 3.1: Left column shows tip speed ratio measures, right column power factor measures and each line is a wind speed: 2.1 m/s, 2.3 m/s and 2.6 m/s, respectively. All with a pitch of 88°



We can see in Figure 3.1 another reason for choosing 14 (2.3 m/s) as an input to the fan motor, with which we were capable of making more measurements than with 13 (2.1 m/s) and less noisy ones if compared to 15 (2.6 m/s).

The next comparison image was made by taking the mean value of each measurement. Figure 3.2 shows the power factor in relation to the tip speed ratio for the three wind speeds listed before.

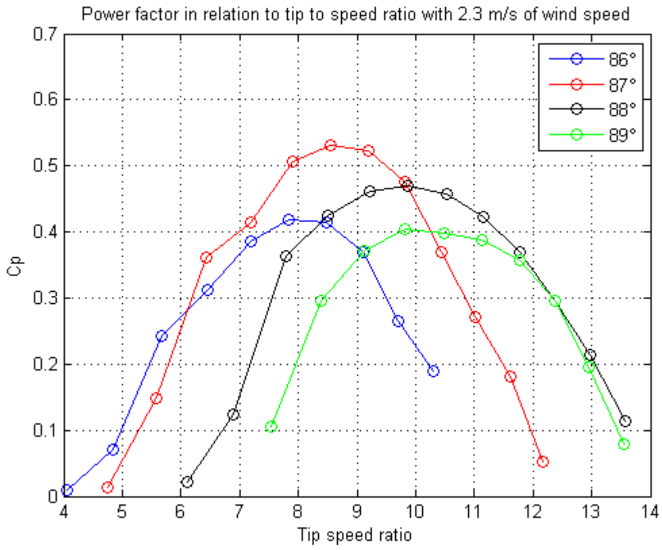
Figure 3.2: Power factor in function of tip to speed ratio for 2.1 m/s, 2.3 m/s and 2.6 m/s with a pitch of 88°



To corroborate our measures, a small part of information regarding wind turbines must be used. According to Betz's law [6] the maximal achievable extraction of wind power by a wind turbine is 59%.Because of inefficiencies, a commercially distributed turbine usually delivers around 44%. These values are very consistent with our measures since we have a power factor point of approximately 0.46 which changes according to the wind speed. Therefore, we can confirm that our measures are consistent to normal wind turbines.

We already measured and saw the effect that different wind speeds have on the power factor's curve but now we wished to examine the effect of different angles of pitch. Consequently, we kept the same wind speed and made the same measures as in Figure 3.2 for various values of angles which would lead to Figure 3.3.

Figure 3.3: Power factor curves for four different angles: 86°, 87°, 88° and 89°



The measures made to create Figure 3.3 were all close to the maximum power factor we could find (around 0.53) with 87° of pitch angle. For other angles the curve gets really distant from these values and, therefore, were omitted in the results. We can see that for each angle we extract a different optimal tip speed ratio: for 87° of pitch angle a good tip speed ratio is of 8.5 and for 88° a good value is 9.8.

Based on the last figures our primary aims were beginning to assume shape. Our power factor represented the amount of energy taken from the wind and, as a consequence, we search to optimize it. For that purpose we needed to control the angular velocity in order to achieve a desirable tip speed ratio rendering us the highest power factor value.

The preparations to start estimating our model were completed at this point. The next step consisted of parameter estimation.

3.1 Conclusion

In terms of analysis of the small wind turbine model itself we finished with this chapter.

We uncovered the dynamic of the power factor given different wind speeds and pitch angles showing that indeed our wind turbine resembles a real one.

We that done we can advance into the parametric estimation of our model always seeking a proper control development.

Chapter 4

Parameter estimation

After a great number of trials to correctly estimate the system we found the methodology described in this chapter as the most suitable one. All the estimations and calculations were carried out using MATLAB®.

Another point of importance is that we did not estimate (2.9) as previously explained because it was just a base equation to keep us aware of the kind of measure was needed. After a few attempts using it for estimation we agreed on the following option: (4.1).

$$J\dot{\omega} = -\beta\omega^2 - \Gamma_{elec} + \Gamma_{wind} \tag{4.1}$$

This chapter used the knowledge from [8] which explains about system identification and data acquiring.

First we'll describe what we used as an input to the process to extract the necessary measures for estimation, and then we'll proceed to the estimation itself.

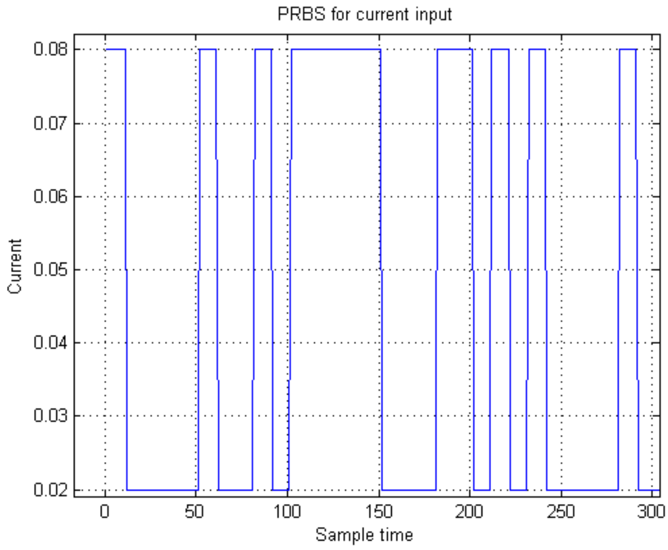
4.1 PRBS input

Estimating a system consist on stimulating it with a given input and check its corresponding output to afterwards extract the behavior and parameters achieving that value.

Our input to the system was the current applied to the DC motor which caused the wind turbine to move slower.

The approach we choose as better used as input a PRBS (pseudo-random binary sequence) [9], which is made of a series of steps with random duration time, centralized around 0.05 A going from 0.02 to 0.08 A as shown in Figure 4.1.

Figure 4.1: PRBS for input



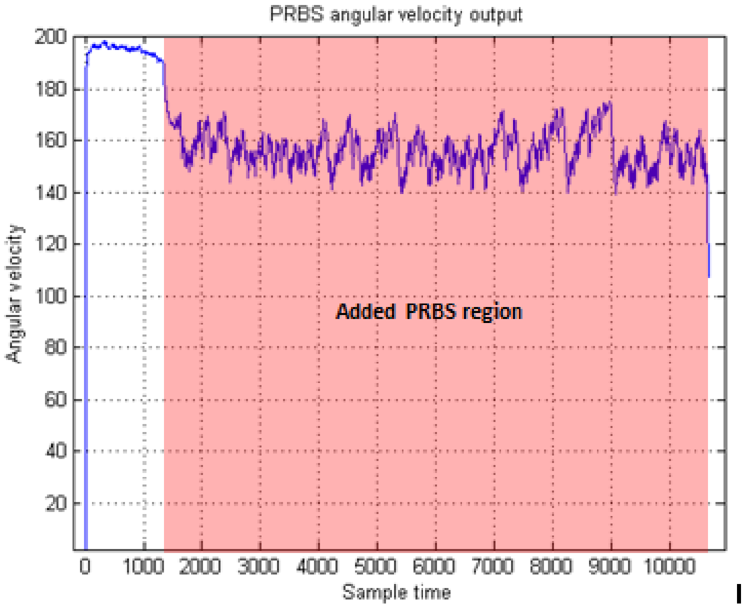
This type of signal as an entry to the process generates a very robust data to use as measures for the estimation. The PRBS stimulates the system at all times with different values of time and frequency making our measures stronger and more reliable.

