Development and evaluation of a pitch regulator for a variable speed wind turbine

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Göteborg, Sweden 2012

THESIS FOR THE MASTER OF SCIENCE DEGREE

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Abstract

In this thesis a pitch regulated speed controller is derived for a variable speed wind turbine for high wind speed region. The pitch regulator parameters are calculated through the output torque, which is a function of the pitch angle in both numerical and analytical models. In order to derive the pitch regulated wind turbine model, blade element momentum theory is explained and reformed analytically. Finally the analytically derived pitch regulated wind turbine model is tested under grid disturbances such as voltage dips and spinning reserve ability.

From this work it is observed that by linearizing the blade profiles, one can analytically derive a pitch regulator. This system is tested under grid disturbances and it is proven that the system is capable of operating well during a 90% voltage dip or using same amount of spinning reserve ability and still maintain a robust turbine control.

Keywords: *Wind turbine, pitch regulation, variable speed operation, blade element momentum theory.*

Acknowledgments

The help and guidance provided by my supervisor Professor Torbjörn Thiringer is most gratefully acknowledged.

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Finally, I thank every member of the Division of Electric Power Engineering for the peaceful and welcoming study atmosphere.

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List of symbols

Abbreviation

a	axial induction factor
a’	tangential induction factor
c	chord
c_D	drag coefficient
c_L	lift coefficient
Cp	power coefficient
D	drag force
F_{Edge}	edge force
F_{Flap}	flap force
J	moment of inertia
ki	integral parameter of the pi controller
kp	proportional parameter of the pi controller
L	lift force
n_b	number of blades
P	power output of the wind turbine
r	radius
R	rotor radius of the wind turbine
t	twist
T_{mech}	torque output of the wind turbine
W	relative velocity
Δr	radius difference between blade segments
ΔT	torque contribution of each blade segment

Greek

α	angle of attack
α_ω	bandwidth of the controller
β	pitch angle
ϕ	relative flow angle
ω_r	angular rotor speed
ρ	air density
v_ω	wind speed
λ	tip speed ratio

1. INTRODUCTION

1.1. General background

Wind energy is not a new concept for humanity. The power in the wind had been used for sailing vessels, pumping water or food production since the early ages, mainly in Asia. By the 11^{th} century, due to the cultural interaction, wind energy had spread to Europe also. The wind energy was used in order to supply a mechanical load; however it was not until the 19^{th} century that the wind was considered as a potential source of electricity generation. Charles Brush, an American inventor, developed a windmill to produce electricity but the design of the turbine was rather impractical with 144 rotor blades. Shortly after, a Danish scientist, Pour la Cour discovered a fast rotating wind turbine with fewer blades, which was generating electric power in a more efficient way. At the 20^{th} century, new advances about the wind turbines came up, such as implementation of AC generators, stall and pitch controls to have a safe operation during strong winds, electromechanical yawing to keep the turbine always at the wind direction and etc., in order to achieve a more and more efficient use of the wind.

The popularity of the wind energy has always been in relation with the fossil fuel prices. After World War II with decreasing fossil fuel prices, wind energy lost its popularity; however the oil crisis in 1970s boosted interest in large scale energy production via wind turbines. [1]

Nowadays due to the increasing concern about the emission caused by the fossil fuels and the security issues regarding nuclear power, wind energy is more popular than ever and as a matter of fact, it is the world's fastest growing energy source. The worldwide installed capacity of the wind generators has increased from 158 GW to 195 GW from 2009 to 2010. At 2010, the wind-based energy supplied was approximately 2.5% of the total energy generation. This ratio has doubled itself in the last three years. By the year 2011, 83 countries are using wind power in commercial basis. Global Wind Energy Council (GWEC) predicts that at the end of 2015, global wind-powered electricity generation capacity will increase up to 450 GW. [1]

With such ambitious targets set forward for Wind Energy, a lot of efforts have been put in developing the existing technology. This project also deals with the wind energy and aims to propose a different point of view to the wind energy studies.

1.2. Problem description

Wind energy studies, regardless the area of interest, generally require modeling and simulation of the wind turbine. Even though it has very reliable outcomes, wind turbine simulations are time consuming; obtaining result may take months. Another disadvantage about the simulations is that, each model is often valid for one wind turbine and therefore simulation results for one particular research effort could be invalid for other researches. There is a lack of traceable pitch regulation design studies too. Combining these one can say that a general and traceable pitch regulated speed control derivation is missing from the studies.

The drawbacks referred above, can be improved if a pitch regulated wind turbine system can be designed using analytical methods, which can be used for different wind turbines.

1.3. Purpose of the work

The main purpose of this thesis is to derive a pitch regulated speed controller for a variable speed wind turbine for high wind speed region and this is done through numerically and analytically expressed output torque. In order to achieve this, there are several objectives to fulfill.

One of the objectives is to study the aerodynamics of the wind turbine, especially the blade element momentum theory in order to have a better understanding to the extraction of the mechanical torque out of the wind. Blade element momentum theory is the key to analytically expressing the output torque and building a pitch regulator.

Another objective is to obtain a Cp-λ curve to investigate the dependence of Cp on the rotor speed of the wind turbine. This is important because if Cp is independent or slightly dependent of the rotor speed, a controller scheme for the whole wind speed range can be derived.

The aim of the previous objectives is to build a wind turbine model which could operate at low, middle and high wind speed regions. With the help of this model, the output torque, rotor speed and pitch angle behaviors of the wind turbine can be studied.

In order to obtain an analytical pitch regulator, the first step is to linearize the lift and drag coefficients. With the new lift and drag coefficients, a new output torque is obtained as a function of the pitch angle. The pitch regulator parameters are calculated through this new output torque and thus the main objective is achieved. After the pitch regulated wind turbine system is derived and working under ideal conditions, the system should also be tested for grid disturbances.

When all the previously mentioned objectives are fulfilled, the development and the evaluation of the pitch regulated variable speed wind turbine for high wind speeds would be complete.

2. AERODYNAMICS OF THE WIND TURBINE

Wind turbine is a device that generates electric energy by converting part of the kinetic energy in the wind to electrical energy. Even though there are different types of wind turbines, the main principal is the same. The aerodynamical force caused by the wind on the rotor blades produces a mechanical torque on the shaft, which is connected to the electric generator usually through a gearbox. Then the electric generator transmits the power to the electrical grid.

Thus, a wind turbine consists of aerodynamic, mechanical and electrical parts. The aerodynamics of the wind turbine is explained in this chapter, so that the aerodynamic force to mechanical torque conversion can be better understood.

Figure 2.1 shows the wind turbine scheme that explains the energy conversion from wind to the electric grid.

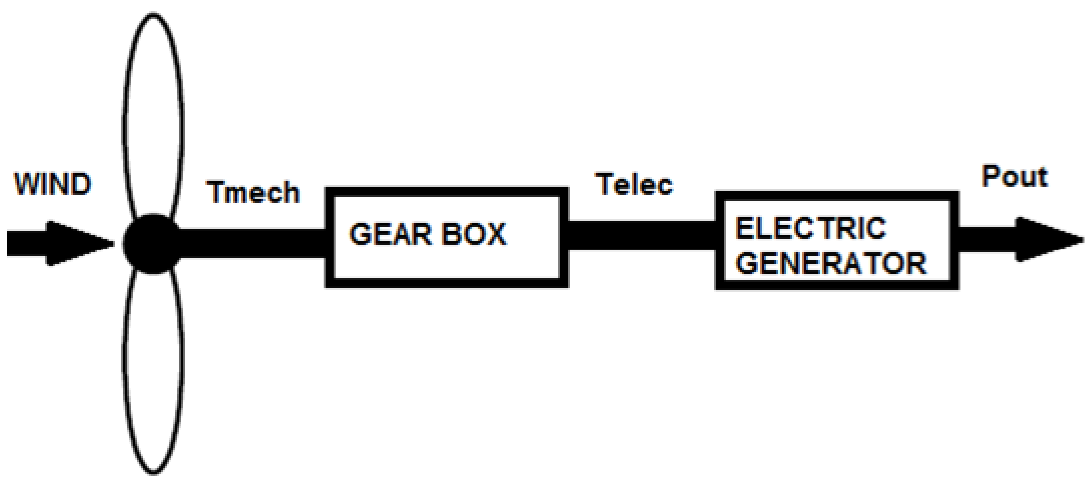


Figure 2.1: Principal of power conversion through wind turbine

2.1. Blade Aerodynamics

There are two main forces acting on the blade of the wind turbine in order to create the rotation. Lift force, which is perpendicular to the wind direction and the drag force, which is parallel to the wind acting on the blade.

These forces are defined according to lift and drag coefficients for a certain angle of attack, which is the angle between the incoming wind flow and the chord line of the turbine blade. Lift and drag coefficients against the angle of attack can be seen at Figure 2.2.

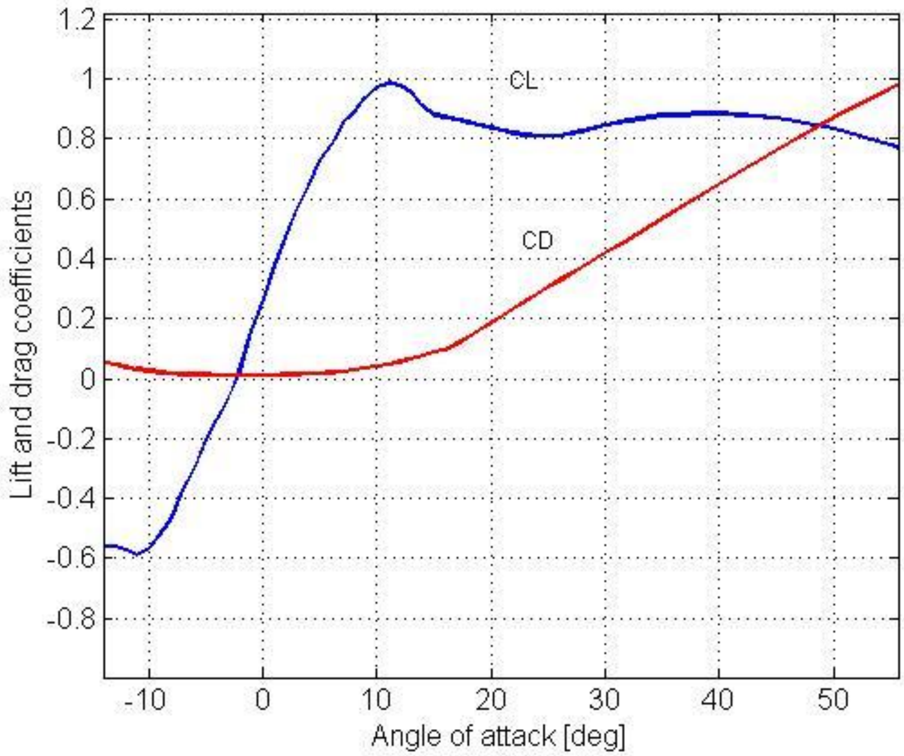


Figure 2.2: Lift and drag coefficients of the airfoil according to the angle of attack

2.1.1. Blade element momentum theory

The wind turbine working principle is based on energy conversion. Energy in the wind will create a rotation in the shaft to produce electricity. In this study, to investigate the relation between the shaft torque and the wind energy, Blade Element Momentum (BEM) Theory is used.

As mentioned before, lift (L) and drag (D) forces act on the airfoil with the incoming wind. But to be able to calculate their effect on the blade, they need to be projected in the tangential and normal directions towards the rotorplane. One of these projected forces is referred to as the edge force (F_{Edge}) and creates the mechanical torque required for the rotation. The other projected force is called the flap force (F_{Flap}), which introduces thrust on the rotor blades.

Figure 2.3 shows the blade and the aerodynamic forces acting on it.

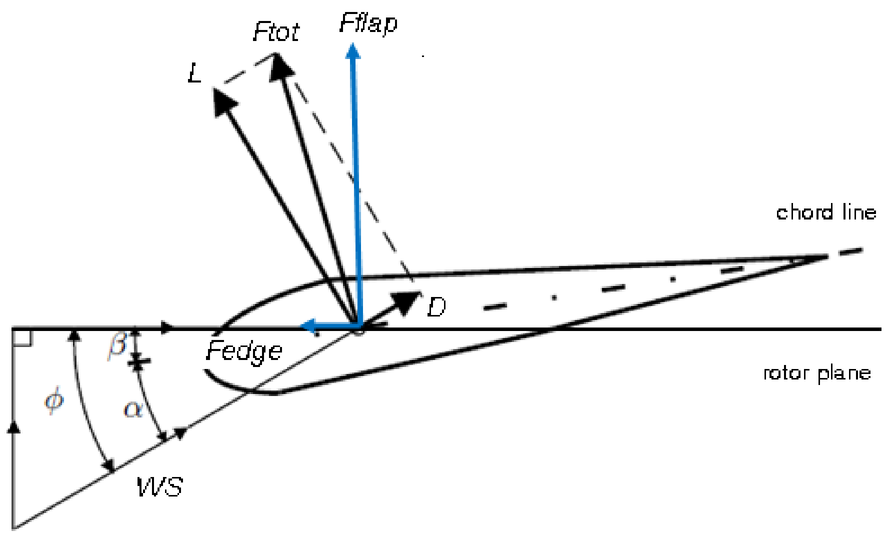


Figure 2.3: Wind and forces on the rotor plane

Flap and Edge forces can be calculated from lift and drag forces in the following fashion:

$$F_{Flap} = L\cos\phi + D\sin\phi \tag{2.1}$$

$$F_{Edge} = L\sin\phi - D\cos\phi \tag{2.2}$$

The angle Φ is the sum of the angle of attack (α) and the pitch angle (β) and it represents the angle between the wind direction and the rotor plane is,

$$\phi = \alpha + \beta\,. \tag{2.3}$$

Once flap and edge forces are calculated, torque and thrust can be calculated through the Blade Element Momentum Theory. The principle of BEM theory is to calculate the flap and edge force contribution of each blade segment by using the blade data such as chord length, blade twist angle as well as the lift and drag coefficients. The sum of all the flap and edge force contributions multiplied with the corresponding radius of the blade segment is needed to calculate the thrust and the torque from the wind,

$$T_{mech} = \sum_{i=0}^{n} r_i F_{Edge} \tag{2.4}$$

$$Thrust = \sum_{i=0}^{n} r_i F_{Flap} \tag{2.5}$$

where r is the radial position of the blade element [2].

2.2. Wind Turbine Operation

2.2.1. Fixed speed operation

Fixed speed operation can be managed by coupling the induction generator directly to the grid. The rotor speed then becomes almost synchronized with the grid frequency, only a small slip (few %) gives a slight deviation. In principle shaft torque created by the wind power is converted through the gear box to obtain the needed torque for driving the induction generator at its nominal speed.

Even though it is based on a simple principle and has a simple control system, fixed speed operation has some disadvantages. First of all, variations in the wind speed would cause ripple at the shaft torque which transfers directly to the power output. A fluctuating output power could cause grid disturbances, more severely on weak grids.

An ideal wind turbine should be extracting the maximum energy from the wind, i.e. operating at maximum efficiency. For the wind turbines this efficiency is represented by the power coefficient Cp, which is a function of the tip speed ratio (λ). From (2.6) and (2.7), we can see that the tip speed ratio is inversely proportional to the wind speed. This means that there is only one wind speed value giving the optimal λ, where *Cp* is at its maximum. Consequently, operation at the maximum efficiency for a fixed speed turbine is only valid for a tiny range of wind speed.

$$\lambda = \frac{\omega R}{\upsilon_w} \tag{2.6}$$

$$P = \frac{1}{2}\rho\pi R^2 C_p(\lambda)\upsilon_w^3 \tag{2.7}$$

In (2.7), ρ represents the air density, R stands for the rotor radius, *Cp* is the power coefficient of the wind which is a function of the tip speed ratio and υ_ω is the wind speed [3].

Due to the extra equipment needed for no-load operation and start-up of the induction generator, mechanical stress on the gearbox due to the torque ripple, unwanted fluctuations at the output power and the low efficiency problems, fixed speed turbines are becoming less and less popular.

2.2.2. Variable speed operation

If the generator is connected to the grid through a power electronic control system, which converts the rotor speed into the desired frequency of the grid, variable speed operation can be maintained. According to (2.6), at low wind speed range (roughly 3-10 m/s) optimal λ can be achieved. This means that for the low wind speeds, *Cp* is always at its maximum, since it is desirable to capture maximum power from the wind turbine.

Since the rotor speed varies according to the incoming wind speed, torque fluctuations are eliminated. Therefore the output power quality is free of ripple and the mechanical stress on the turbine is reduced.

Due to the varying rotor speed at high wind speed operations, the output power can exceed the rated value. In order to have constant rated power as output, an aerodynamic control is used, called pitch control.

2.3. Effect of the aerodynamics on wind turbine operation

There is an ideal operation point for each wind turbine but due to the varying wind speed this point cannot be reached at all times. However according to (2.7), to get as much output power as possible from the wind turbine for as long as possible, some aerodynamic properties can be controlled.

2.3.1. Pitch Angle Effect

2.3.1.1 Active Stall Control:

Active stall control can be performed on fixed speed turbines, if the wind turbine blades are able to pitch. The main idea is to change the pitch angle in order for the wind turbine to work as close as possible to the ideal operation point. For low wind speeds, the blades can be pitched to form a slightly higher torque. For high wind speeds, where the output power may exceed the rated value, the blades are pitched to increase the angle of attack. This gives the possibility to always operate at rated power, regardless of the temperature and the pressure.

Figure 2.4 shows that by pitching the blades slightly (0-4 degrees) at high wind speeds, rated power can be achieved. This change of pitch angle has almost no effect on the thrust at the corresponding wind speed level, as observed Figure 2.5.

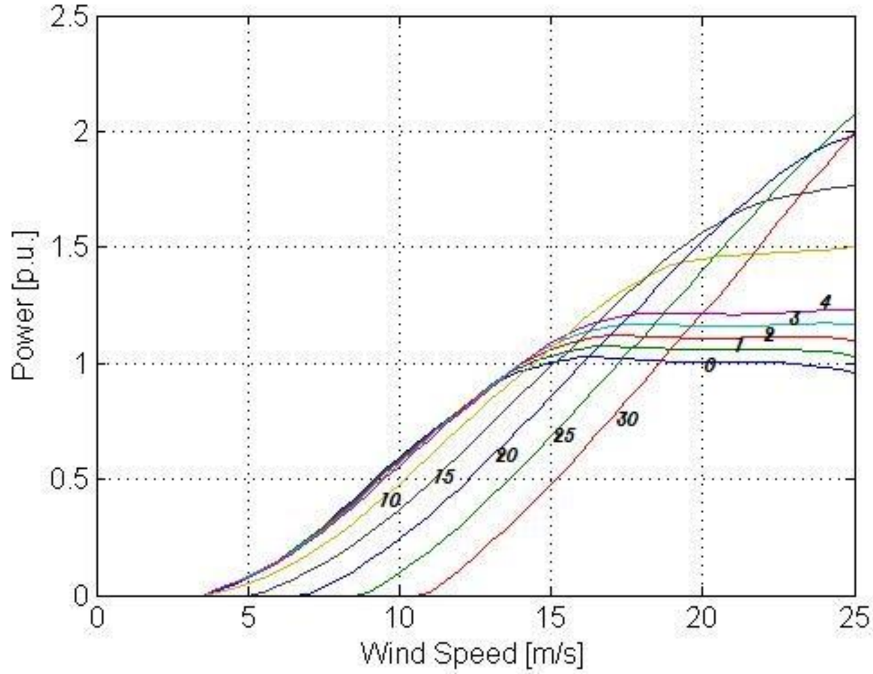


Figure 2.4: Output power vs. wind speed for different pitch angles for nominal rotor speed

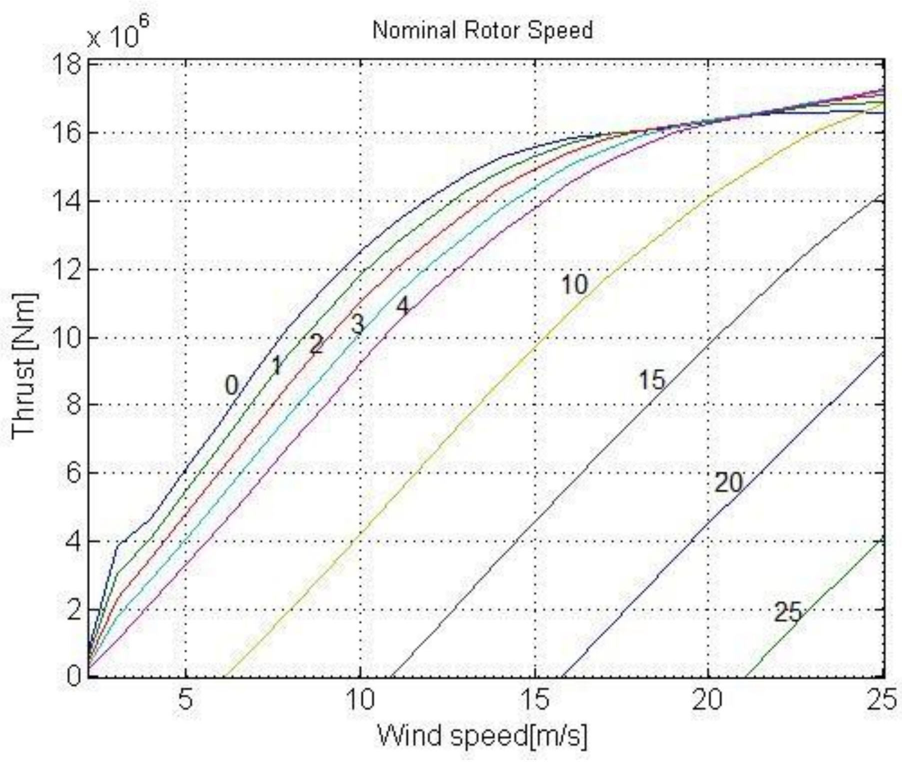


Figure 2.5: Power from the thrust vs. wind speed for different pitch angles

2.3.1.2 Pitch control:

Pitch control has mainly the same idea as the active stall control; tilt the blades in order to get the desired output from the wind turbine. But instead of having a slight deviation in the pitch angle, pitch control occurs in a rather large operating range, roughly between 0-35 degrees.

Pitch control allows extracting maximum energy from the wind at low wind speeds and limiting the power and torque to their rated values at high wind speeds. Pitch control provide great benefit for variable speed wind turbines in order for the system to operate in high wind speeds and to maintain secure operation at this speed range.

The power output of the wind turbine is monitored by the power electronic controller of the system and when the output power is exceeding the rated value, the controller commands the blades to pitch in order to decrease the energy from the wind. The same sort of control is performed to go back to the initial condition when the wind speed decreases to the optimal value. Figure 2.6, Figure 2.7 and Figure 2.8 show the power and *Cp* behavior against wind speed and *Cp* as a function of tip speed ratio and pitch angle, respectively. These results are obtained for the nominal rotor speed, 19 rpm.

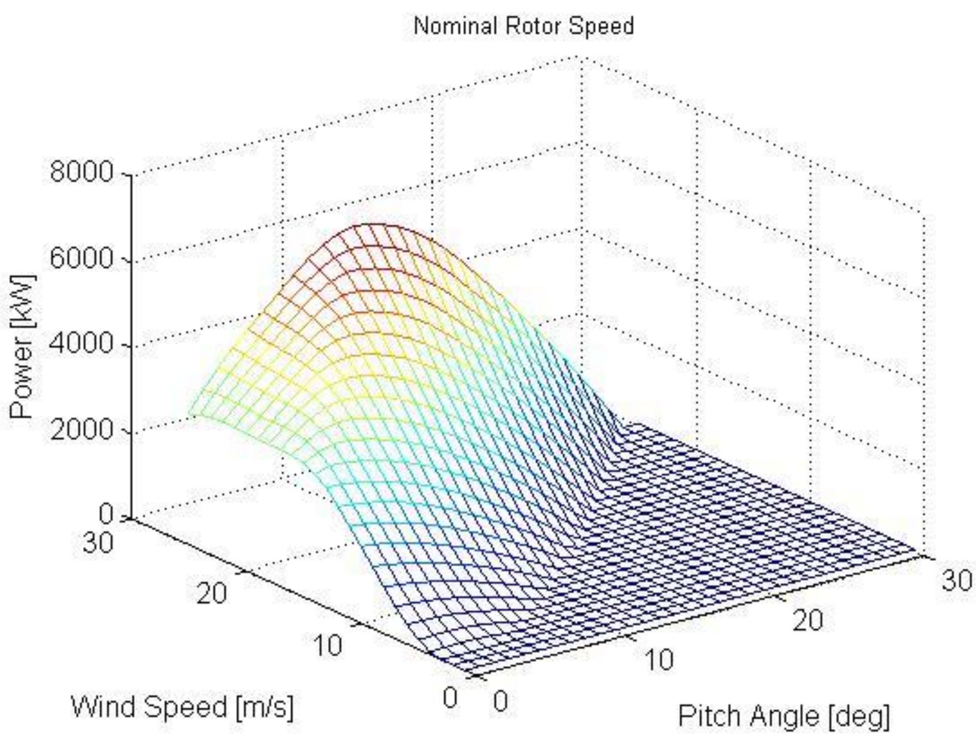


Figure 2.6: Power vs. wind speed and pitch angle for nominal rotor speed

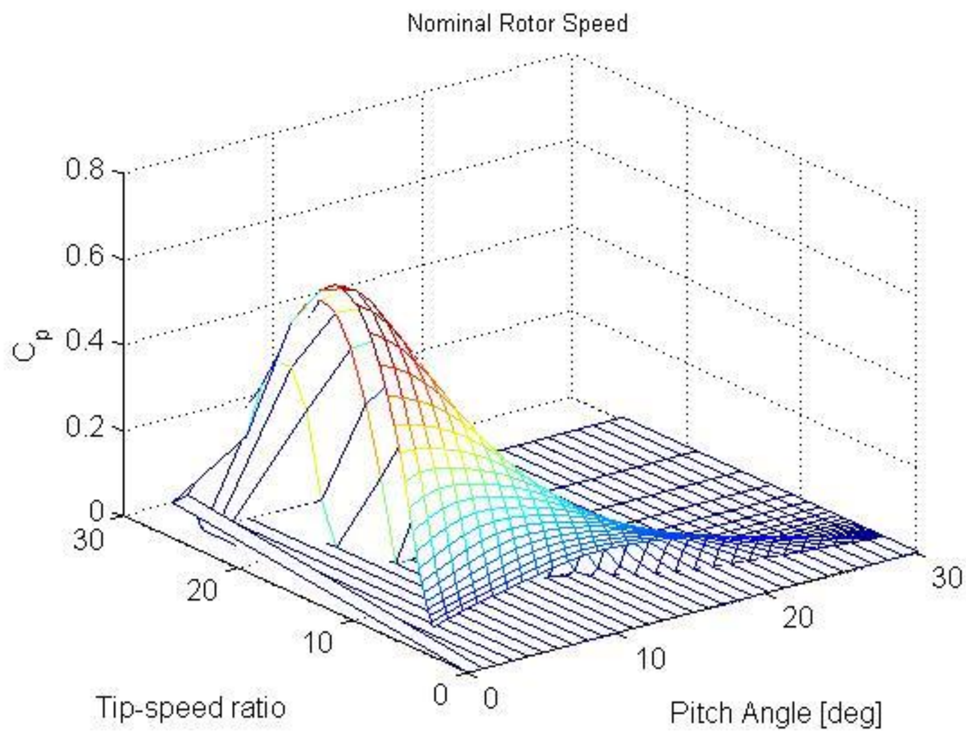


Figure 2.7: Cp (λ, β) for nominal rotor speed

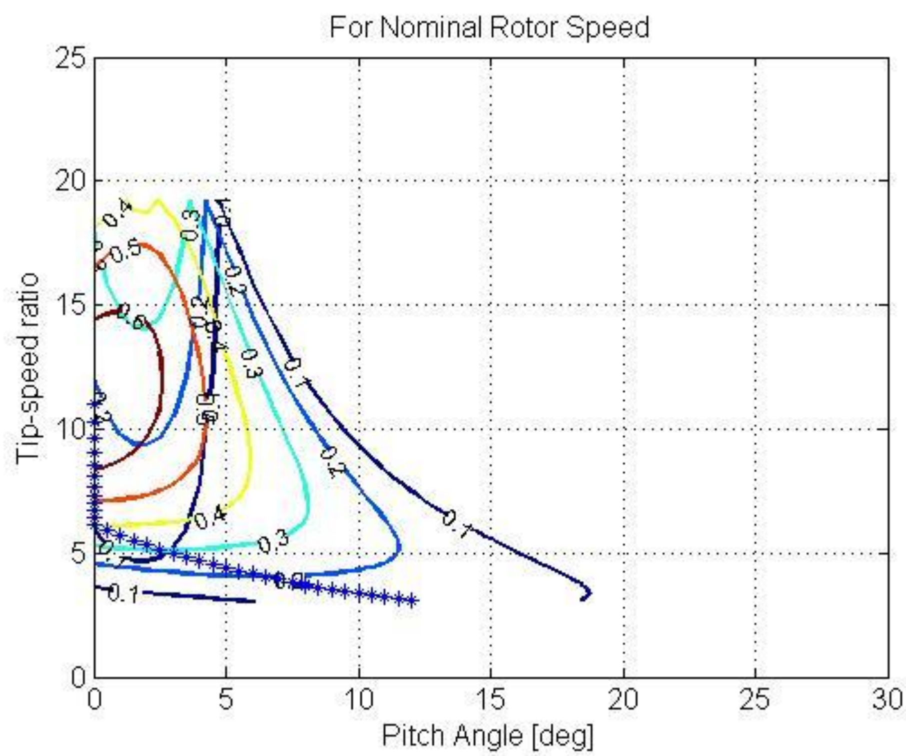


Figure 2.8: Cp (λ, β) expressed as contour lines where each lines shows a specific Cp value for nominal rotor speed. Starred line shows the optimal operation for different tip speed ratio and pitch angle combinations

From the Figure 2.6, Figure 2.7 and Figure 2.8 above, it is possible to observe that when the pitch angle increases, *Cp* decreases. Since pitching is done in order to reduce the output power for high wind speeds, this relation is natural.

2.3.2. Rotor Speed Effect

Wind speed change in variable speed turbines result in a change in the rotor speed also. Even though this deviation can cause difference in the output power, *Cp (λ, β)* remains relatively constant; which means the output torque remains unchanged too. According to that, the controller settings can be fixed correctly based on output torque. From Figure 2.9 and Figure 2.11, it is observed that even though *Cp* is different for high tip speed ratios for different rotor speeds, the optimal lines which are used to design the controller are fairly same. This means the Cp is independent of the rotor speed in the area of operation.

Also, Figure 2.13 shows the comparison between Cp values for maximum, nominal and minimum rotor speed. Again, from this figure, it is observed that at the operating range all the Cp values are overlapping. This proves that Cp is not dependent on the rotor speed. Therefore one can say that even though the rotor speed changes are inevitable for low wind speed region, controller design is not affected by it.

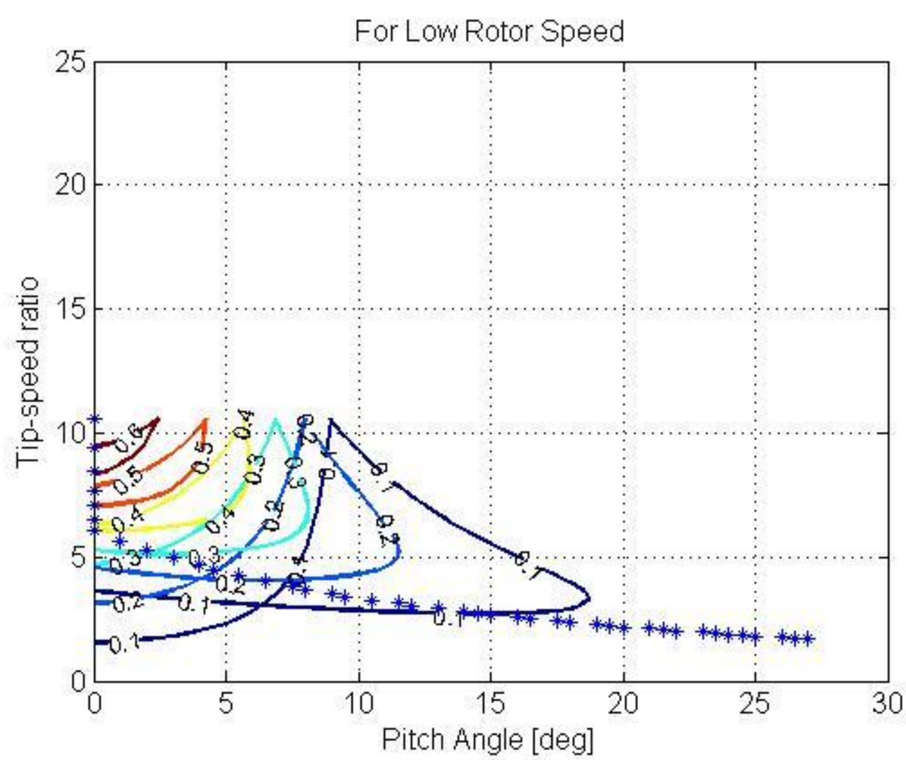


Figure 2.9: Cp (λ, β) expressed as contour lines where each lines shows a specific Cp value for minimum rotor speed. Starred line shows the optimal operation for different tip speed ratio and pitch angle combinations

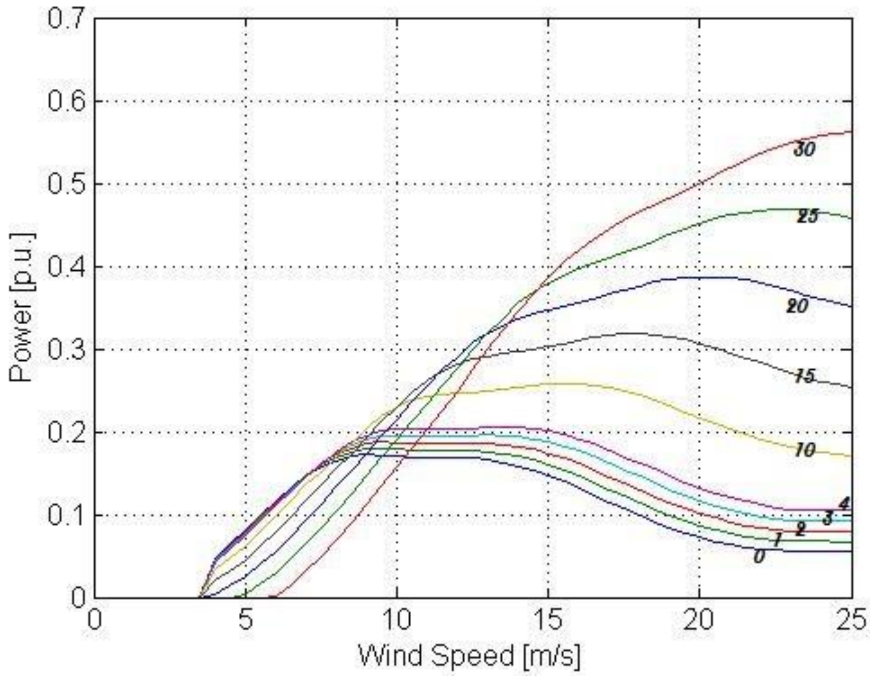


Figure 2.10: Output power vs. wind speed for different pitch angles at minimum rotor speed

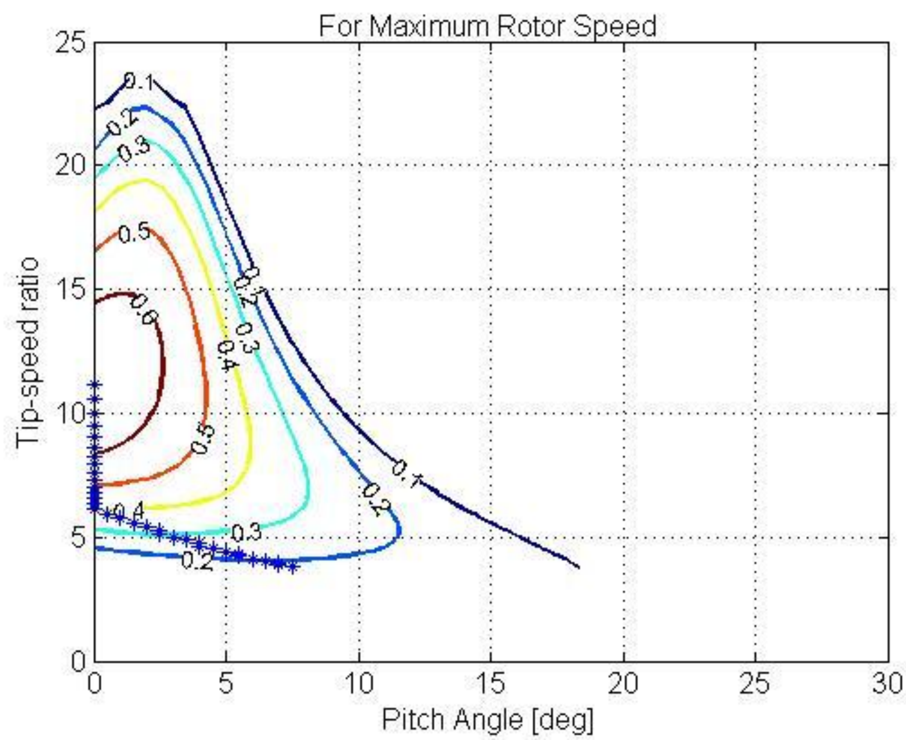


Figure 2.11: Cp (λ, β) expressed as contour lines where each lines shows a specific Cp value for maximum rotor speed. Starred line shows the optimal operation for different tip speed ratio and pitch angle combinations