The PRBS was chosen by a series of tests done seeing which one got good results. We used a Simulink®block that only demanded a sample time and a register value, we kept the register at 10 and the sample time the same as we used to measure. For the amplitude of the signal we checked that 0.08 A is already strong for the small wind turbine making it stop completely if kept constant at this value. So to keep the system stimulated at all times we choose 0.02 A as the low limit.

We must add the PRBS parameters was made by trial and error based on our work time frame. We believe it can be done in a more appropriate way.

For the measurement itself we brought the turbine to a stable speed and started the PRBS as the current and left the system acquiring data for about five minutes. The corresponding angular velocity output is shown in Figure 4.2

Figure 4.2: PRBS for input



As expected the angular velocity of the wind turbine kept changing depending on the inputted current. This measure gave us all the necessary data to obtain a more robust estimation considering that by adding a PRBS we achieved angular acceleration as well as different speeds throughout the sample time.

4.2 Least squares estimation

We checked a few ways to estimate the system and concluded that a linear least squares estimation would be the most suitable one. This approach worked because our non-linear model is linear on the parameters. The least squares was calculated recursively, meaning that for each measure it tried to fit its parameters by interaction.

We added in this approach an extra parameter c used as a multiplier of the error for each interaction by working as a BIAS to the estimation. It took the error of each estimation and used it to better estimate the next interaction.

We recursively estimated our parameters and compared to the generated error until our estimation converged to a constant value. The MATLAB®code bellow shows our algorithm.

```
p = [0;0;0;0];

P = 1e6*eye(length(p));

alpha = 0.95;
```

```
FF = 0;

e(1) = 0;

result=[];

for k = 1:length(phi)

    phiaux = [phi(k,:) e(k)];

    FF = alpha*FF + 1 - alpha;

    Lm = P*phiaux'*inv(phiaux*P*phiaux' + FF);
    P = (1/FF)*(P - P*phiaux'*inv(phiaux*P*phiaux' + FF)*phiaux*P);

    e(k+1) = gamma_elec(k) - (p'*phiaux');

    p = p+Lm*e(k+1);

    result(k,:) = p;
end

e = e(2:end);
```

Our way of calculating the system estimation had the following form described in (4.2).

$$-\Gamma_{elec} = J\dot{\omega} + \beta\omega^2 - \Gamma_{wind} = \phi P \tag{4.2}$$

$$\Gamma_{wind} = C_p \frac{P_w}{\omega} \tag{4.3}$$

$$\phi = \begin{pmatrix} \dot{\omega}10^{-5} & \omega^2 10^{-8} & \frac{P_w}{\omega} & e \end{pmatrix} \tag{4.4}$$

$$P = \begin{pmatrix} J \\ \beta \\ C_p \\ c \end{pmatrix} \tag{4.5}$$

Since we know Γ_{elec} from equation (2.3) we calculated using least squares and obtained the following results from equation (4.6) to (4.9).

$$J = 1.5 * 10^{-3} \pm 4.1415 * 10^{-5} Kg.m^2 \tag{4.6}$$

$$\beta = 1.438 * 10^{-8} \pm 2.834 * 10^{-9} kg.m \tag{4.7}$$

$$C_p = 4.339 * 10^{-1} \pm 2.05 * 10^{-2} \tag{4.8}$$

$$c = 7.41 * 10^{-1} \pm 2.29 * 10^{-2} \tag{4.9}$$

To better show the recursive behavior of our estimation Figure 4.3 4.4 and shows the evolution of the estimation through all the measurements until it maintained a constant value.

Figure 4.3: Recursive least squares estimation (Inertia)

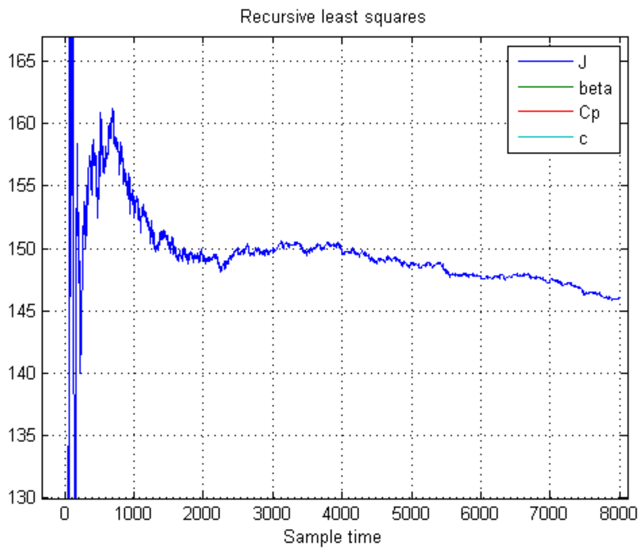
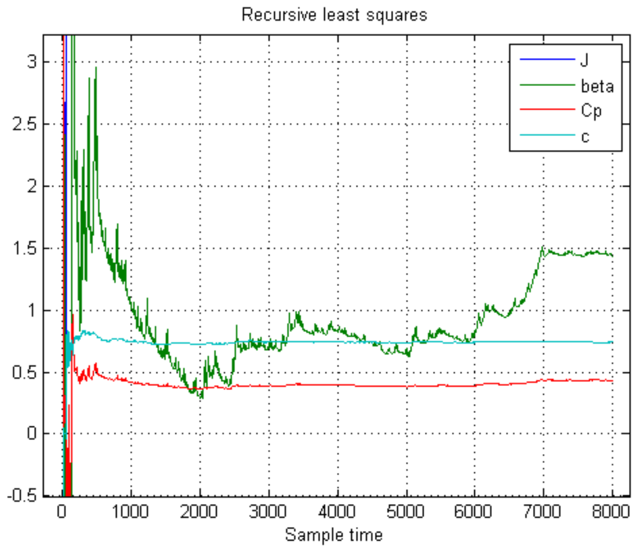


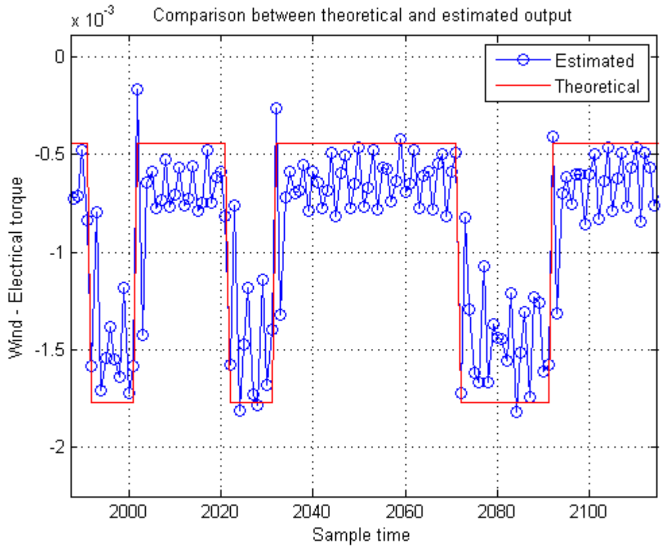
Figure 4.4: Recursive least squares estimation (Beta, Cp and c)



Estimating this way we received more physically correct parameters and were enabled to move on into analyzing the quality of the estimation. Figure 4.5 shows the comparison between the estimated electrical torque and the theoretical one. Equation (4.10) shows the nature of the squared wave for the theoretical electrical torque.

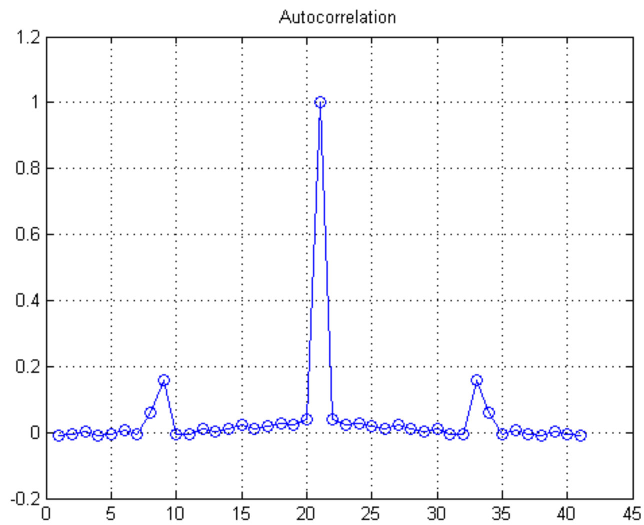
$$\Gamma_{elec} = KI = \phi P \tag{4.10}$$

Figure 4.5: Theoretical and estimated electrical torque output comparison



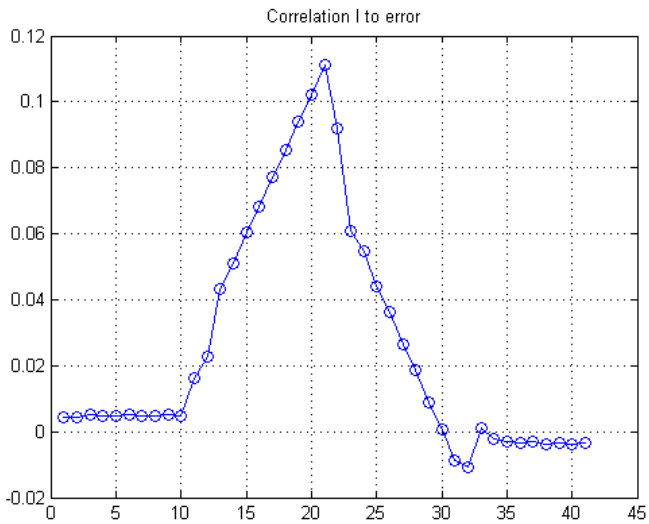
As we can see the estimation achieved good results based on the output comparison allowing us to validate the parametrization. To further analyze the estimation Figure 4.6 and Figure 4.7 shows respectively the autocorrelation and the correlation between the entry current and the resulting error of estimation.

Figure 4.6: Autocorrelation of error



A perfect autocorrelation plot for us would be one value at one of amplitude (as there is always) and all the other values close to zero. This would mean that our error would basically be white noise without any influence from any linear factor. It is, of course, an ideal scenario. The acquired autocorrelation is a good one even with the peeks of around 0.18. We can conclude that we managed to properly estimate the linearities of our system with the error being mainly white noise.

Figure 4.7: Correlation of the input current to the estimation error



To confirm whether this was a good estimation an additional correlation was concocted. As seen directly above, the behavior of the estimation error by applying a current. Since all values were below 0.12 a proper estimation of the parameters could be confirmed. Until now this estimation value is kept as our last and most precise one

4.3 Conclusion

It is important to bare in mind our initial purpose for the estimation: have a system to make a robust control law.

A recapitulation of our approach shows that we estimated a parameter called power factor (C_p) based on our measures. However, this was precisely what we wished to control. We had a certain wind speed whose optimum value for the power factor we wanted to optimize by controlling our wind turbine's angular velocity through the current. A good value for it is around 0.45 and since our estimation got 0.43, we were entitled to accept the value as it was.

With everything estimated we could simulate the system, compare it to the real wind turbine and start developing a control law.

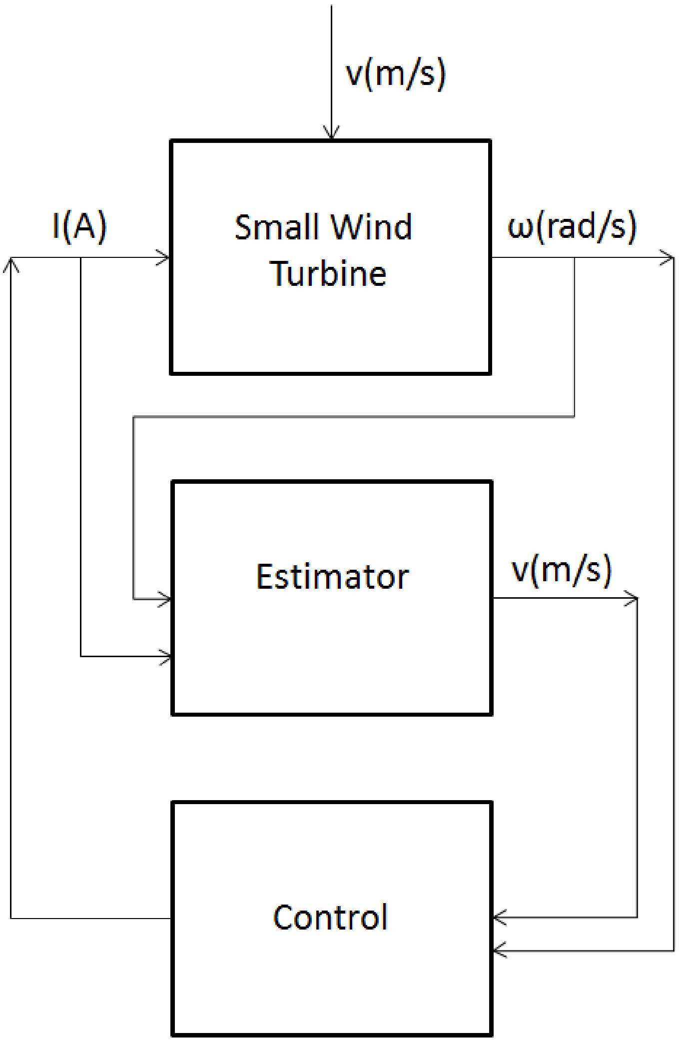
Chapter 5

Control laws

We were now at our final objective stage that consisted of getting our estimated system and using it to create a proper control law that could be applied directly to the small wind turbine.