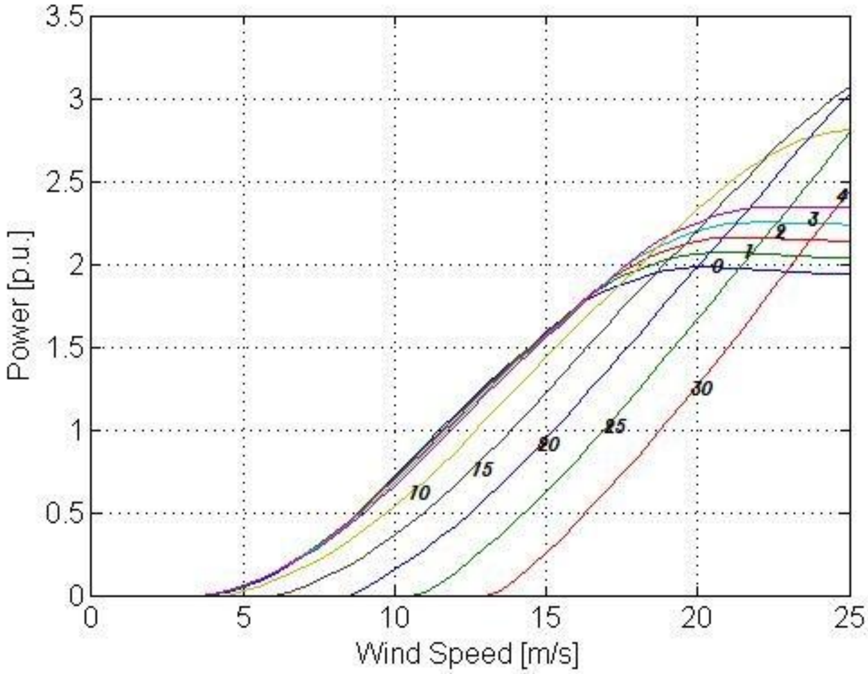


Figure 2.12: Output power vs. wind speed for different pitch angles at maximum rotor speed

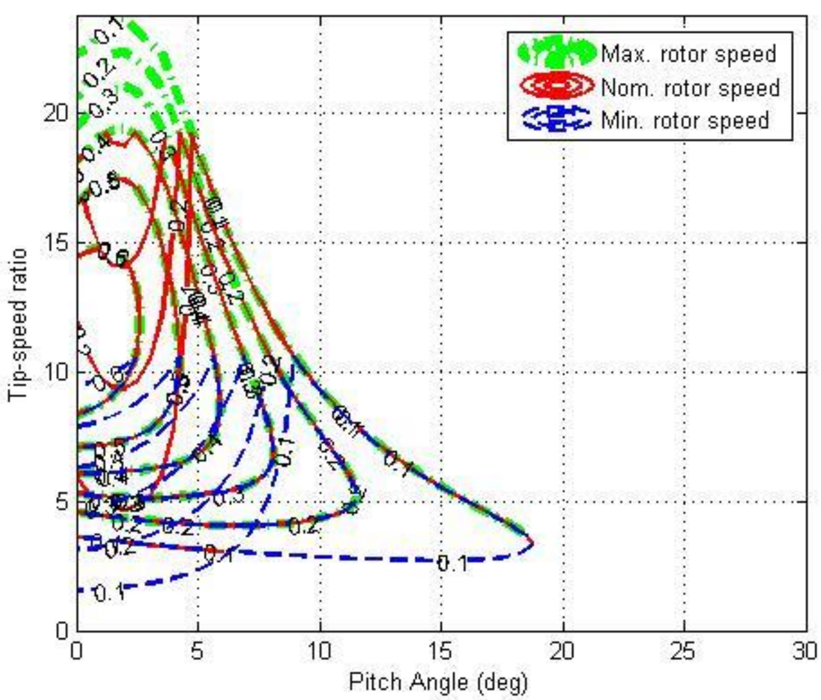


Figure 2.13: Comparison of the Cp values for different rotor speed levels

3. CONTROL SYSTEM OF THE VARIABLE SPEED WIND TURBINES

For each wind speed level, the variable speed wind turbine operates differently. This behavior requires different control strategies for different wind speed levels. Figure 3.1 shows the power and rotor speed behavior for different wind speed levels. This data is particularly important in order to derive a suitable control system, since the controller basically aims to keep the output power at a suitable value while the wind speed changes.

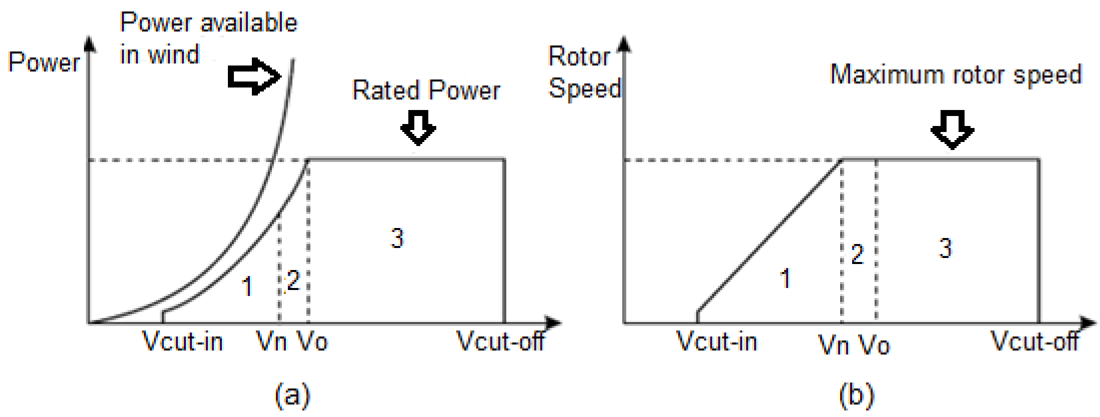


Figure 3.1: : (a) Output power for different wind speed ranges, (b) Rotor speed for different wind speed ranges from controller point of view

Low Speed Interval (1): This speed range represents the speed variation between cut-in wind speed (V_{cut-in}) and the nominal speed (V_n). In this region both the rotor speed and the output power are increasing until the rotor speed reaches nominal level.

Middle Speed Interval (2): In this region wind speed goes from V_n to the rated wind (V_0). For the middle wind speeds the desired rotor speed is constant at its nominal and the power is still increasing.

High Speed Interval (3): High speed region represents the region between the rated wind (V_0) and the cut-off speed ($V_{cut-off}$). In this region, the wind turbine operates at the rated power and the maximum rotor speed and pitch control takes place to limit the output power to its rated value.

3.1. Low wind speed interval

3.1.1. Control strategy

For low speeds, the aim is to keep the efficiency maximum in order to extract the maximum energy from the wind. Therefore the maximum Cp must be achieved at all times. In order to ensure maximum Cp, the corresponding tip speed ratio is fed to the speed controller and the reference rotor speed is calculated in order to achieve the ideal operation at maximum efficiency. At low speed interval, pitch control is not used.

3.1.2. Modeling of the control system

Figure 3.2 shows the controller diagram for the low wind speed interval.

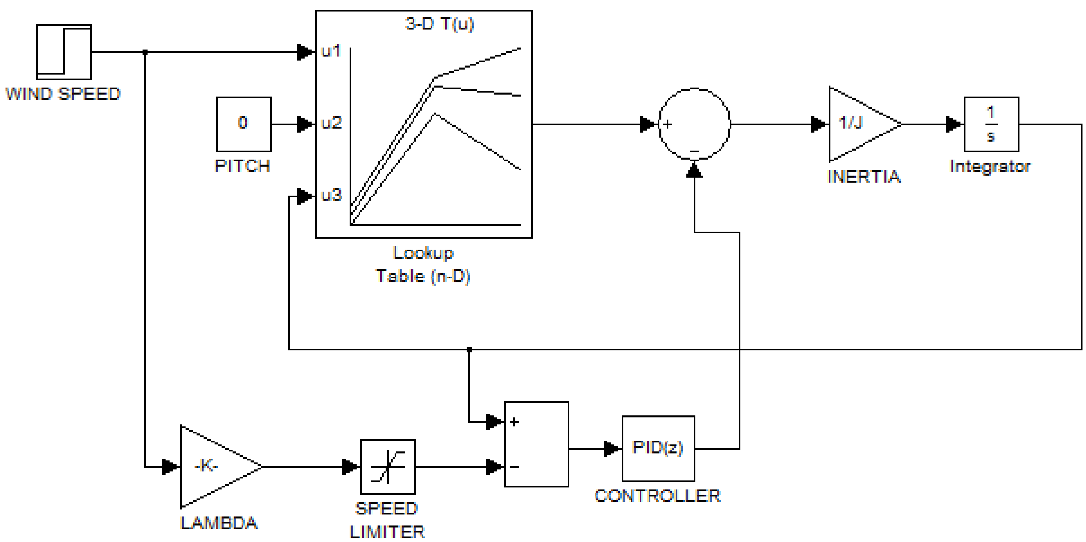


Figure 3.2: Control system for low speed interval

It is observed from the figure that the wind speed is measured. Afterwards this wind speed is fed into the look-up table of the system together with the rotor speed and pitch (=0 for low speed) in order to get the mechanical torque at this operation point. The difference between the actual and the reference torque is an input to the integrator and through it the new actual rotor speed is calculated and fed back.

On the other hand the reference rotor speed is determined by (2.6), $\lambda = \frac{\omega R}{\vartheta_w}$, where λ is the tip speed ratio corresponding to the maximum *Cp*. The difference between the actual and the reference rotor speed is then fed to the PI-controller in order to obtain the reference torque. When designing this PI-controller, friction is neglected. Hence the PI-controller coefficients are calculated as below:

$$k_p = \alpha_\omega J \tag{3.1}$$

$$k_i = \alpha_\varpi^2 J \tag{3.2}$$

3.1.3. Simulation Results

When the wind speed is between 4 and 9 m/s, the low speed operation strategy takes place. Figure 3.3 shows the wind speed steps in the mentioned speed interval.

Figure 3.4 shows the rotor speed behavior of the wind turbine for each wind step. Although the rotor speed reference is directly derived from the wind speed using the optimal tip speed ratio, it has been delayed by a ramp limiter in order to create a smoother increase. The actual rotor speed experiences overshoots due to the PI-controller, but reaches steady state quickly.

With each wind step, the mechanical torque is updated. Figure 3.5 shows the behavior of the electrical and mechanical torques of the turbine. In a less complicated controller development, the rotor speed reference could be a step instead of a ramp but then at each wind step the electrical torque experiences drastic overshoots. This happens because there is a big error between the reference and the actual rotor speed values until the controller fixes it. Also this big error is accumulated doe to the integral part of the controller. In order to prevent this, the rotor speed reference is made a ramp through a ramp limiter and the error between the actual and reference rotor speeds is reduced. This way the drastic torque overshoots are reduced to a reasonable level.

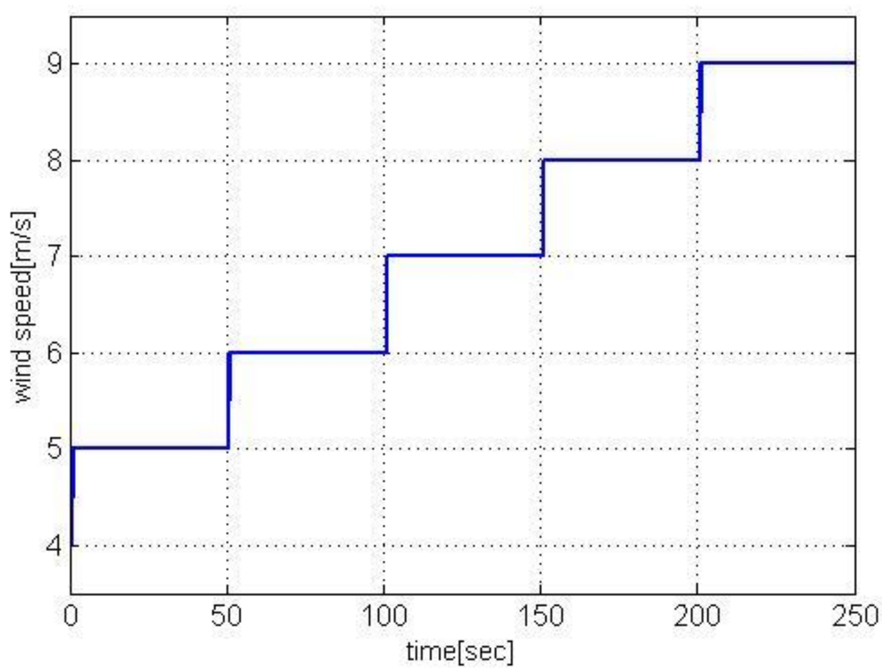


Figure 3.3: Wind speed response for low wind speed region

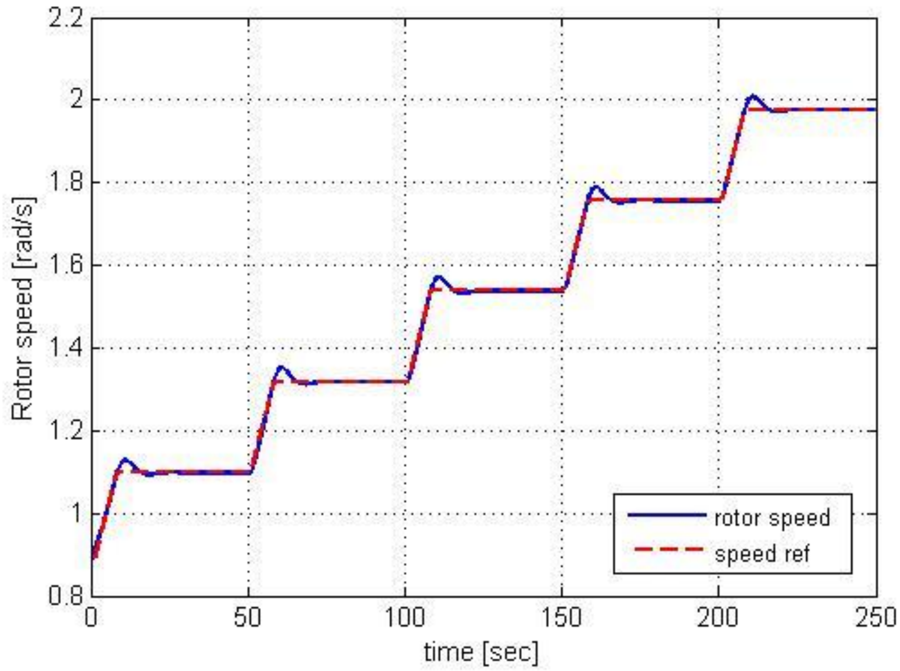


Figure 3.4: Rotor speed response for low wind speed region

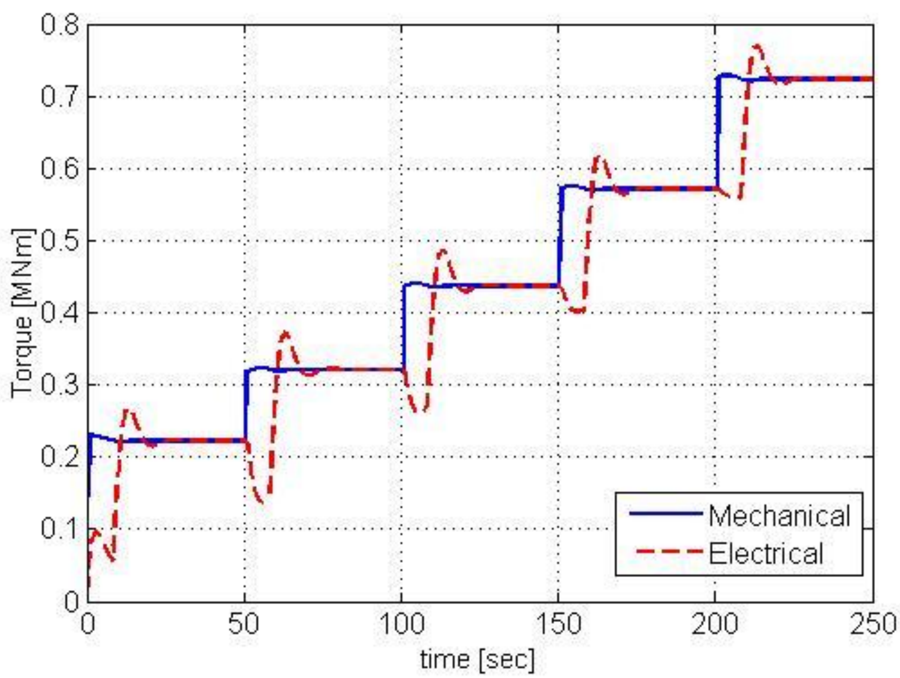


Figure 3.5: Torque response for low wind speed region

3.2. Middle wind speed interval

3.2.1. Control strategy

For middle speeds, the rotor speed reaches its maximum value, but the output power is still increasing. The control strategy for the middle speed interval is fairly similar to the low speed operation, except that the reference rotor speed is constant. Theoretically there is no pitching at middle speed interval since output power has not reached nominal yet, however close to the rated power pitching might start in order to ensure a smooth transition into the high wind speed interval.

3.2.2. Modeling of the control system

Figure 3.6 shows the controller scheme for the middle speed operation.

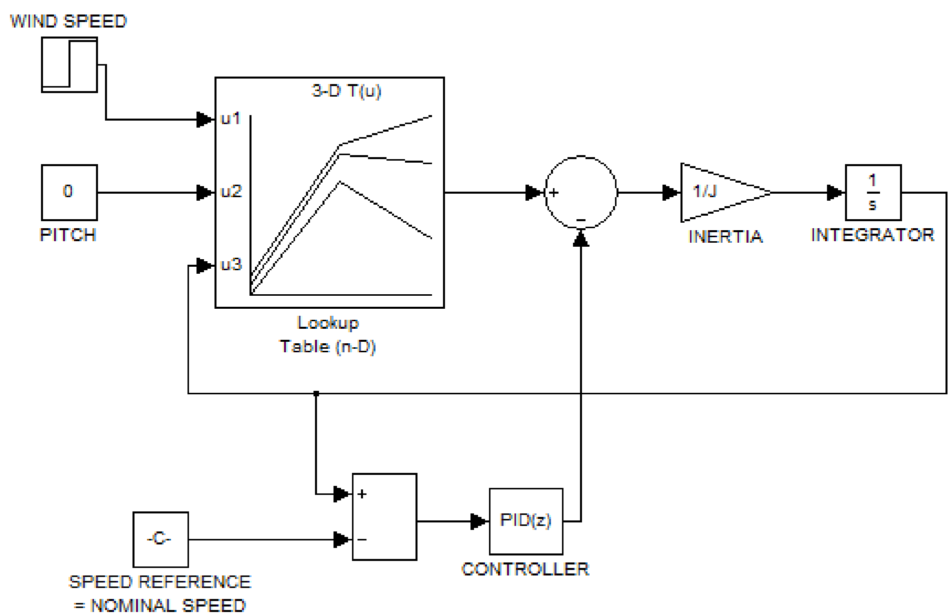


Figure 3.6: Control system for middle speed interval

Although the control strategy for middle speed is similar to that of the low speed operation, there are a few differences in order to have a better control. Firstly, the rotor speed reference for middle speeds is fixed at the nominal rotor speed value for the wind turbine; therefore Cp is not at its maximum anymore.