For a simple understanding of our control problem the scheme in Figure 5.1 shows our measured output (angular speed) and input (current) and the estimated wind. To clarify our control is responsible for keeping the angular speed at a certain value of maximum generation.

Figure 5.1: Control scheme



To summarize we got a parametric model of the system that allowed us to estimate and create a control law.

This chapter describes the step-by-step process of achieving the control law with simulations and concludes with a direct application of it onto the turbine model.

5.1 Linearized system

Taken from the estimations made on the previous chapter we arrived at a final equation for the dynamic behavior of the plant. Equation (5.1) shows it, and, as we can see, is nonlinear.

$$J\dot{\omega} = -KI - \beta\omega^2 + \frac{1}{2}\rho\pi r^2 v^3 \frac{C_p}{\omega} \tag{5.1}$$

There are a few approaches we can take when working with nonlinear equations in terms of control and analysis but for this case we made use of the most common one: linearize it and then apply linear techniques.

Taking into account the fact that we cannot measure the wind speed and, therefore, need to estimate it we created a first order model of the wind's behavior considering an random portion as the variation, $\tilde{v}$, around a mean value v_0. The equilibrium value can come from a knowledge of the wind behavior on that region, that is usually seasonal. Equation (5.2) shows this first order model.

$$\dot{\tilde{v}} = a\tilde{v} \tag{5.2}$$

$$\tilde{v} = v - v_0 \tag{5.3}$$

$\tilde{v}$ is the wind speed variation while v is the speed at the given moment. a represents the dynamic of the wind variation and we had set to the value on Equation (5.4) by testing possible solutions.

$$a = -0.125s^{-1} \tag{5.4}$$

Now for the linearization itself we calculated the Jacobian, equation (5.8), considering states as in Equation (5.5), the variations of wind and angular speed, and input as in Equation (5.6), the variation of current applied.

$$x = \begin{pmatrix} \tilde{v} \\ \tilde{w} \end{pmatrix} \tag{5.5}$$

$$u = \begin{pmatrix} \tilde{I} \end{pmatrix} \tag{5.6}$$

The Jacobian is calculated as described in Equation (5.7) from our nonlinear system (5.1) together with our first order model of the wind speed variation (5.2).

$$JacA = \frac{df(x,u)}{dx} \tag{5.7}$$

$$JacA = \begin{pmatrix} a & 0 \\ \frac{3\rho\pi r^2 v_0^2 C_p}{2J\omega_0} & \frac{-2\beta\omega_0}{J} - \frac{\rho\pi r^2 v_0^3 C_p}{2J\omega_0^2} \end{pmatrix} \tag{5.8}$$

To achieve the system representation as seen in Equation (5.10) we merely needed to apply the equilibrium point to the calculated Jacobian to obtain A. For the wind speed we picked $v_0 = 2.3m/s$ because the measures of the estimation were extracted using this value as speed (value taken by hand using an anemometer). For the angular velocity of the wind turbine we picked $\omega_0 = 156.0rad/s$ because it is the mean value from the measures made during the estimation. To acquire B we calculated as in Equation (5.9) the Jacobian and then applied the constant values.

$$JacB = \frac{df(x,u)}{du} = \begin{pmatrix} 0 \\ \frac{-K}{J} \end{pmatrix} \tag{5.9}$$

$$\begin{aligned} \dot{x} &= Ax + Bu \\ y &= Cx \end{aligned} \tag{5.10}$$

With all the necessary values (including the ones taken from the estimation) we were able to arrive at our state space representation of the system shown in equation (5.11).

$$\begin{aligned} \dot{x} = \begin{pmatrix} -0.125 & 0 \\ 1.3085 & -0.0095 \end{pmatrix} x \begin{pmatrix} 0 \\ -15.1375 \end{pmatrix} u \\ y = \begin{pmatrix} 0 & 1 \end{pmatrix} x \end{aligned} \tag{5.11}$$

An analysis of the state space representation showed us that it is completely observable with one uncontrollable state being the wind speed.

5.2 Observer conception

Since our system was completely observable and we needed an estimated value of the wind speed it was clear the necessity of an observer. To create this observer we used LQR (Linear-quadratic regulator) to calculate the observer gain and minimize the cost function in Equation 5.12, giving raise for a good estimation. This observer was a full order one [11].

$$J = \int x^T W x + u^T V u \, dt. \tag{5.12}$$

Taken into account that our plant was a very slow one and that our control will be very saturated (our current could not go higher than 0.08 A, this will be explained later in this chapter) there was no need for us to have a fast observer. Yet, it was hoped to be as close to the real value as possible. It follows, that the parameters W and V used in the cost function where chosen as below in Equations (5.13) and (5.14).

$$W = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \tag{5.13}$$

$$V = \begin{pmatrix} 10 \end{pmatrix} \tag{5.14}$$

Having a higher order V than W means we wanted to focus our efforts on a slower estimation and less strong, minor overshoot, rather than to achieve a perfect estimation. Equation (5.15) shows the acquired gain for the observer from the LQR method.

$$L = \begin{pmatrix} 0.2404 \\ 0.7838 \end{pmatrix} \tag{5.15}$$

To check the observer we ran a simulation using our nonlinear equation (5.1) and checked if our observer managed to estimate. Figure 5.2 shows the Simulink®block scheme of the simulation while Figure 5.3 shows the comparison of the real wind to the estimated one.

Figure 5.2: Simulink®block scheme for nonlinear plant with observer

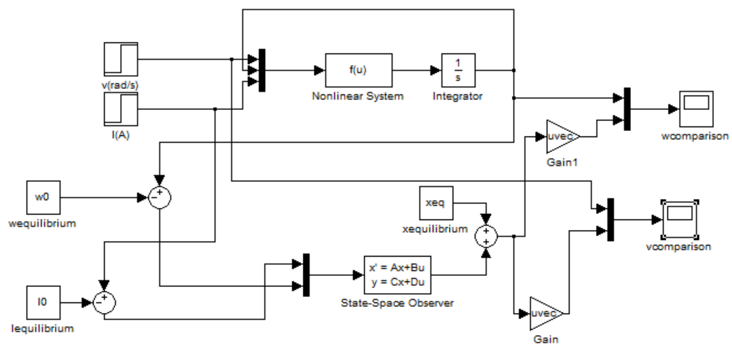
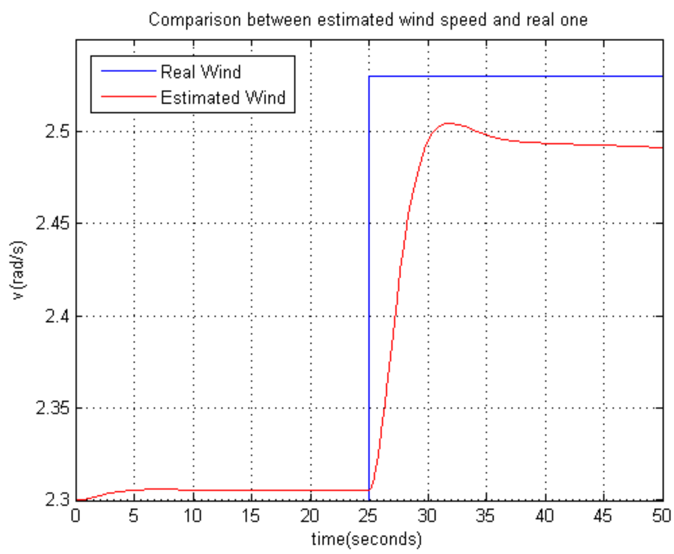


Figure 5.3: Comparison between estimated wind and real one applied to nonlinear plant



Based on the second image we concluded that the observer did in fact estimate the wind speed. Of course the higher the difference from the equilibrium points, the higher was the error of estimation. In this case, the use of 10% variation of wind speed had the error jump from 0.24% to 8.37%. Those were good values for an estimation of a parameter that is known to be very unstable in reality.

It is important to add that this error of estimation seen in the figure above is expected since our measures of the wind speed are not reliable and we used it throughout the estimation of the system as well.

In simulations our observer presented good behavior and sufficiently precise estimation of the wind speed.

5.3 State-feedback conception

We now needed a control responsible of stabilizing the system. This was achieved by using a state-feedback control because we were looking at our states through the observer.

The objective of this control lied in the maximization of the power generation of the wind turbine. The relation of proportionality had to be kept all the while, which can be seen in Equation (5.16).

$$\omega = \frac{\lambda}{r} v \tag{5.16}$$

Using this approach we were always around a certain tip-to-speed ratio (λ) that could be chosen to get a higher power factor (C_p).

So to achieve this objective we had a variable change in our control, thus making it receive as reference a z which is calculated as follows in Equation (5.17).

$$z = \tilde{\omega} - \frac{\lambda}{r} \tilde{v} = H x^T \tag{5.17}$$

$$H = \begin{pmatrix} \frac{-\lambda}{r} & 1 \end{pmatrix} \tag{5.18}$$

With H calculated we used LQR as well for the control gain calculation, minimizing Equation 5.19. For the control we picked the following Q and R for the synthesis seen in Equation (5.20) and (5.21) with λ calculated as presented in Equation (5.22).

$$J = \int x^T Q x + u^T R u \, dt. \tag{5.19}$$

$$Q = H^T H = \begin{pmatrix} 4.6031 & -0.0678 \\ -0.0678 & 0.0010 \end{pmatrix} 10^3 \tag{5.20}$$

$$R = \begin{pmatrix} 10000 \end{pmatrix} \tag{5.21}$$

$$\lambda = \frac{\omega_0 r}{v_0} = 10.17 \tag{5.22}$$

The Q calculated like this sought to minimize a factor through the LQR calculation that would reduce the error of following references. In our case we sent a reference to z as zero due to the correctness of its value and eventually rendered the statement from Equation (5.16) correct as well.

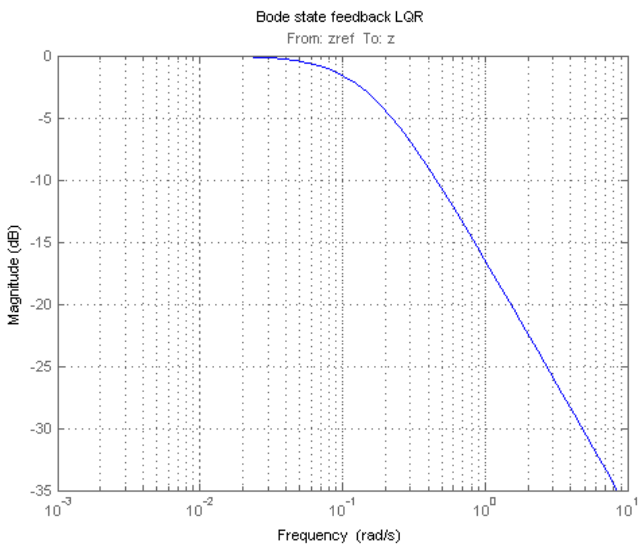
The R chosen was this high because our system had high constraints regarding the input saturation. Through tests we noticed that if we maintained a current of 0.08 A the wind turbine would eventually come to a stop. So, based on this, we made the system saturate from 0 to 0.08 but if the control demanded higher values it would remain saturated at 0.08 and stop the wind turbine. That is why we needed a softer control that was achieved by a higher R value.

Calculating the LQR for the preceding inputs to the algorithm we obtained the control gain that through our state space values seeks to minimize z shown below in Equation (5.23).

$$F = \begin{pmatrix} 0.3268 & -0.0094 \end{pmatrix} \tag{5.23}$$

Figure 5.4 show the Bode plot of the system with the state-feedback added.

Figure 5.4: Bode plot of the system with state-feedback



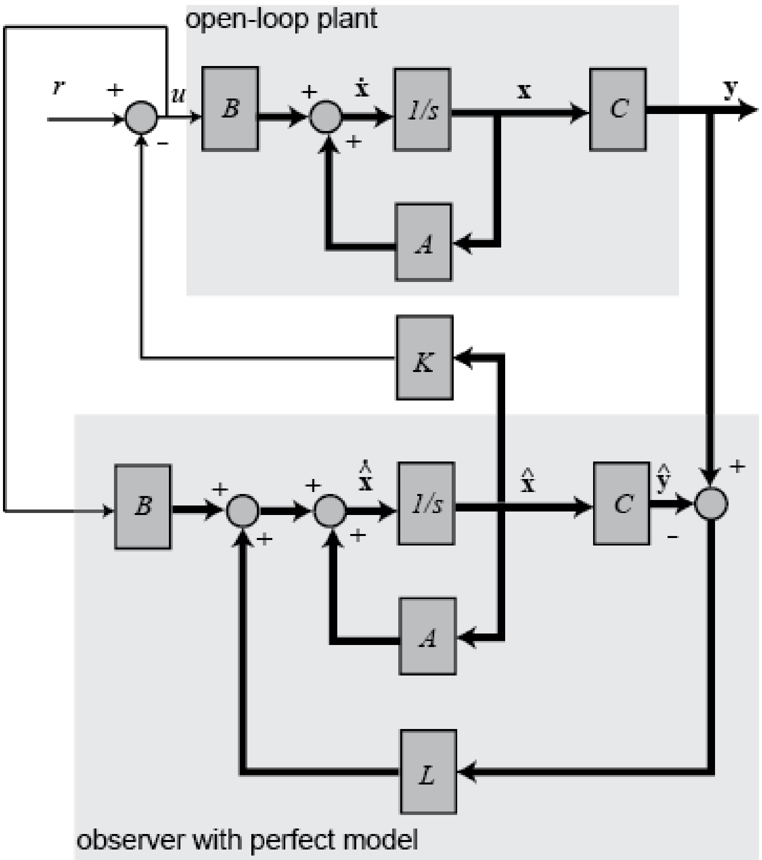
Based on the Bode plot we were able to see that the system had a gain of 0 db for lower frequencies meaning that it would follow the reference to z.