Secondly, for middle speed operation a robust control for the torque is needed. This is managed by having a stronger P-controller and a rather weak I-controller. In this way the torque ripple is minimized by letting the rotor speed fluctuate in between the limits.

3.2.3. Simulation Results

For wind speeds between 9 and 12 m/s, the wind turbine operates in the middle speed interval. Figure 3.7 shows the wind speed steps in this interval.

For the middle speed interval, it is preferred to have a robust torque control by permitting fluctuation on the rotor speed, as mentioned before. Figure 3.8 and Figure 3.9 below, shows the control strategy mentioned above. Compared to the low wind speed control, the torque fluctuation decreased significantly, as intended. On the other hand, the rotor speed has a higher ripple than it had in the low wind speed operation. One can observe that the rotor speed ripple decreases with each step, since the rotor speed is getting closer to the reference value when wind speed increases.

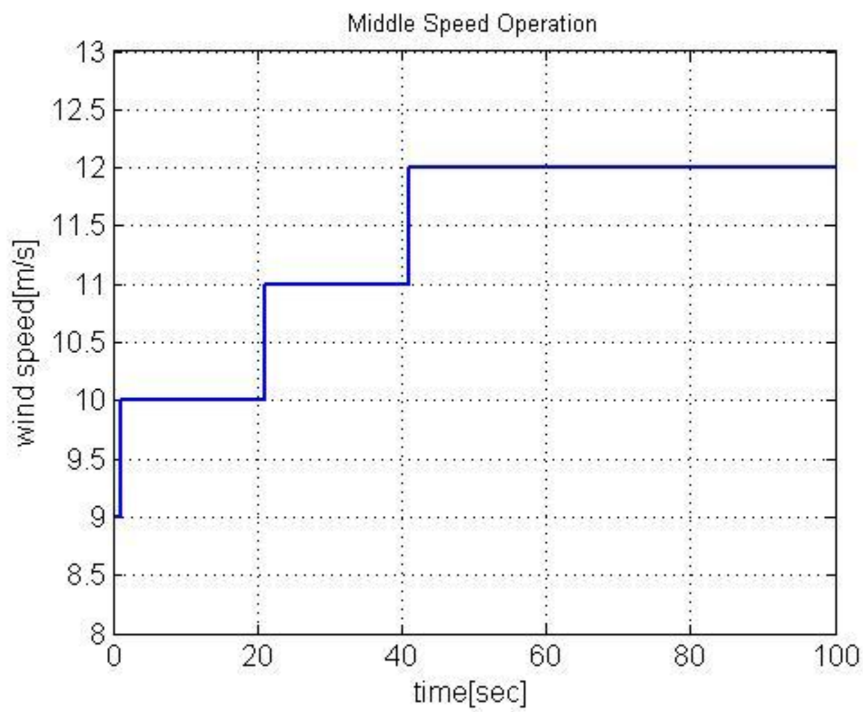


Figure 3.7: Wind speed response for middle wind speed region

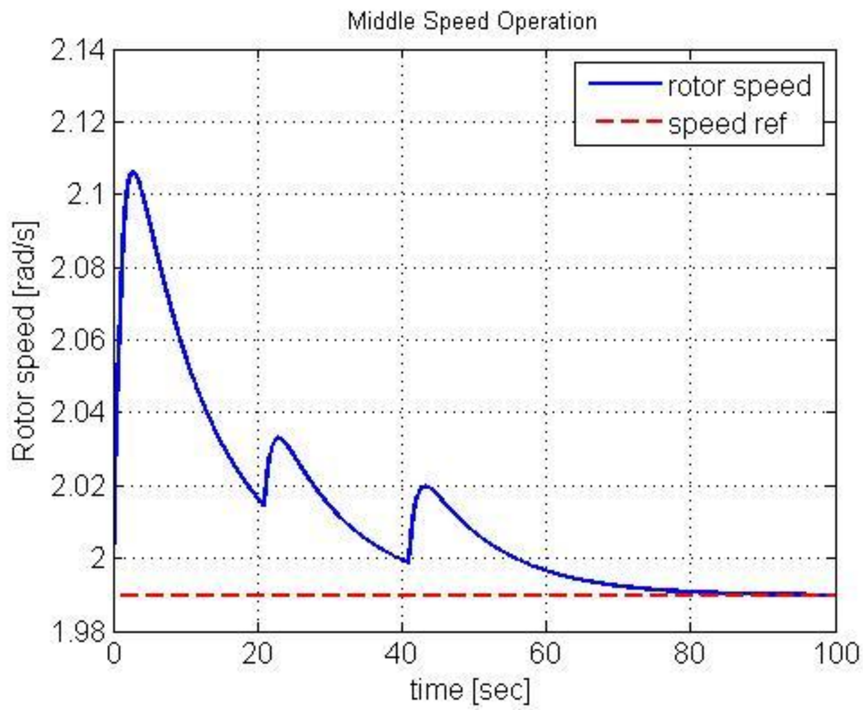


Figure 3.8: Rotor speed response for middle wind speed region

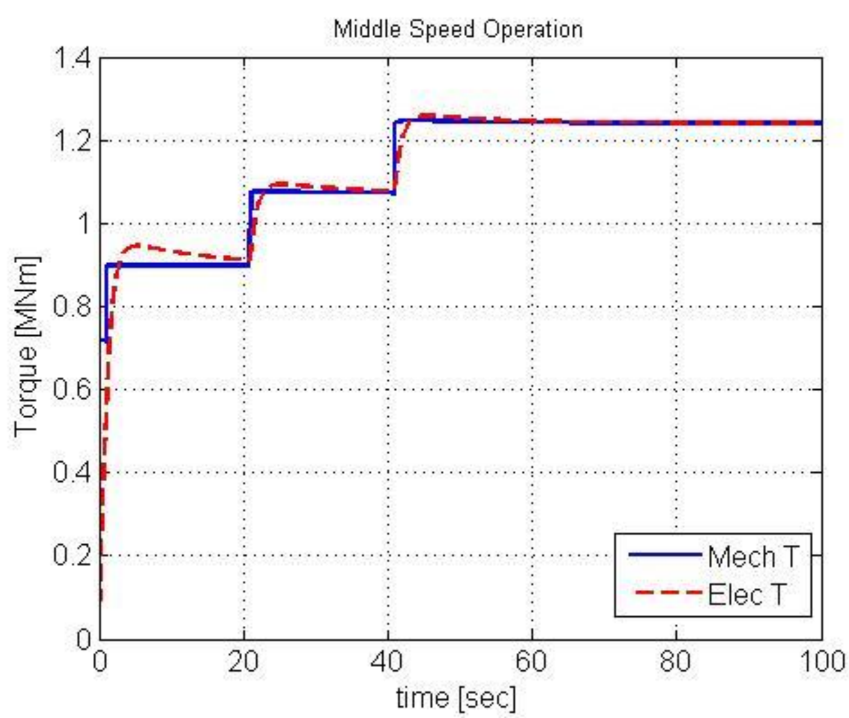


Figure 3.9: Torque response for middle wind speed region

3.3. High wind speed interval

3.3.1. Control strategy

When operating in the high wind speed interval, it is very important to be able to limit the output power to the rated value. Therefore when the output power is exceeding the rated value, the control system is designed in such a way that *Cp* decreases to keep the balance. Since Cp is a function of the pitch angle as well as the tip speed ratio, the output power can be kept at the desired value using the proper control of the pitch angle.

3.3.2. Modeling of the control system

Figure 3.10 presents the control system used for high wind speed interval.

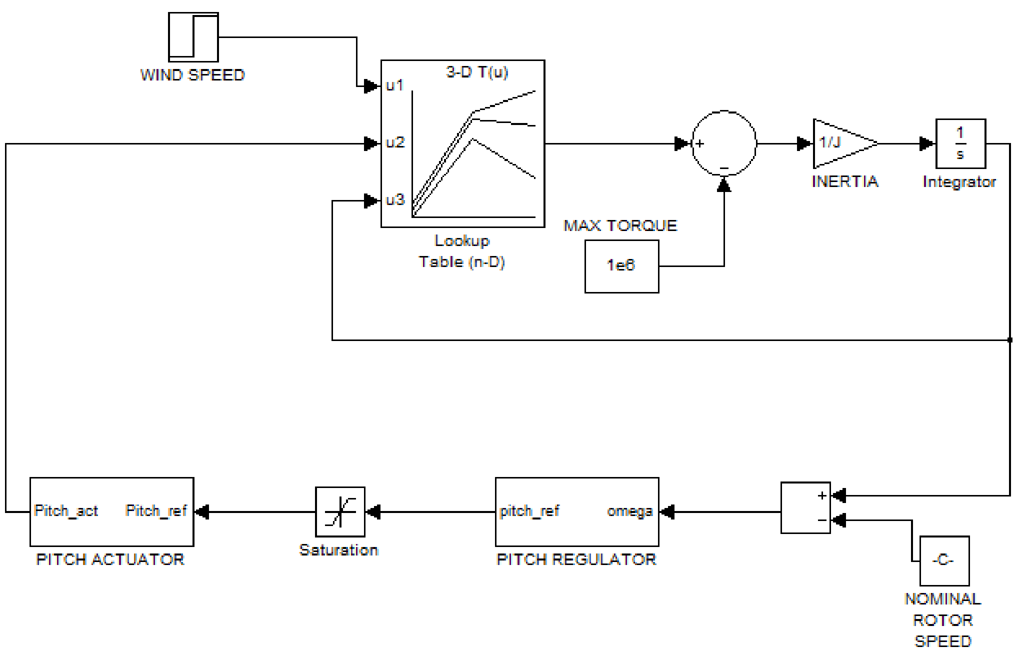


Figure 3.10: Control system for high speed interval

As mentioned before, pitch control is introduced at high speeds in order to prevent the output power and rotor speed to exceed their maximum values.

The detected wind speed, rotor speed and pitch angle are inputs to the system look-up table in order to obtain the mechanical torque for that instant. For high wind speeds the reference torque is the nominal torque and it is constant through the operation. The torque error fed to the integrator which represents the drive train and actual rotor speed is calculated.

The actual rotor speed is important to detect, in order to establish the needed pitching. The rotor speed error is the input to the pitch regulator which includes a PI-regulator and a pitch angle limiter, in order to obtain the pitch angle reference. The pitch actuator is a first order transfer function and calculates the actual pitch angle value in order to keep the system within the desired limits.

3.3.3. Simulation Results

When the wind speed is between 12 and 25 m/s, the wind turbine operates in the high wind speed interval. Figure 3.11 shows the wind step behavior of this simulation.

At high wind speeds, the controller should keep the shaft torque and the rotor speed constant at their nominal value. From Figure 3.12 and Figure 3.13, it is observed that with each wind step, the rotor speed and shaft torque tend to increase, but with the effect of the controller they fluctuate around the nominal value and reach steady state. Limitation of torque and rotor speed, despite the increasing wind speed is managed by the pitch controller. Whenever the rotor speed is higher than the speed reference, the pitch angle is increased to keep the balance. This can be observed from Figure 3.14.

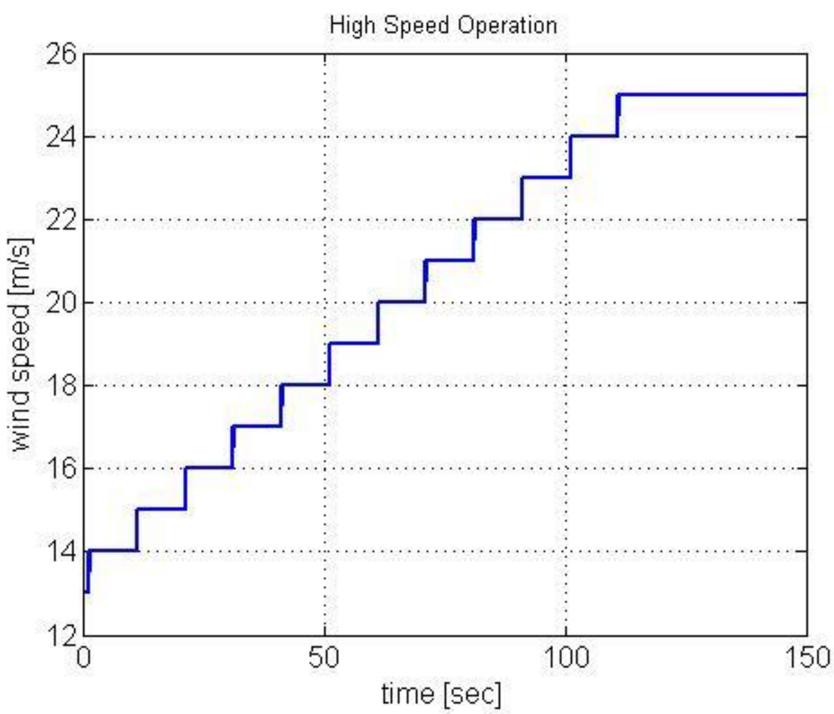


Figure 3.11 Wind speed response for high wind speed region

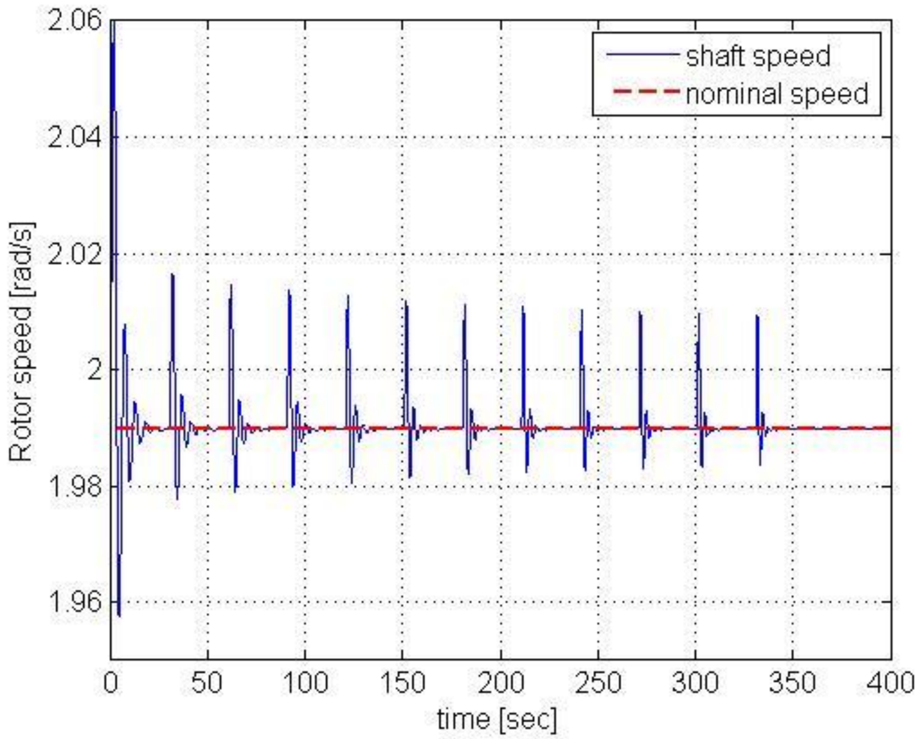


Figure 3.12: Rotor speed response for high wind speed region

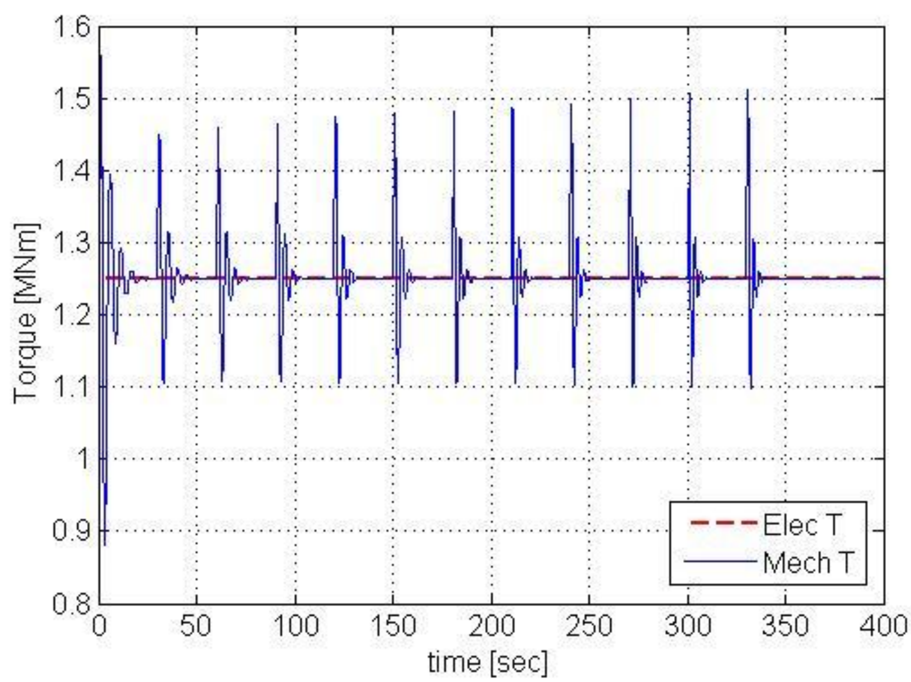


Figure 3.13: Torque response for high wind speed region

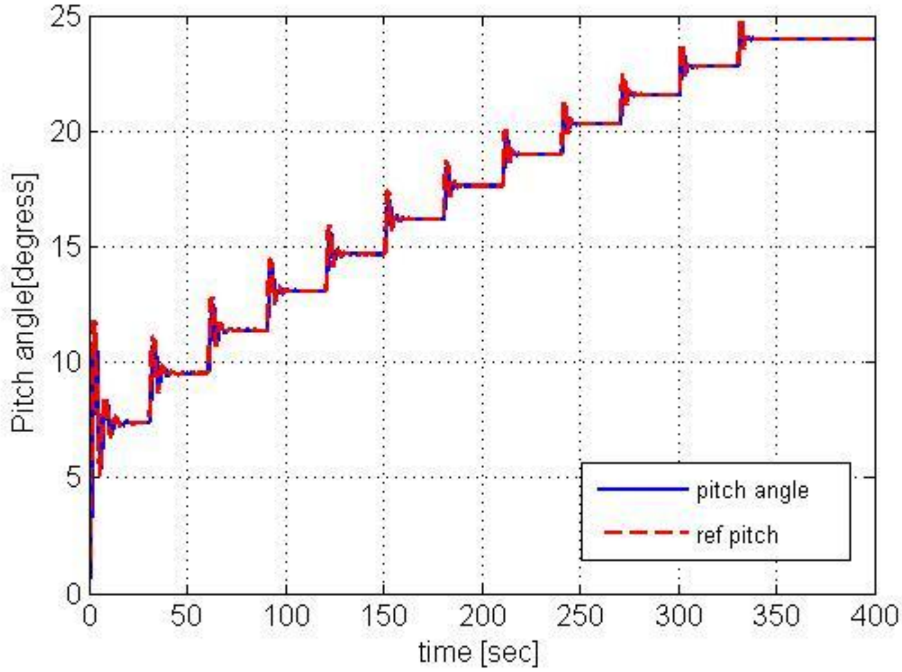


Figure 3.14: Pitch angle response for high wind speed region

In order to have a closer look on the pitch controller's performance it is wise to check the behavior of the parameters in question in a shorter time scale. Figure 3.15, Figure 3.16 and Figure 3.17 show the rotor speed, torque and pitch angle behaviors of the system for only two wind steps. For this system, it is assumed that the response time for the pitch actuator is 0.5 seconds. This is introduced to the system as a first order transfer function as mentioned before. Consequently, in Figure 3.17 the delay between the actual and the reference pitch can be seen.

Figure 3.15 and Figure 3.16 show the regulation of the rotor speed and torque more in detail. Both parameters follow a similar path, and the steady state is reached approximately in 15 seconds.

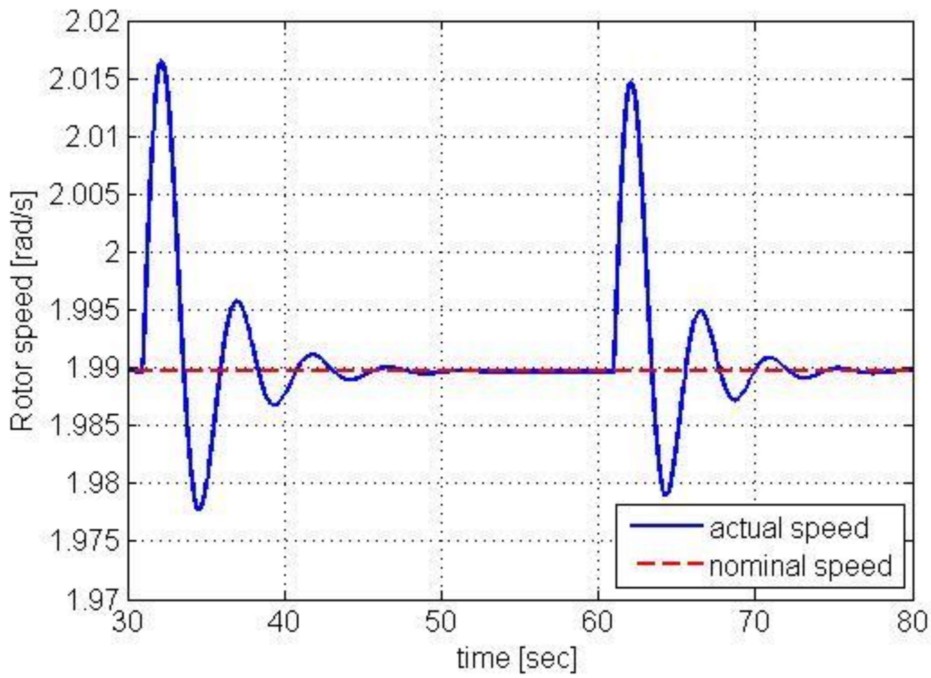


Figure 3.15: Details of rotor speed response for high wind speed region

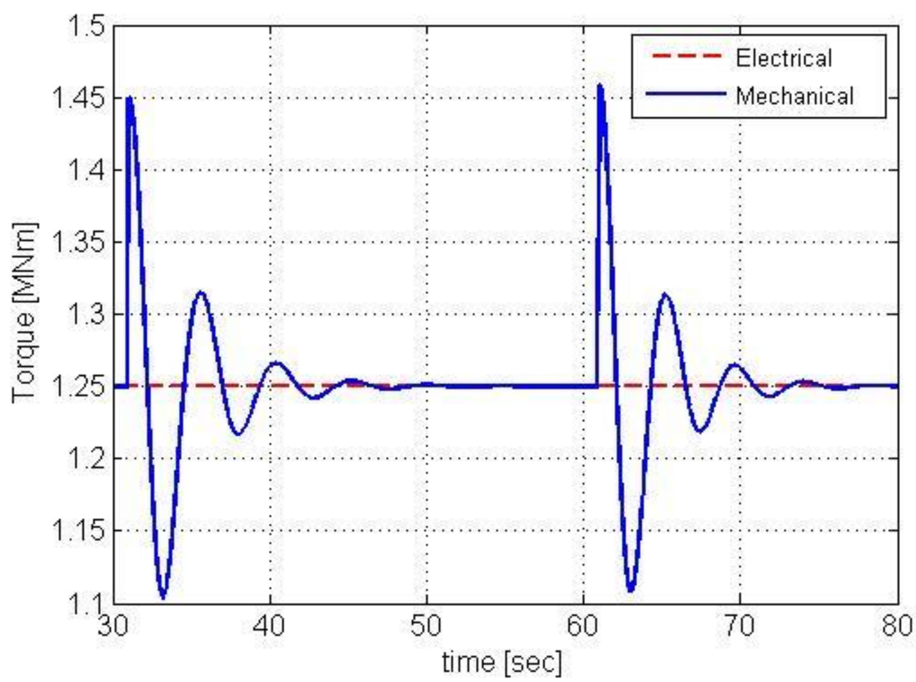


Figure 3.16: Details of torque response for high wind speed region

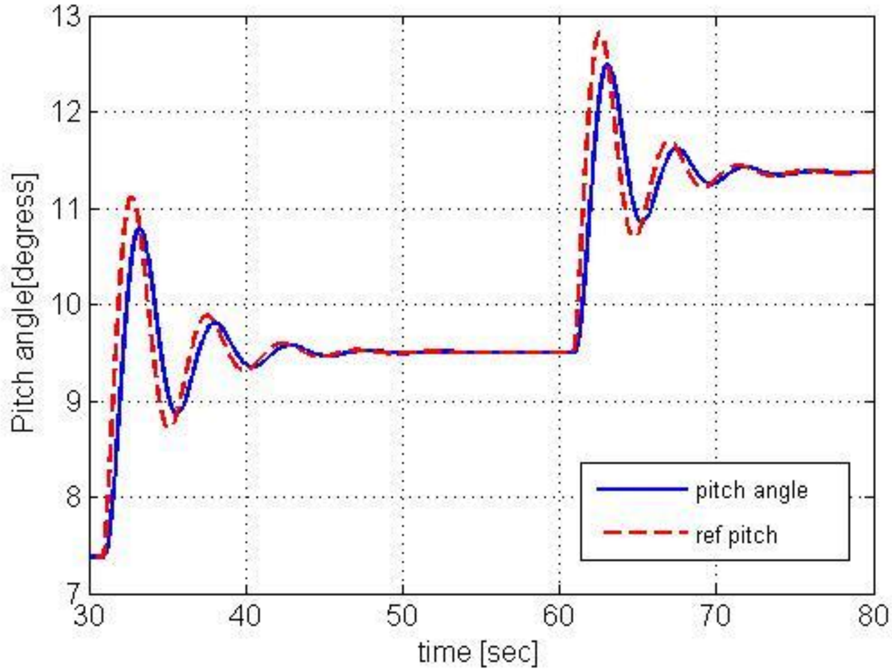


Figure 3.17: Details of pitch angle response for high wind speed region

4. COMBINED CONTROL SYSTEM FOR WHOLE WIND SPEED RANGE

As explained in the previous chapter, there are different control strategies for different stages of the wind speed. Therefore, in practice, a wind turbine system should have a controller that can provide the required control strategy, under realistic conditions, such as random wind speed. The way to achieve this operation is to combine all three control strategies (low, middle and high wind speeds) and to implement a suitable switching pattern between them.

Figure 4.1 shows the controller scheme for the whole wind speed range operation.

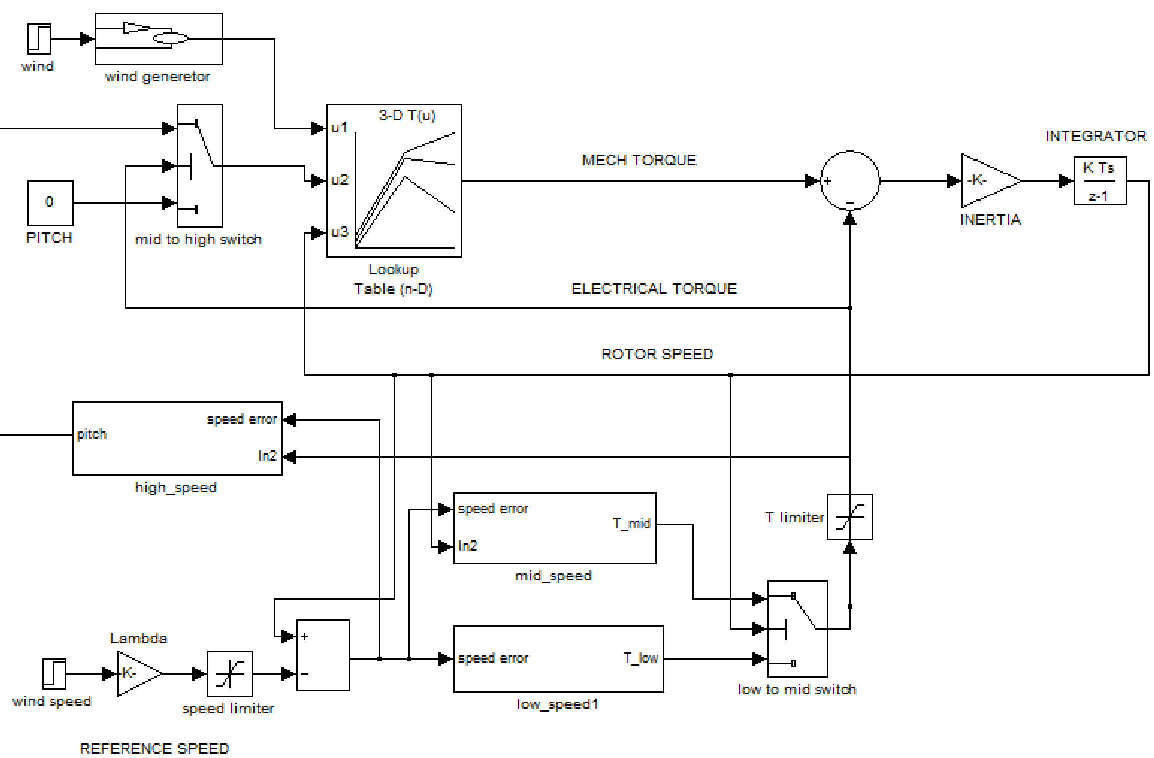


Figure 4.1: Control system for the whole wind speed range

It is seen from the figure that there are two switches. One is to choose between the low and middle wind speed controllers while the other enables the transition between the middle and the high wind speed controller. The switches used in this scheme operate instantly; therefore it is a hard switching.

4.1. SWITCHING STRATEGY

It has been mentioned earlier that there are two switches between three different controllers in order to create a controller that is valid for the whole wind speed range. But of course there is a trigger for each switch according to the differences between the wind speed intervals.

When the rotor speed reaches the nominal value while the power still increases, the low wind speed interval has been passed and the middle wind speed interval has been reached. Therefore the difference between the low and the middle wind speed intervals is the rotor speed controller. Afterwards while wind speed continues to increase, the rotor speed is kept constant and power increases further. When the output power of the turbine reaches the rated value as well as the rotor speed, the controller should switch from the middle speed region to the high speed region. Hence, the difference between the middle and high speed region from the turbine operation's point of view is the output power. Since the output power is in indirect relation with the electrical torque at high speeds, the output power is represented by the electrical torque in this project.

In theory, it is easier to detect the wind speed and trigger the switches according to the wind speed limits for the different wind speed intervals but detecting the wind speed is a highly complicated. Therefore in order to prevent unnecessary measurement devices, parameters that are already measured, actual rotor speed and electrical torque is used as the triggering parameters for the switches.

Before implementing the switching strategy, a few modifications have been made in the system. First of all, the rotor speed difference between the actual and reference rotor speeds is an input to all controllers. Although the reference speed is an increasing value for low speeds, it is constant at the rated speed for middle and high speeds. Therefore a speed limiter is added to the reference speed in order to keep it constant at the rated value after the low speed interval has passed. In this way, only one reference speed block is valid for all three controllers.

Secondly, the electrical torque value remains constant at rated torque for high wind speeds, while it is varying for low and middle wind speeds. Therefore, instead of an extra switching action between the varying and the constant reference torques, a torque limiter is implemented to the reference torque calculation. Therefore the electrical torque would be kept constant at the rated value when it is reached.

After the adjustments mentioned above are implemented, the switching criteria must be considered. Since the difference between the low and middle speed regions is the rotor speed behavior, the switch that handles this transition is triggered by using the rotor speed value. This switch is named *"low to mid switch"* at Figure 4.1. While the actual rotor speed is under 19 rpm, which is the nominal rotor speed of the wind turbine, the low speed controller is connected. When the rotor speed reaches 19 rpm, the middle speed controller is switched on. One important issue about the transition is that since there is a PI controller in the middle speed controller, one must make sure that the integrator of this PI – controller should not accumulate errors during the low wind speed region.

For switching between middle and high speed regions, the trigger parameter of the switch is the electrical torque. This switch is named *"mid to high switch"* at Figure 4.1. While the electrical torque is under the rated value (1.25 MNm), the high wind speed region is not reached yet, therefore the pitch angle is fixed at the initial pitch value and no pitch action is necessary. When the electrical torque reaches its rated value, the high wind speed control is turned on by the switch and the pitch control is activated. It is again important to correctly initiate the I-part of the PI-controller when the high wind speed region is reached and not before.

For both switches, it needs to be considered that the trigger parameters (actual rotor speed and the electrical torque) tend to fluctuate; therefore a tolerance band must be introduced in order to prevent unnecessary switching.

4.2. SIMULATION RESULTS

As mentioned before, this combined control system must be valid for whole wind speed range that the wind turbine should be able to operate. Figure 4.2 shows that the wind speed starts at 4 m/s which is the cut-in wind speed for the turbine that is used for this project and the highest wind speed is 25 m/s, otherwise mentioned as the cut-off wind speed. For this simulation, the wind speed is expressed as wind steps that sustain for 30 seconds.

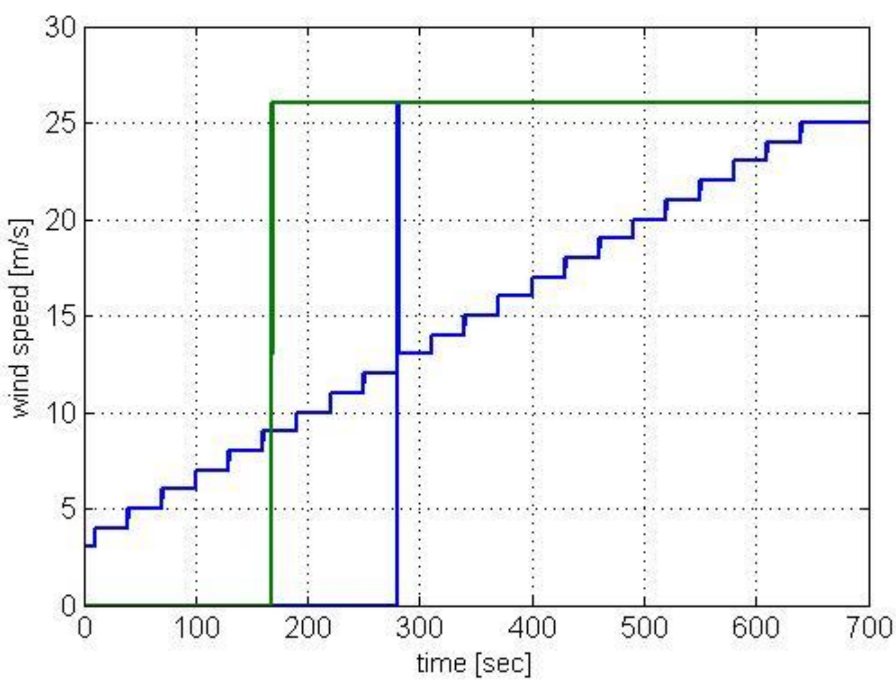


Figure 4.2: Wind speed steps for whole speed range operation

Figure 4.3 shows the rotor speed behavior of the wind turbine, when it is controlled with the combined control system. It is observed, as intended, that the wind turbine can maintain the low speed operation at start and continues until the rotor speed reaches its nominal value. At the point where the rotor speed reaches the nominal, the controller changes the operation to the middle wind speed operation. Middle speed operation continues until the electrical torque reaches nominal value, as seen from Figure 4.4. It is also seen from Figure 4.3, just as the rotor speed, mechanical and electrical torques follow the pattern that is intended and there is not a significant transition defect during the switching. But when it comes to switching between middle and high speed controllers, both rotor speed and mechanical torque experiences higher ripple for a short while, approximately one wind step long.