5.4 Full closed loop system

To fully comprehend our control law combining state feedback with an observer we used the scheme shown next.

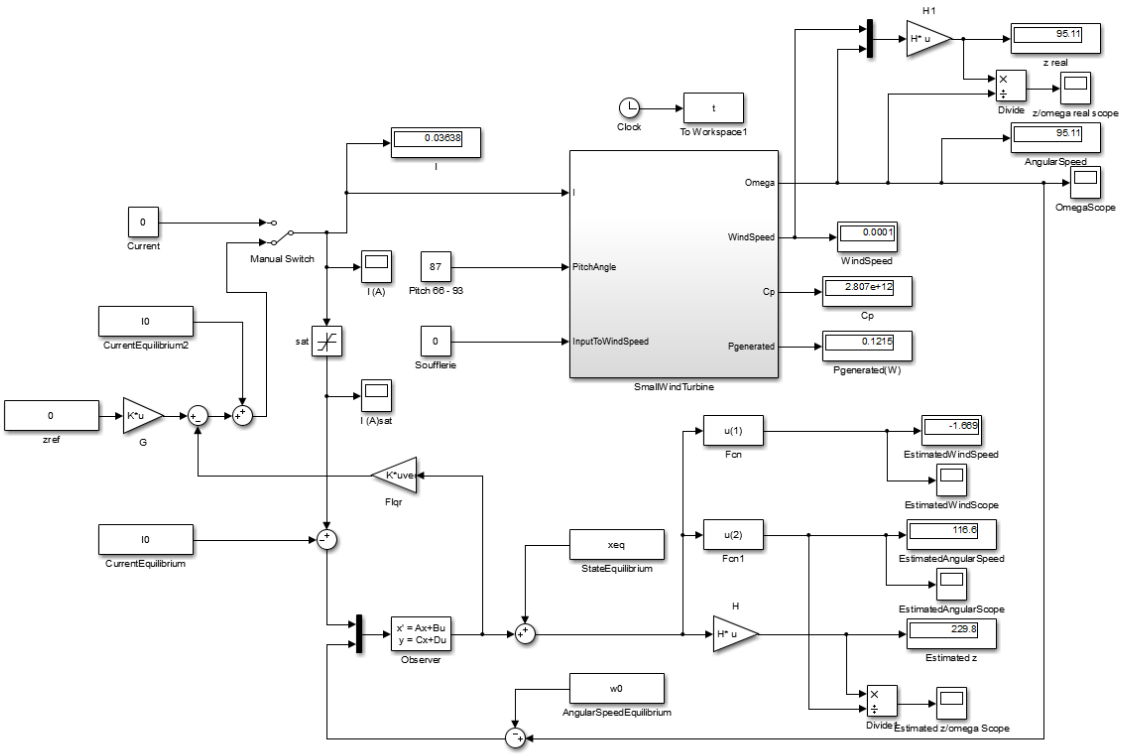
The system scheme is shown in a simplistic way in Figure 5.5. Where K is the state-feedback gain and L the observer gain.

Figure 5.5: System block Scheme with state-feedback and observer [11]



The used scheme directly at the plant is shown in Figure 5.6. We used a Simulink®real time application.

Figure 5.6: Simulink®real time application



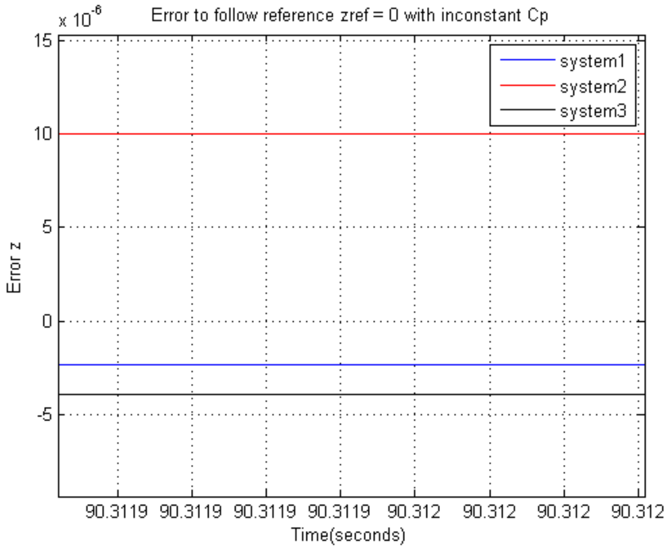
To complete this design we made a robustness analysis shown next.

5.5 Robustness analysis

For this analysis we considered our power factor (C_p) parameter as a varying value ranging from 0.3 to 0.5 and recalculated 3 different systems based on this. Then, we applied the same control scheme calculated and ran simulations.

Figure 5.7 shows that even with a varying power factor our z managed to follow the reference achieving close to zero error for the three plants with only a small difference between them.

Figure 5.7: Robust analysis of following reference error of Z with varying C_p



Considering the error to z our system is robust. Now we can validate the control design directly at the plant.

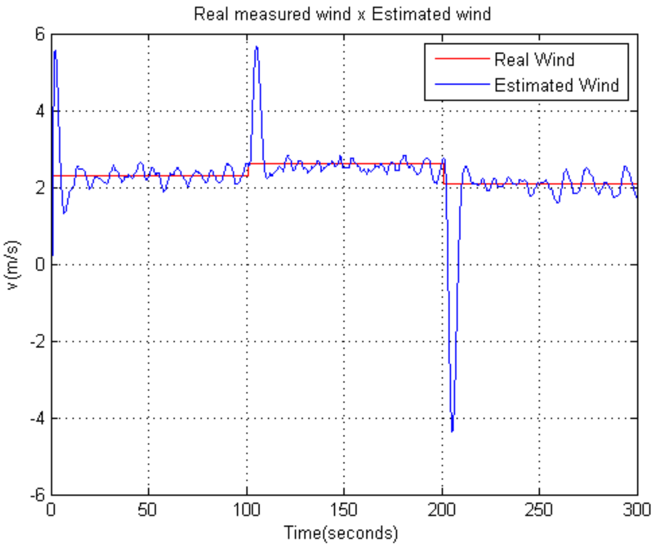
5.6 Real time validation

We were now certain that our control design was ready to be used directly on our small wind turbine. Using a real time Simulink®application we added our control to the real turbine and checked if it succeeded in estimating the wind as well as keeping our z following our reference of zero.