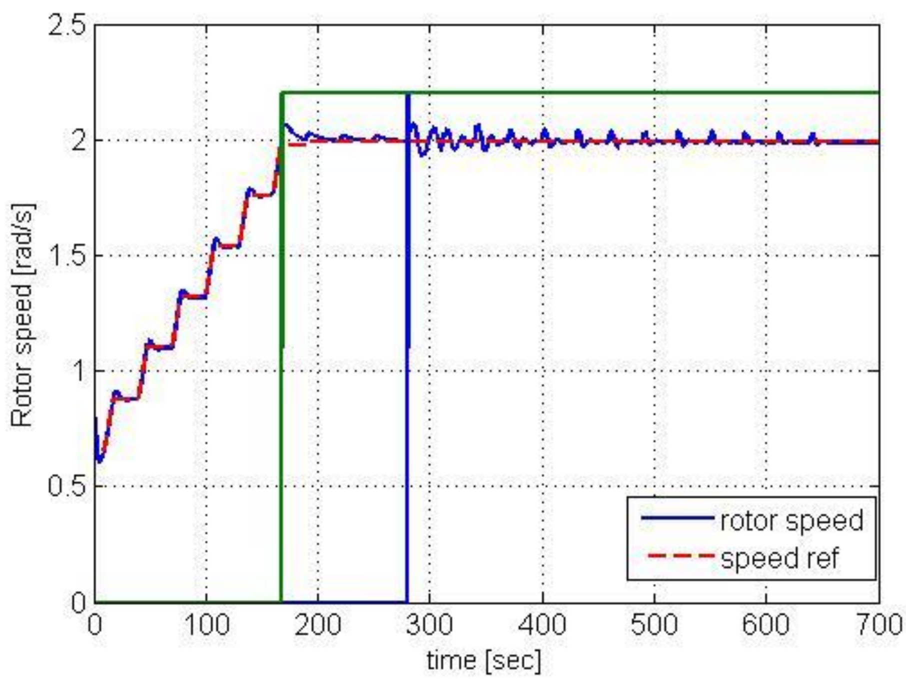


Figure 4.3: Rotor speed response for whole speed range operation

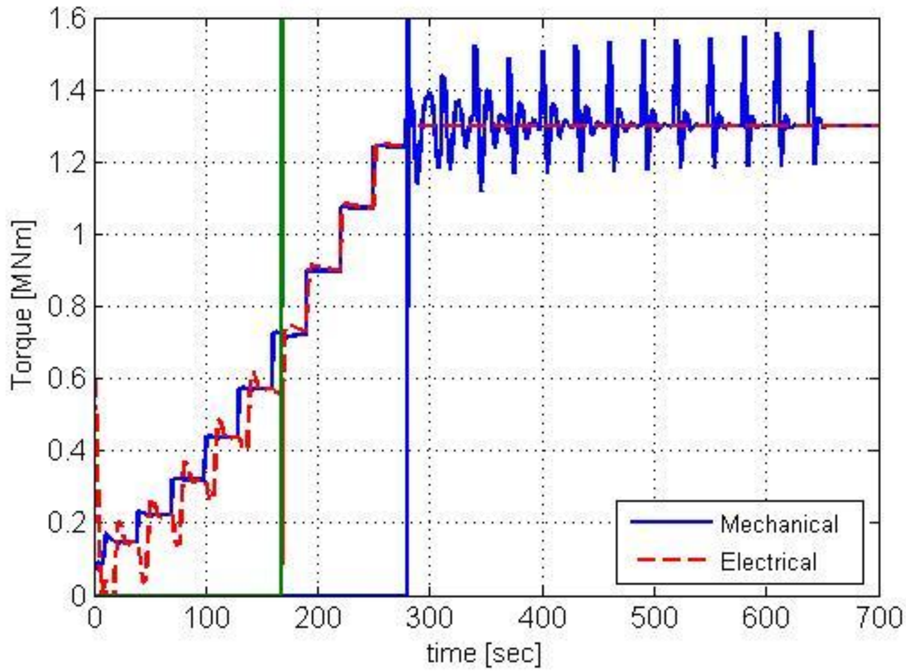


Figure 4.4: Torque response for whole speed range operation

Figure 4.5 shows the pitch angle behavior of the wind turbine for the whole wind speed range. It is observed that the pitch controller is not activated until the wind reaches high speed; therefore it is only 0°, which is the initial pitch. When the high speed is reached, the rotor blades pitch according to the rotor speed error. The rotor speed of the wind turbine experiences some larger oscillations than usual due to the hard switching action between middle and high speed controllers. Due to this fact, the pitch angle experiences a slight defect too. This defect can be prevented by pre pitching, which would cause a smooth transition.

Figure 4.6 shows the switching pattern of the control system. According to the wind speed, the middle speed operation is reached at the 160^{th} second of the operation, where the wind speed is 9 m/s, but when it is observed from Figure 4.6, middle speed operation starts slightly later. This is caused by the choice of the triggering parameters for the switches. As explained before, in order to avoid measuring the wind speed, the switches are controlled by the rotor speed and the electrical torque values. While the reference rotor speed has an instant leap to the nominal value, the actual rotor speed rather slowly increases to the steady state value. Therefore the middle speed operation is triggered only after the actual rotor speed has reached the nominal rotor speed value.

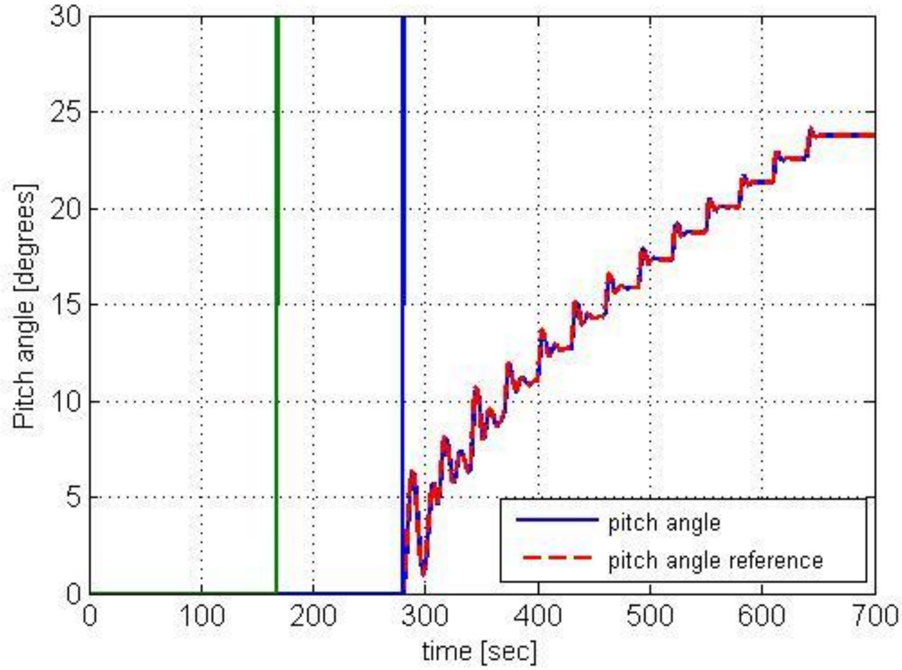


Figure 4.5: Pitch angle response for whole speed range operation

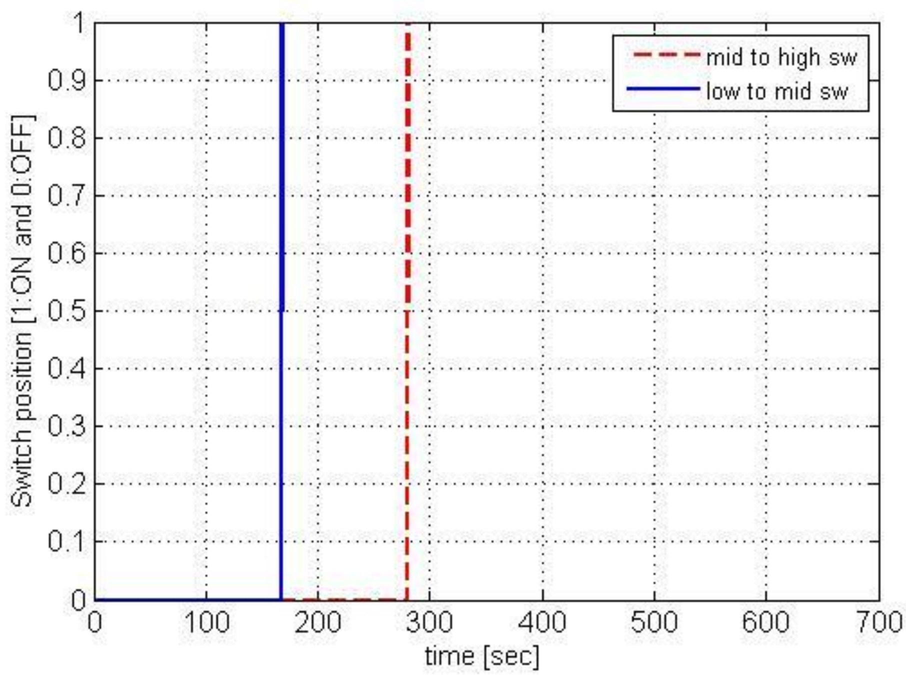


Figure 4.6: Switching pattern for the whole speed range operation

5. ANALYTICAL WIND TURBINE MODEL USED FOR DERIVING A PITCH CONTROLLER

Wind turbines generate electrical energy based on the energy conversion principle. The first step of the energy conversion is to convert the wind energy into mechanical energy by the wind turbine blades and the shaft. This conversion is modeled on the basis of the Blade Element Momentum Theory in this project. Even though the results obtained by this method are quite reliable, it involves iterative calculations. This means that the output cannot be expressed directly as a function of inputs of the system. From the control system point of view, this situation might be a problem. Therefore, aerodynamic – mechanical conversion is normally expressed as a look up table of *"T (ws,ω_r, β)"*. However, in order to derive a controller based on the model structure, it is necessary to obtain an analytical expression of the wind turbine model.

Due to the reasons explained above, designing and running the simulation of the wind turbine models are time consuming. Nonetheless, by simplifying the turbine data and expressing BEM theory in an "iteration free" way, a wind turbine can be represented analytically, resulting in a time saving simple method for wind turbine studies.

5.1. Constructing the analytical model

5.1.1. Eliminating of the iterations from the Blade Element Momentum Theory

As mentioned before, the energy from the wind is converted into mechanical energy, which is calculated by the BEM theory. The application of this theory, however reliable, is quite time consuming, owing to the fact that it mainly depends on iterative methods. In order to construct an analytical expression for the wind turbine, iterative methods must be eliminated. In this chapter, developing a substitute method that would allow one to eliminate the BEM theory will be explained thoroughly.

Chapter 2 shows that the mechanical torque is calculated through the Edge force (F_{Edge}), which is a function of Lift and Drag forces as well as the angle *Φ*. This angle *Φ* is called the relative flow angle and it represents the angle between the rotor plane and the oncoming wind direction, as shown in Figure 2.3. This angle is the key point to the BEM theory, since angle of attack, Edge and Flap forces are functions of *Φ*. The main problem is that, it is calculated through an iterative method by using BEM. Therefore in order to develop an analytical expression, angle *Φ* must be analytically expressed first.

The analytical equation that represents this angle is

$$\frac{1}{\sin\phi} = \sqrt{1+\left(\frac{\omega_r r}{\upsilon_w}\right)^2} \tag{5.1}$$

In (5.1), ω_r is the rotor speed, r is the length from the inner radius to the end of the segment, and WS is the wind speed [4]. Figure 5.1 shows the blade elements that are mentioned in the blade element momentum theory. Here, c represents the airfoil chord length, dr is the radial length of the blade segment, r is the radius and R is the rotor radius of the wind turbine [6]. As observed from Figure 5.1, the turbine blade is divided into several pieces and every piece is called a blade segment.

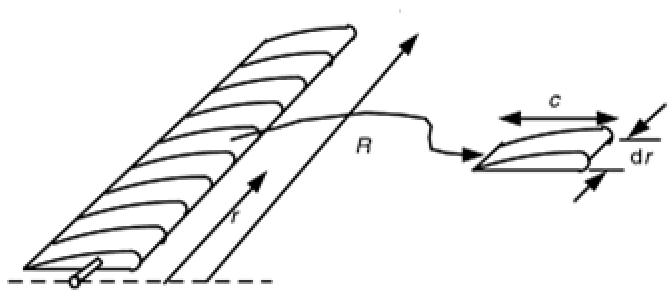


Figure 5.1: Schematic of the blade elements

From then on, the mechanical torque contribution of a single blade segment is calculated by the equation below:

$$F_{Edge} = \frac{1}{2}\rho \upsilon_w^2 c \Delta r (c_L \sin\phi - c_D \cos\phi) \tag{5.2}$$

$$\Delta T = F_{Edge} r \tag{5.3}$$

By summing up the torque contributions obtained from each blade segment and multiplying it with the number of blades, the mechanical torque on the shaft can be determined:

$$T_{mech} = n_b \sum_{s=1}^{m} \Delta T \tag{5.4}$$

Where n_b is the number of blades and m is the number of blade segments.

Another important part of analytical expression of the wind turbine is the angle of attack description. The angle of attack is a significant parameter, since the lift and drag coefficients are determined through it. For this expression the angle of attack is expressed as:

$$\alpha = \phi - (\beta + t) \tag{5.5}$$

where α is the angle of attack, Φ is the relative wind angle [2], β is the pitch angle and t is the twist which means the manufactured tilt angle of the wind turbine blades.

5.1.2. Model Simplifications

Even though it is possible to express the wind energy conversion process analytically, by altering aerodynamic data slightly, this expression may be simplified even further. Simplifications of question are performed on the system and each step of alteration is compared with the original Torque outputs from the BEM in order to evaluate the accuracy of the model.

The first step of the simplification process is to adjust the blade profile into a uniform lift and drag output for the same angle of attack in order to obtain the output torque in fewer calculations. The blade profile term represents the lift and drag coefficients for different angle of attack values. Secondly, the shape of the turbine blade is to be reformed according to the percentage of the torque contribution from each blade segment. And lastly, the chord and twist of the blade are to be adjusted as constant values, therefore they would not be a function of the blade segment, resulting in an appropriate reference case.

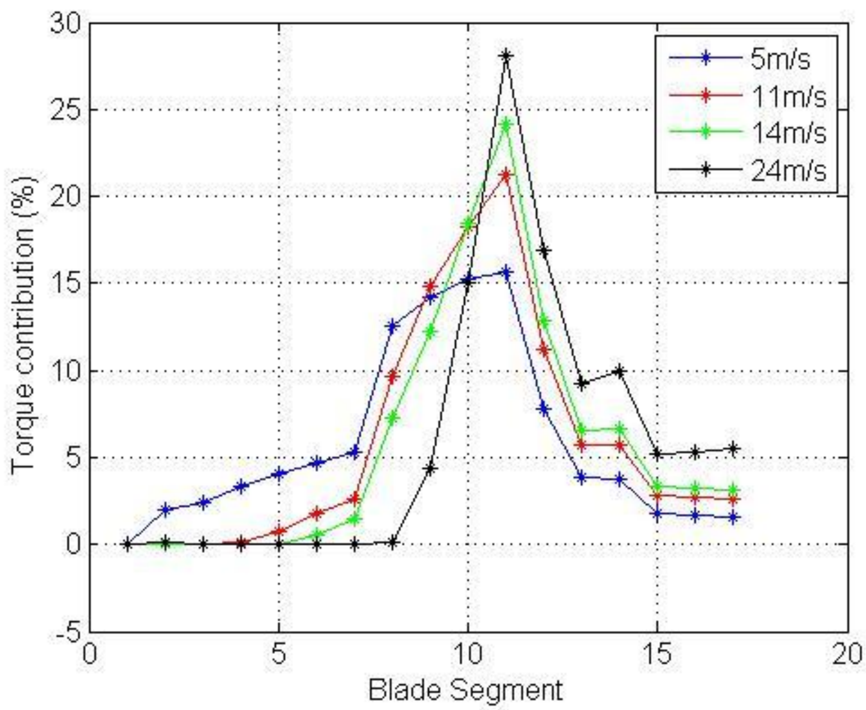


Figure 5.2: Torque contribution of each blade segment for different wind speeds

Figure 5.2 shows the torque contribution from each segment for the specific blade that is used. From this figure, it can be observed that the torque contributions obtained from the first 7 blade segments are much smaller than the rest, therefore they can be neglected. This means that the output torque can be calculated only by using torque contributions from blade segments 8 to 17. Furthermore, if the blade profile of the model is compared with the blade segments of importance, it is seen that all these blade segments have the same aerodynamical data.

Figure 5.3 shows the comparison between output torques according to the wind speed for different blade profiles. These blade profiles can be described as the original blade, which represents the blade profile with 4 different aerodynamical data sets and all 17 blade segments are taken into account. A uniform blade, where all 17 blade segments have a uniform aerodynamical data and the knife blade, which has a uniform aerodynamical data and also the torque contribution from blade segments 1 to 7 are neglected. It can be observed from the figure that the difference in output torque from three different blade profiles is within acceptable range for designing the pitch regulator. Due to these facts explained above, the wind turbine blade could be transformed into a simplified blade model (the knife blade), which has a uniform aerodynamical data while the total shaft torque is obtained only from 8th to 17th blade segments.

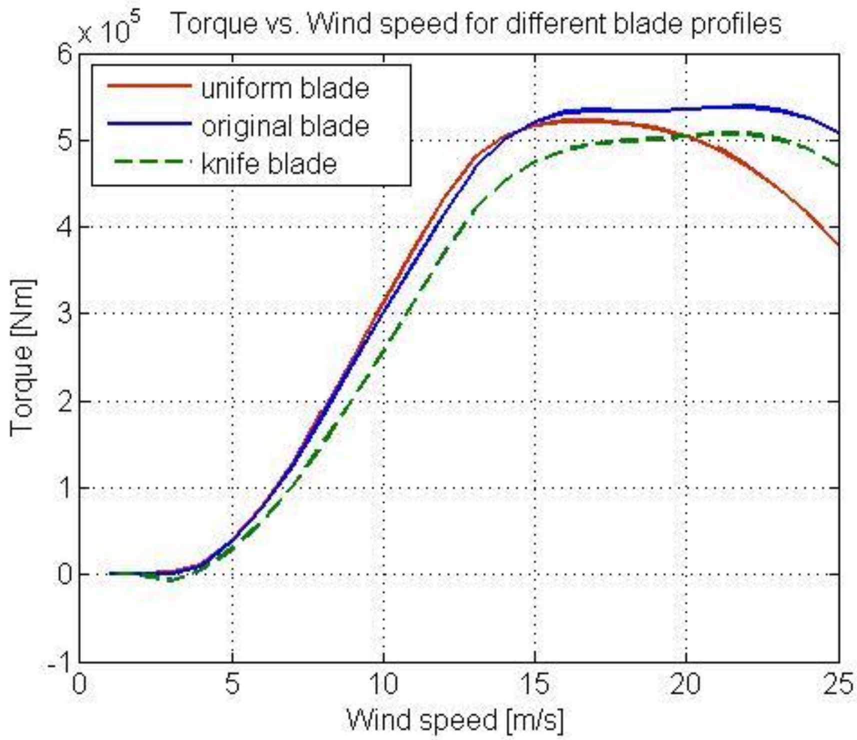


Figure 5.3: Torque vs. wind speed for different aerodynamic profiles

In order to calculate the torque output, the torque contribution of each blade must be obtained. Therefore, even though the analytical model is used, the torque contribution would be a function of blade segment. As a result of a uniform aerodynamical data set, the blade profile is no longer a function of the blade segment; however chord and twist of the blade still depend on it. Consequently, for further simplification, chord and twist of the blade is to be averaged to constant values, in order to be independent of the blade segment. This way the calculation of the output torque would be even simpler.

Figure 5.4 shows the output torque for different combinations of chord and twist alterations. The difference between each system is very little; therefore the most simplified model is selected to be used in the analytical calculations. This model is when the blade profile is uniform and the blade segments are reduced, also chord and twist values are constant for every blade segment. From Figure 5.3, it is shown clearly that, the torque outputs obtained from the original model and the simplified model are proven to be quite similar.