First we checked if the system manages to estimate our wind speed. The value we regarded as the real one to the wind speed was taken from an anemometer as described in chapter 2.4

Figure 5.8 shows the comparison between the real wind and the estimated one by the observer in real time with the plant. For test we changed the wind speed two times, starting at 2.3m/s (equilibrium point) then moving on to 2.6m/s and finalizing at 2.1m/s.

Figure 5.8: Real and estimated wind comparison

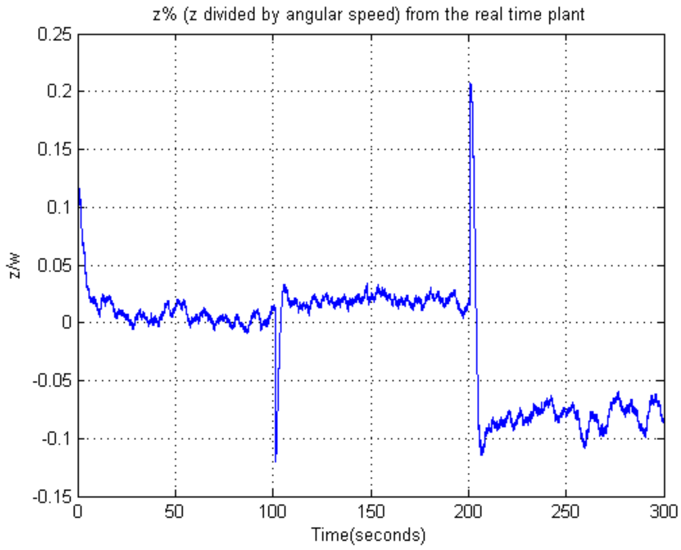


Based on the real and estimated wind comparison above we were able to ensure that our system managed to estimate but with a wave form that changed the mean value according to the wind. That probably happened because, as previously mentioned, the real wind had been measured by hand and considered as constant but while in fact it was not. Moreover, inside the wind turbine's box there are probably reverberations that created this wave of sinusoidal form to the wind behavior, it could be because of noise amplification as well. Since wind is prone to change, it was expected that our estimator tried to compensate these variations.

The reason for the transitory values on the image is unclear, we noted during our several tests on the plant that it had spikes like that on measures and a fair amount of noise but this didn't invalidate de work done.

With the observer checked we could then proceed to our control and see whether was is managing to put z to zero in steady state. Figure 5.9 shows the percentage value of z based on the angular velocity at the moment. This means that we looked how far, on percentage, away from the desired speed the system is.

Figure 5.9: Percentage of z away from the reference 0

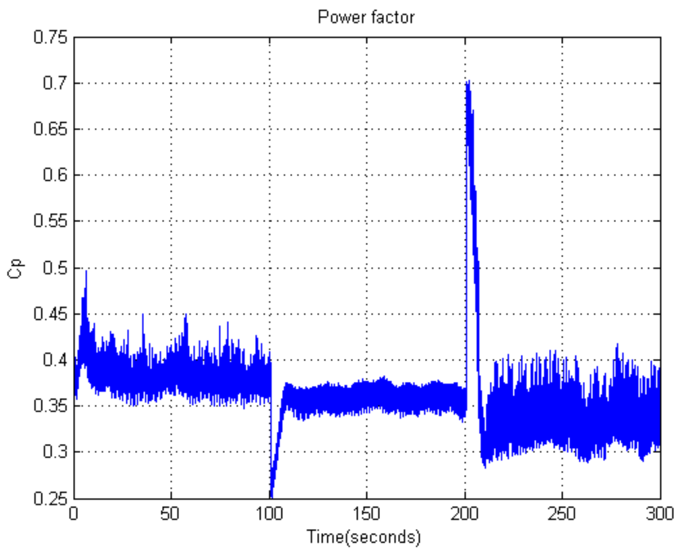


It was seen that z kept close to zero having its worse values (10% of error) when the speed was 2.1m/s. All the peaks seen in the image occurred when the wind speed changed and can be regarded as transitory behaviors of the system.

The next step was to check if our power factor stayed around a certain value. After all, good efficiency of the turbine was the main goal of employing our z. The z value approaching zero made the system tend to the same tip speed ratio (λ) based on Equation (5.17). As seen in chapter 3 the tip speed ratio had a related power factor, which is exactly what we need to optimize.

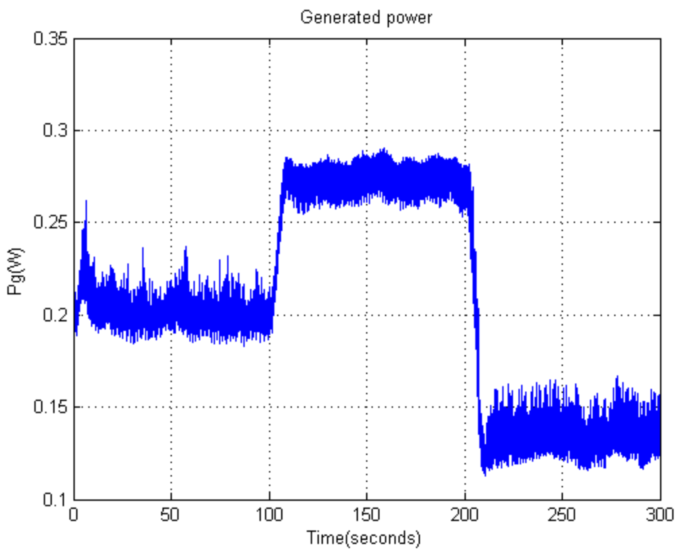
Figure 5.10 shows that our power stayed inside a range of 0.3 to 0.4 at all times even with wind changing 13% (to the equilibrium speed). This validates our control which is furthermore shown in Figure 5.10 which proves that the power factor and tip speed ratio change in accordance with the wind speed.

Figure 5.10: Real Cp with wind changes



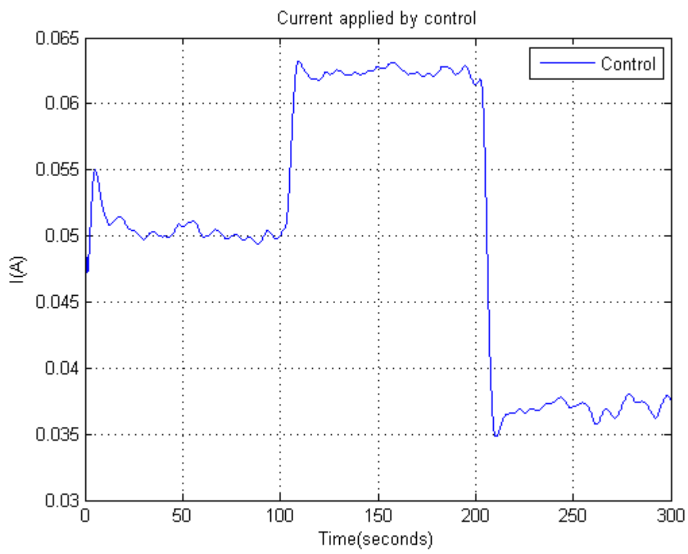
It is essential to keep in mind that we were working with a wind turbine. Thus, it is important to mention its power generation. Figure 5.11 shows in Watts (W) the amount of energy generated during this test. It is, of course, a very small value matching the small model we worked with.

Figure 5.11: Power generated



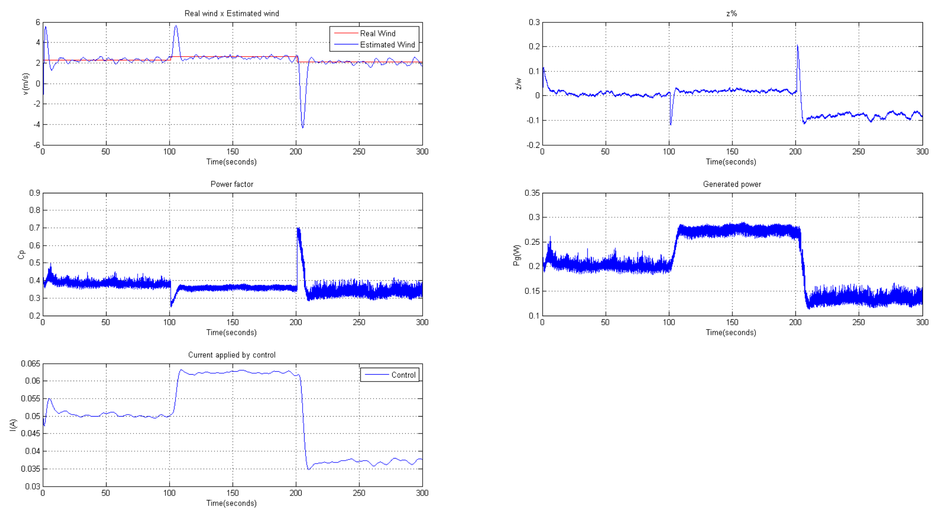
Finalizing, to validate our control Figure 5.12 shows the applied current to the system during the test. As we can see for bigger wind speeds the control tried to slow down the wind turbine adding more current while for smaller speeds it tried the opposite.

Figure 5.12: Control



For a clearer point of view of all discussed in this chapter Figure 5.13 shows all the preceding plots in one image.

Figure 5.13: Control



Chapter 6

Achieved results and further development

The expected goal of the project was met by the intern within the necessary time frame.

The small wind turbine model was thoroughly analyzed with a step-by-step documentation. It allows future workers to better understand previous work as well as encourage them to start their own research.

The present paper described the robust methodology that was found during the process of extensive testing. Because of this development the next models that will be crafted are likely to be more easily estimated.

The control law employed here is the same usually taught in courses here at ENSE3. However, instead of using simulations the work presented in this paper was conducted on an actual wind turbine. This helps validate the control design and expands the knowledge on important information about the model.

In summary, the achievement of our goals opened room for more advanced development usually concerning control design. A common control approach was applied to the system (state-feedback with observer) but there are other sets of design that could obtain good results, such as MPC (model predictive control) or Robust control. As the system is nonlinear there are more options of analysis as well as of control which tries to avoid any linearization.

Another untouched point consists in a pitch angle control that is used on real wind turbines and which is very important for them as it allows the turbine to work with a wilder range of wind speeds.

Regarding further development of the plant itself, we recommend adding more sensors on the new copies to be built in the future. Those sensors should be used to check important information like the wind speed and air density.

It is important as well for the next researchers on the wind turbine model to redo and validate further the PRBS estimation. It showed results that even working in a real time validation were not completely reliable.

Overall the small wind turbine model showed us that we have plenty of possibilities to not just control it better but to use it as a tool to introduce students into the field.

Bibliography

[1] ENERGY.GOV, *How do Wind Turbines Work?* retrieved on Jun 09, 2014 from http://energy.gov/eere/wind/how-do-wind-turbines-work

[2] Elizabeth Salerno, *U.S. Department of Energy report: Wind power costs near record low* retrieved on Jun 02, 2014 from http://www.aweablog.org/blog/post/us-department-of-energy-report-wind-power-costs-near-record-low

[3] GWEC.NET, *GWEC, Global Wind Energy Outlook 2011* retrieved on Jun 09, 2014 from http://gwec.net/wp-content/uploads/2012/06/Annual_report_2011_lowres.pdf

[4] Jean Remy Davée Guimarães, *Bons ventos evitarão calor e fome?* retrieved on July 02, 2014 from http://cienciahoje.uol.com.br/colunas/terra-em-transe/bons-ventos-evitarao-calor-e-fome/

[5] GWEC, *GWEC-GLOBAL WIND 2010 REPORT* retrieved on Jun 09, 2014 from http://www.ewea.org/fileadmin/ewea_documents/documents/00_POLICY_document/Offshore_Statistics/GWEC_Global_Wind_Report_2010Extract.pdf

[6] Kira Grogg, *The Physics of Wind Turbines* Carleton College, 2005, p.8 apps.carleton.edu/campus/library/digitalcommons/assets/pacp_7.pdf

[7] John Sandoval-Moreno, Gildas Besançon and John J. Martinez, *Observer-based maximum power tracking in wind turbines with only generator speed measurement* , Paper, Gipsa-Lab, Control Systems Department, Grenoble Institute of Technology, Ense3, 2013.

[8] L. Jung, *System Identification: Theory for the user (2nd Edition)* , Book, 1999. http://en.wikipedia.org/wiki/Pseudorandom_binary_sequence

[9] Paul H. Bardell, William H. McAnney, and Jacob Savir,*Built-In Test for VLSI: Pseudorandom Techniques* , John Wiley & Sons, New York,1987.

[10] MathWorks, *Linear Correlation* retrieved on May 05, 2014 from http://www.mathworks.fr/fr/help/matlab/data_analysis/linear-correlation.html

[11] Control Tutorials For MATLAB® & Simulink®, *State-Space Methods for Controller Design* retrieved on May 21, 2014 from http://ctms.engin.umich.edu/CTMS/index.php?example=InvertedPendulum\&section=ControlStateSpace