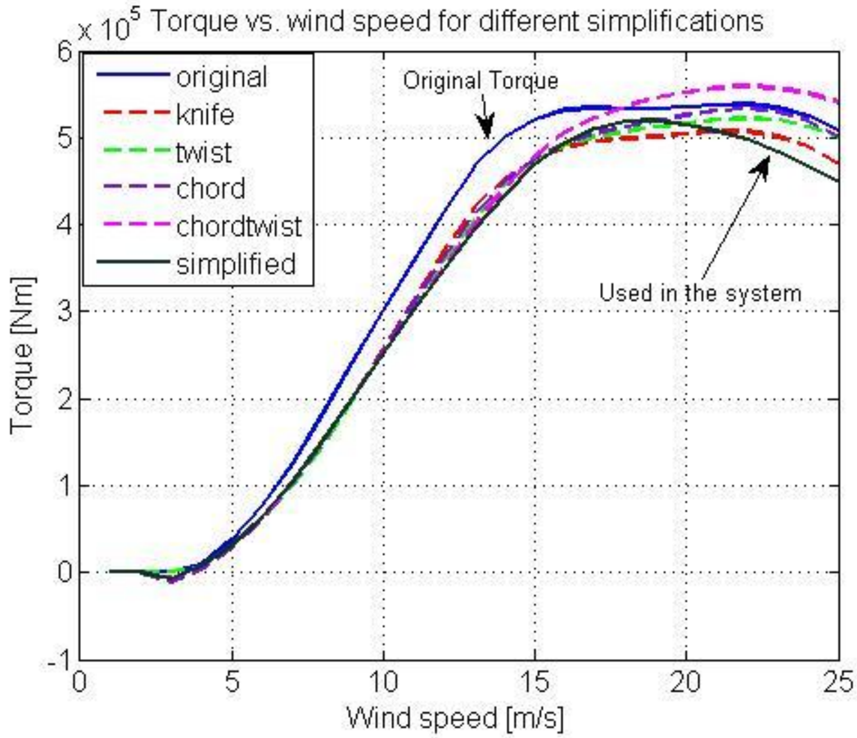


Figure 5.4: Torque vs. wind speed for different simplification adjustments

5.2. Verification of the Analytical Model

Once the analytical expression is constructed, it needs to be checked in order to understand the validity of the model for different operation conditions. The way to achieve this is to investigate the torque behavior from the original model, simplified model and analytical model while pitch and rotor speed are changing according to the variable speed operation.

Further in this chapter, results from the torque comparison for each three systems mentioned above would be explained for different operation conditions while the wind speed is changing between the cut in and cut off speeds.

5.2.1. Middle Speed Operation

The first operation condition is when the wind speed varies between the minimum and maximum values permitted while the pitch angle and rotor speed are constant at a given value. Due to the basic nature of this operation, the pitch angle is selected to be 0°, which is the initial pitch of the wind turbine. Similarly, the rotor speed is selected as 19 rpm, which is the nominal rotor speed of the turbine. Figure 5.5 shows the torque comparison at this operation condition. Even though the results seem quite similar, the error between the original model and the analytical model is calculated for a better comparison Figure 5.6 shows the output torque error between two models for middle speed region, the thick lines represent the operation range. Middle speed region starts at 9 m/s and end at 13m/s. It is observed from the figure that in between these wind speed values, maximum error is around 23%.

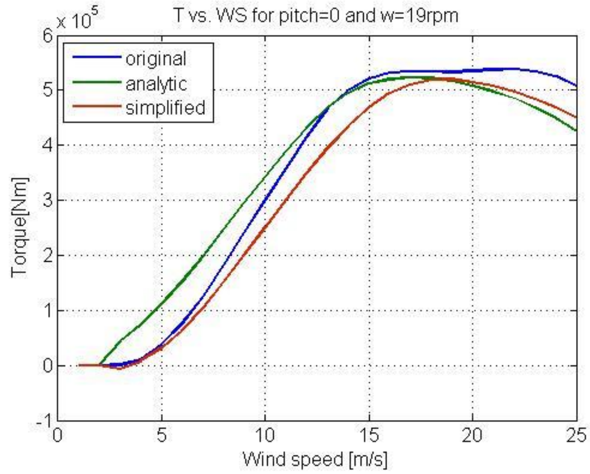


Figure 5.5: Torque vs. wind speed for original, simplified and analytical models

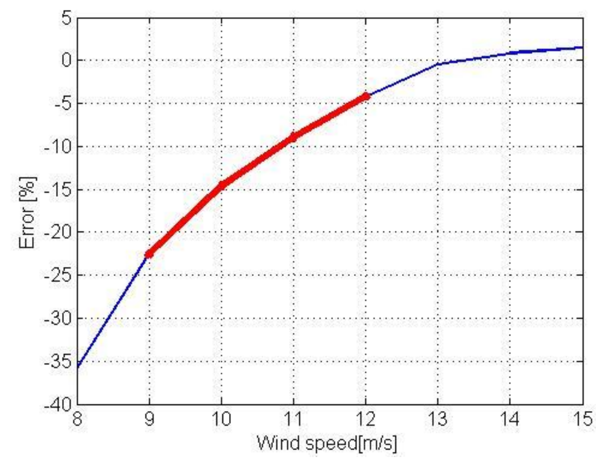


Figure 5.6: Error in torque output of original and analytical models for middle wind speed range

5.2.2. High Speed Operation

At this operation condition, the pitch angle varies between the 0° and 30°, while the rotor speed is constant at nominal speed. In practice, this operation condition represents the high wind speed operation; therefore the output torque would be examined at two different wind speed values at the high speed region.

Figure 5.7 shows the torque behavior at different pitch angle values, while the wind speed is 14 m/s, which is at the beginning of the high wind speed region and Figure 5.8 shows the error in output torque between original and analytical models. Since 14 m/s is in the beginning of the high speed region, the turbine would be pitched only slightly. Therefore the pitch angle would be very small. From Figure 5.8, it can be observed that when pitch angle is low, the error is quite small too and the error increases with increasing pitch angle. The maximum error is around 15%.

Figure 5.7 shows the torque behavior at different pitch angle values, while the wind speed is 24 m/s, which is at the beginning of the high speed region and Figure 5.10 shows the error in output torque between original and analytical models. At 24m/s wind speed is almost the maximum allowed wind speed for this turbine, which means for this wind speed, pitch angle must be high. Therefore the pitch angle values of interest are in between 15° and 25°. Maximum error for this wind speed can go up till 55%.

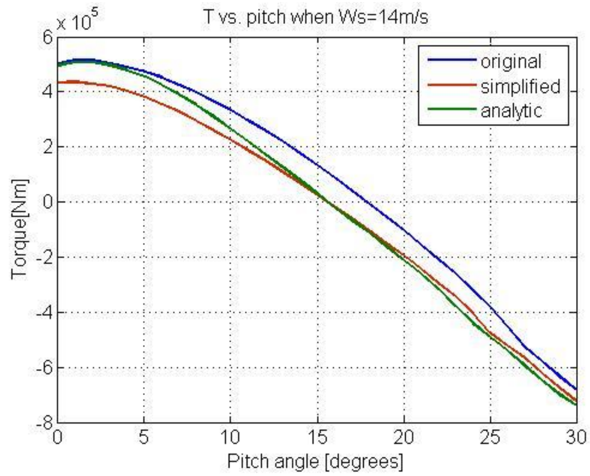


Figure 5.7: Torque vs. pitch angle at 14 m/s wind speed for original, simplified and analytical models

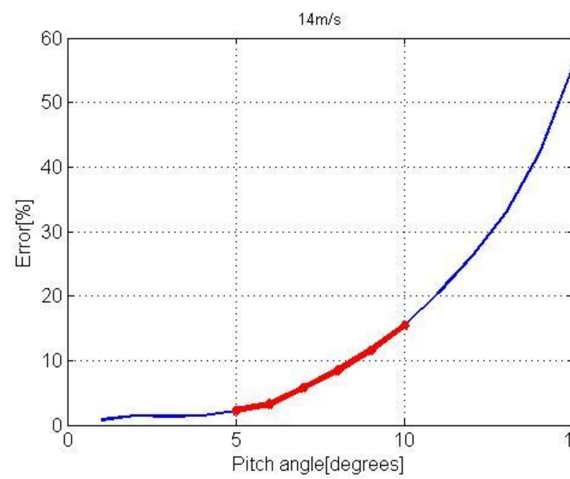


Figure 5.8: Error in torque output of original and analytical models for high wind speed range

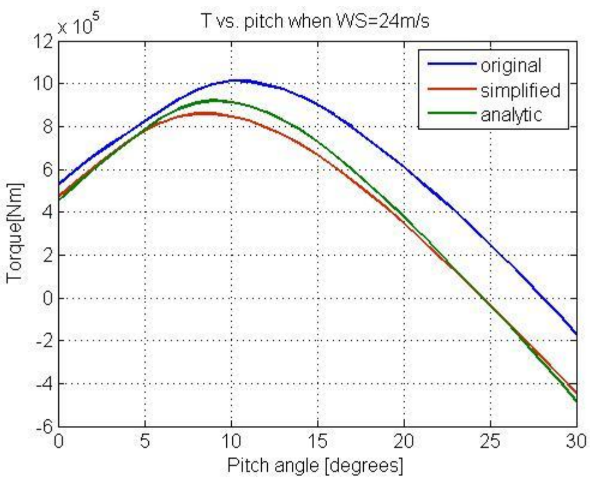


Figure 5.9: Torque vs. pitch angle at 24 m/s wind speed for original, simplified and analytical models

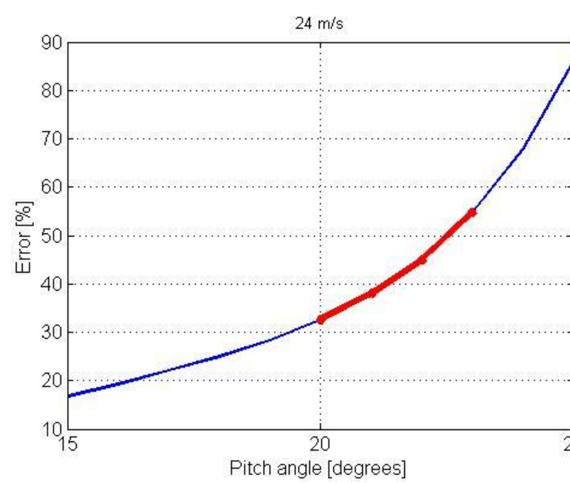


Figure 5.10: Error in torque output of original and analytical models for high wind speed range

5.2.3. Low Speed Operation

For this condition, the pitch angle is kept constant at its initial, 0°, while the rotor speed changes between the minimum and maximum values available (10 – 25 rpm). In practice, this operation represents the low wind speed and mid wind speed operations, therefore in order to verify this condition; the torque output would be presented according to the different rotor speed values for two different wind speed values.

Figure 5.11 shows the torque behavior for different rotor speeds while the wind speed is 5 m/s and operation is in the low wind speed range. The output torque values are obtained from the three different models as before. Figure 5.12 shows the error between the output torques obtained from original and analytical models. It is seen that the error in this region is very high and this is because of the uniform twist value that is used for whole wind speed range is not very appropriate for low speeds.

However, this would not cause a problem because it can be fixed by adjusting the twist of the blade. On the other hand, the analytical model is needed mostly for the pitch controller; therefore the large error in low speed operation does not disqualify the use of the analytical model.

Figure 5.13 shows the torque behavior for different rotor speeds at the low speed range with 11 m/s wind speed, for different models again. Figure 5.14 shows the error between output torques obtained from the original and analytical models. It is observed that the maximum error is 12% in the area of interest, so it can be said that the analytical model matches with the original model adequately.

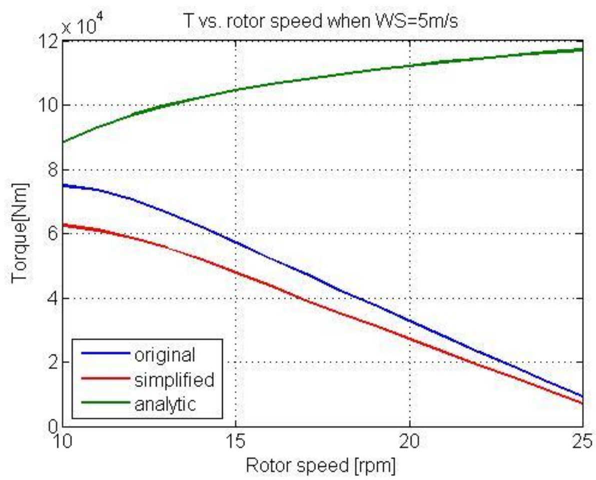


Figure 5.11: Torque vs. rotor speed at 5 m/s wind speed for original, simplified and analytical models

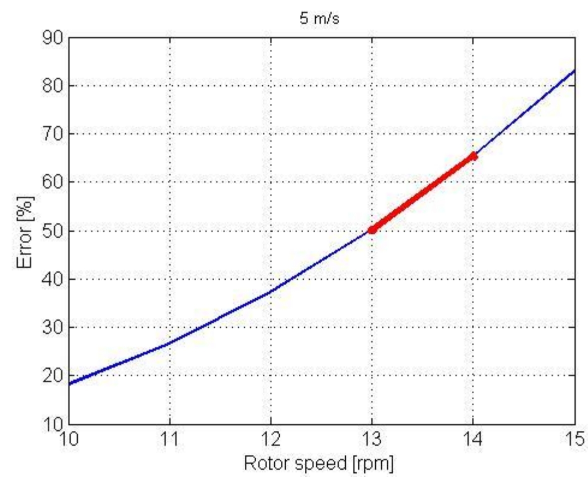


Figure 5.12: Error in torque output of original and analytical models for low wind speed range

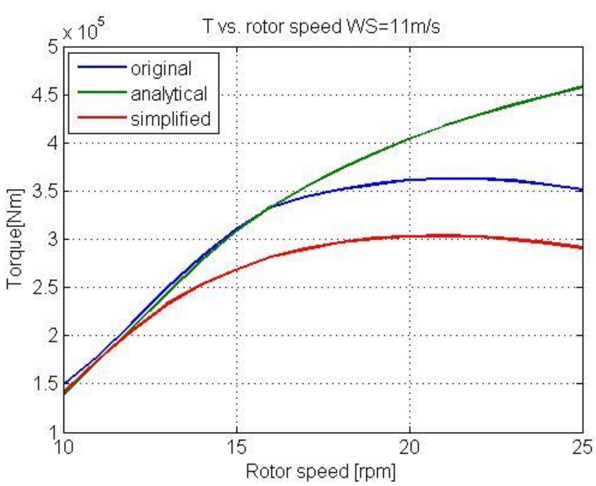


Figure 5.13: Torque vs. rotor speed at 11 m/s wind speed for original, simplified and analytical models

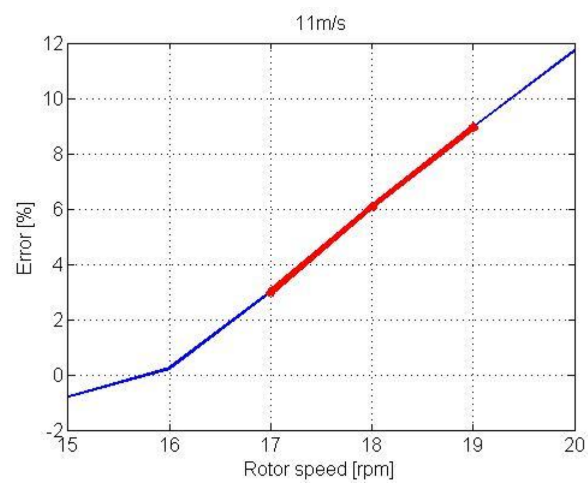


Figure 5.14: Error in torque output of original and analytical models for low wind speed range

5.3. Linearization of the Lift and Drag Coefficients

Earlier in this chapter, the BEM theory is expressed analytically by performing simplifications on the model. One of the main motivations of these simplifications is to have a uniform blade profile for each segment. This means that it is desired to keep as many parameters used for calculating the torque as possible constant for different blade segments.

Furthermore, from the previous studies of this project, it is discovered that the angle of attack of the wind to the wind turbine blade for this variable speed pitch controlled wind turbine is between -10° and 70°. The angle of attack is an important parameter, due to the fact that the lift and drag coefficients are functions of this angle. By carefully analyzing the lift and drag coefficient behavior for different attack angles, it is discovered that these parameters can easily be expressed linearly if the angle of attack is between -10° and 70°.

By linearizing the lift and drag coefficients, constant re-calculation and data selection for each different blade segment would be eliminated while calculating the output torque. Also, as a more practical result, the pitch controller design would also be simplified.

5.3.1. Fitting of the curves

The way to linearly express the lift and drag coefficients according to the angle of attack is to fit these data down to a first order line. While doing this, several regions of attack angle can be used in order to minimize the error. The general shape of the linearized curves would be as following:

$$c_L = a\alpha + b \tag{5.6}$$

$$c_D = d\alpha + e \tag{5.7}$$

Constants a,b,c,d would be changing for each region that fitting is different. Table 5.1 shows the c_L and c_D formulas used in the system:

Table 5.1: Linearized lift and drag coefficients for different angle of attack regions

Angle of attack (α)	Lift coefficient (c_L)	Drag coefficient (c_D)
-10° --- 10°	0.1092* α+0.4466	$2.23e^{-4}$* α+0.0077
10° --- 18°	-0.0043* α+1.5293	0.0238* α-0.2076
18° --- 28°	-0.0597* α+2.5141	0.0238* α-0.2076
28° --- 45°	$-1.08e^{-4}$* α+0.9029	0.0238* α-0.2076
45° --- 70°	-0.0164* α+1.6722	0.0238* α-0.2076

As shown in Table 5.1, for the angle of attack between -10° and 70°, lift and drag coefficient have been linearized piece wise. Figure 5.15 shows the original and linearized lift and drag coefficients. As it is seen from the figure, the linearized and the original data are very closely matched.

If during the torque calculation, the angle of attack exceeds the limits, then the lift and drag coefficients are set to zero.

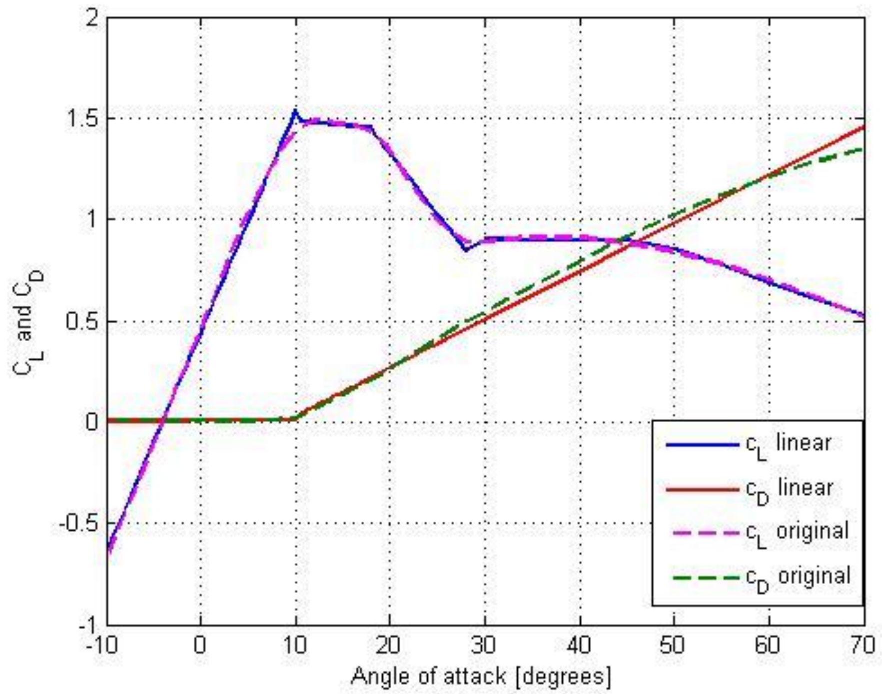


Figure 5.15: Linear fit of the lift and drag coefficient

5.3.2. Verification of the use of linearized lift and drag coefficients

As it can be observed from (5.2), c_L and c_D are used for calculating the torque output of the wind turbine blade. Previously, these parameters were selected through interpolation of a data table, however after linearization; they can be directly expressed in the analytical model. In order to verify the effect of the linearized aerodynamic tables, torque contributions and output torque is to be compared with the original models.

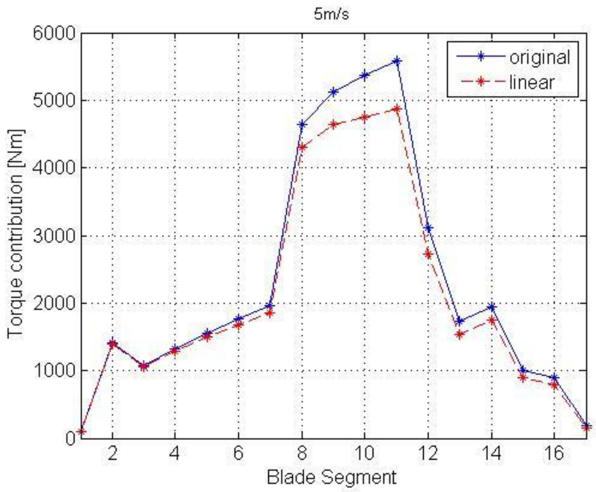


Figure 5.16: Torque contribution of each blade segment for original and linear aerodynamic data at 5m/s wind speed

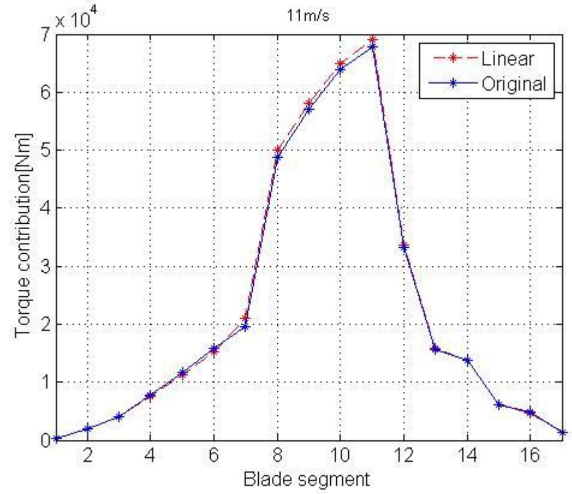


Figure 5.17: Torque contribution of each blade segment for original and linear aerodynamic data at 11m/s wind speed

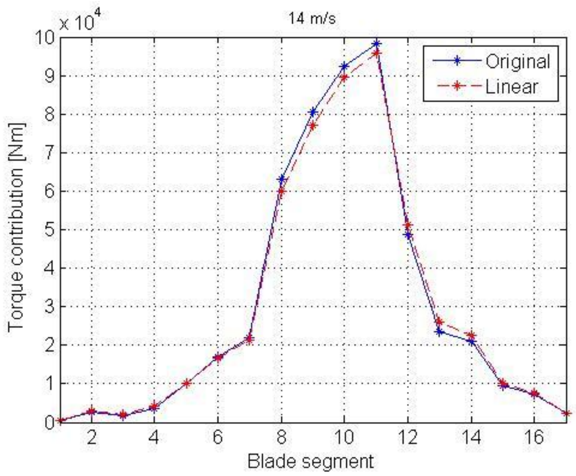


Figure 5.18: Torque contribution of each blade segment for original and linear aerodynamic data at 14m/s wind speed

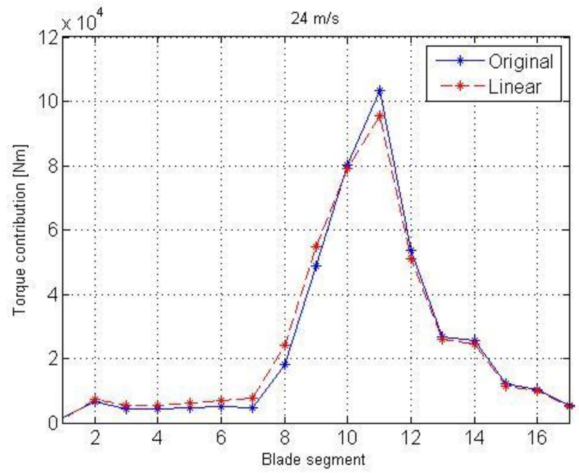


Figure 5.19: Torque contribution of each blade segment for original and linear aerodynamic data at 24m/s wind speed

Figure 5.16, Figure 5.17, Figure 5.18 and Figure 5.19 show the torque contribution obtained from each blade segment at different wind speeds for the original and the linearized lift and drag coefficients. The simplifications mentioned previously, such as twist and chord adjustments, are not performed for this model, in order to only study the effect of the linearization of the aerodynamical data. When the figures above observed, it can be seen that output torques from the two different conditions match quite accurately. This proves that the linearized coefficients can be used in the system to calculate the output torque without causing any significant error.

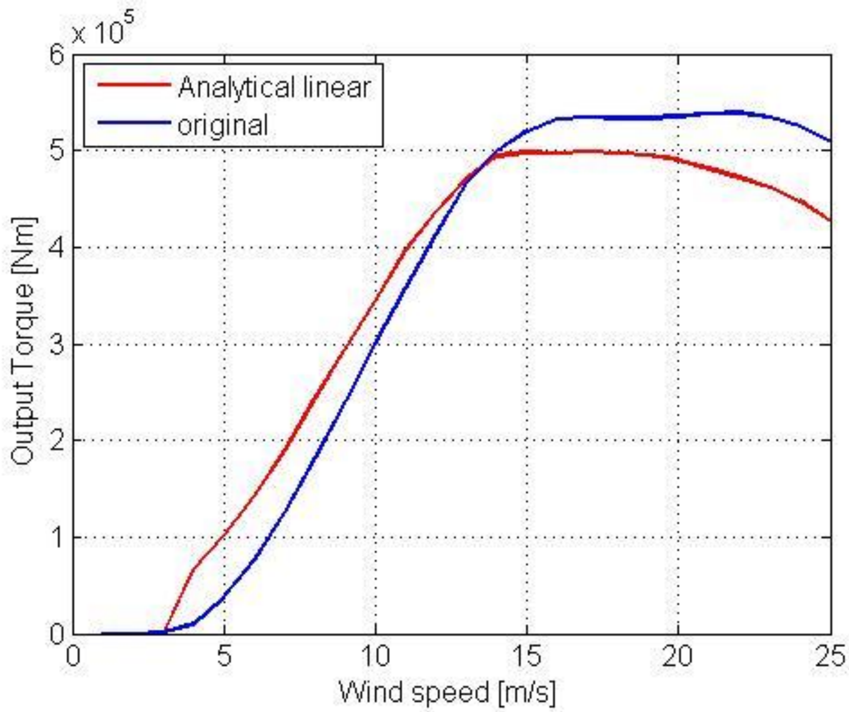


Figure 5.20: Torque vs. wind speed for different wind turbine models for middle speed operation

Figure 5.20 shows the output torques obtained from the analytical model which uses the linearized blade profile data and the original model of the wind turbine. This figure can be compared with Figure 5.5 in order to have a better explanation. Figure 5.5 shows the output torques for the original system and the analytical system which uses the original aerodynamical data. It can be seen that the two graphs are quite the same, which means that the linearized lift and drag coefficients are quite similar to the original ones.

Since the linearized analytical model will be used for deriving a proper pitch controller, it is crucial to verify the high speed operation of this model. Figure 5.21 shows the torque outputs obtained from the original and the linear analytical models for 14 m/s wind speed. It can be seen that the results are fairly similar, except for the area after 18° pitch angle. Even though this result may seem like a mismatch, for 14 m/s wind speed, the pitch angle is quite low (e.g. 5°-10°), therefore the mismatch calculated after 18° does not cause any harmful results since it is out of the interesting range. The mismatch is caused by the strict limitation of the angle of attack.

Figure 5.22 shows the torque outputs obtained from the original and the linear analytical models for 24 m/s wind speed. Again it can be observed that the results from both systems are fairly similar, therefore the analytical linear model can replace the original model for simplification.

From both figures it is seen that the linearization causes almost no error at all.

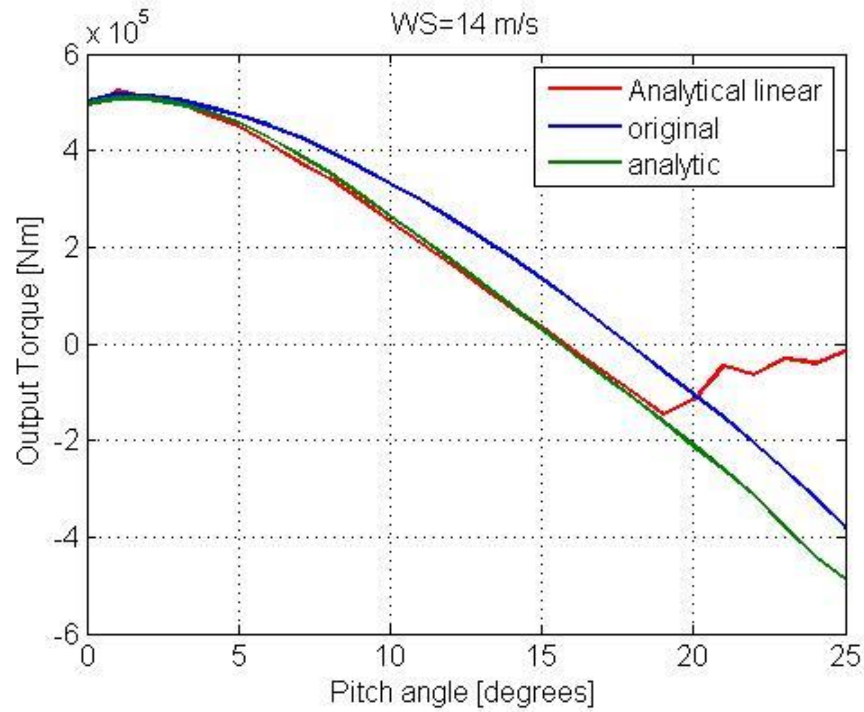


Figure 5.21: Torque vs. pitch angle at 14 m/s wind speed for original, analytic and linear analytical models

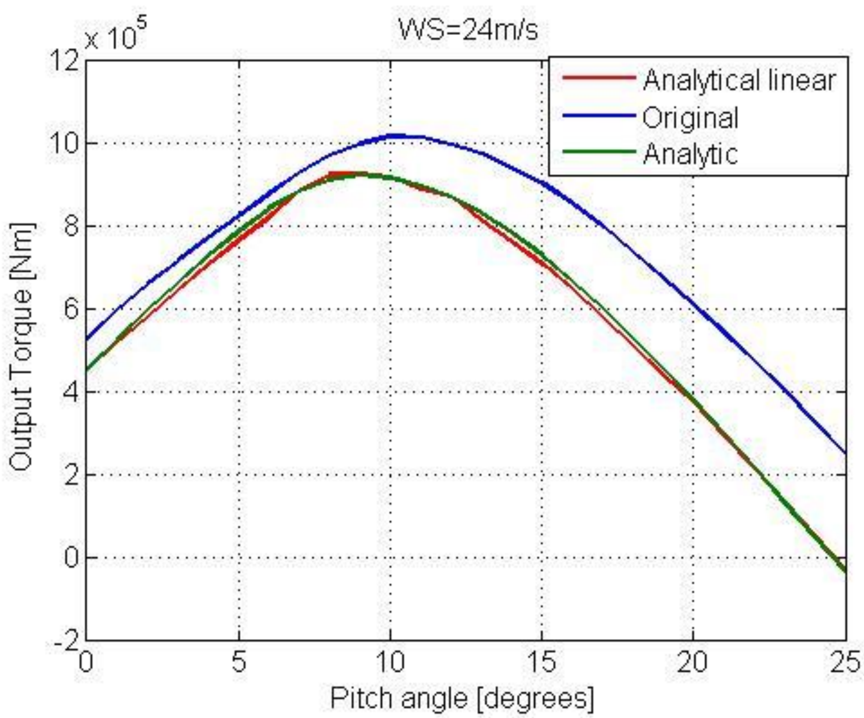


Figure 5.22: Torque vs. pitch angle at 24 m/s wind speed for original, analytic and linear analytical models

In order to verify the accuracy of the linear analytical model, the error of the output torques from the original and the linear analytical models are calculated.

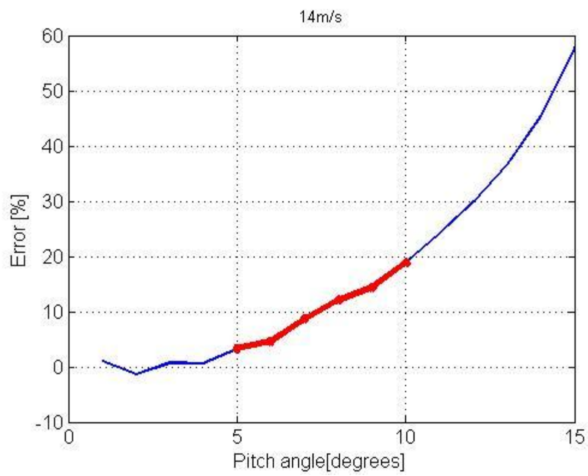


Figure 5.23: Error in torque output of original and analytical models for 14 m/s wind speed

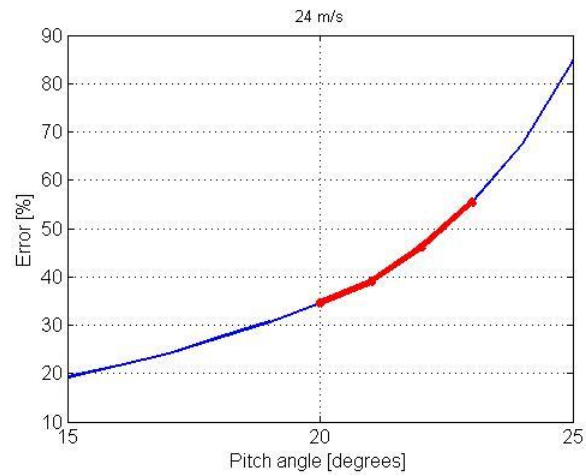


Figure 5.24: Error in torque output of original and analytical models for 24 m/s wind speed

Figure 5.23 and Figure 5.24 show the torque output error for different wind speeds in the high wind speed region. For 14 m/s the pitch angle is very low, therefore the error would be less than 20%. Secondly for 24 m/s, the maximum pitch would be between 20°-23° during operation; therefore the error would be around 50%.

The errors obtained for the linear analytical model are quite similar to the ones obtained for the analytic model, as seen from Figure 5.6Figure 5.6 and Figure 5.7. All of the studies done before, proves that the linearization of the lift and drag coefficients are quite accurate and the overall analytic model gives fairly similar results to the original model. As a result, all the simplifications that have been introduced in this chapter can be used to derive a simple and accurate pitch controller for the variable speed wind turbine.

5.4. Verification of the analytical Blade Element Momentum Theory

As it is mentioned in the previous sections, the main difference between the original wind turbine model and the analytical one is the execution of the BEM theory. The execution of the BEM theory with original and analytical model has been iterative and formula based respectively.

To be more specific, one should look deeper into the calculation of the angle ϕ, which is the total angle between the rotor plane and the oncoming wind direction. In the original BEM, this angle is calculated as:

$$\phi = tan^{-1}\frac{\upsilon_w(1+a')}{r\omega_r(1-a)} \tag{5.8}$$

where a is called the axial induction factor and a' is the tangential induction factor. These factors help to calculate properly, the induced flow of the oncoming wind in axial and tangential directions. [5]

The execution of the BEM, as mentioned before, is an iterative method. This is done by guessing the first a and a' factors, calculating the angle Φ and from the results which are obtained by Φ, and afterwards calculating the secondary a and a', only to continue the iteration process. This is performed until angle Φ produces reasonable torque values for a given wind speed.

However, in the analytical model the a and a' factors are neglected and the angle is then calculated as follows:

$$\phi = tan^{-1}\frac{\upsilon_w}{r\omega_r} \tag{5.9}$$

$$tan\,\phi = \frac{\upsilon_w}{r\omega_r} \tag{5.10}$$

which can be formed as:

$$1 + tan^2\phi = 1 + \frac{\upsilon_w}{r\omega_r}^2 \tag{5.11}$$

After some trigonometric transformation, (5.11) can transform to (5.1). If ϕ is extracted from (5.1), it can be represented as:

$$\phi = sin^{-1}\frac{1}{\sqrt{1+(\frac{\omega_r r}{\upsilon_w})^2}} \tag{5.12}$$

which is a formula based calculation that is independent of the flow induction factors a and a'.

5.4.1. Accuracy of the analytical calculation

In the previous chapters, the performance of the simplified analytical system has been tested in a large operating range. However, in order to investigate the performance of the analytical calculation of the BEM, only difference between the original and the analytical models must be according to the BEM. Therefore, the following results are obtained by comparing the original and the analytical model, whilst keeping all the geometric data of the turbine identical for both cases.

First step of verifying the performance of the numerical BEM is to test it on only one blade segment. For this comparison, blade segment 11 is chosen according to the high torque contribution rate. The obtained results are as follows:

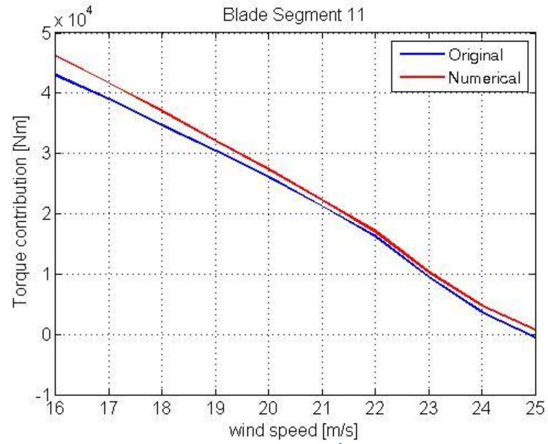


Figure 5.25: Torque produced by 11th blade segment for the iterative and numerical BEM

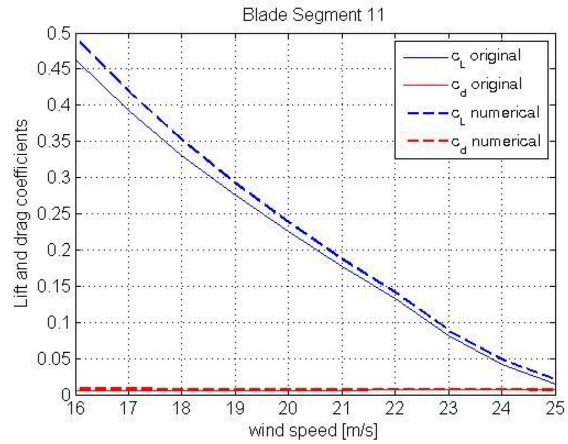


Figure 5.26: Lift and drag coefficients obtained for the iterative and numerical BEM

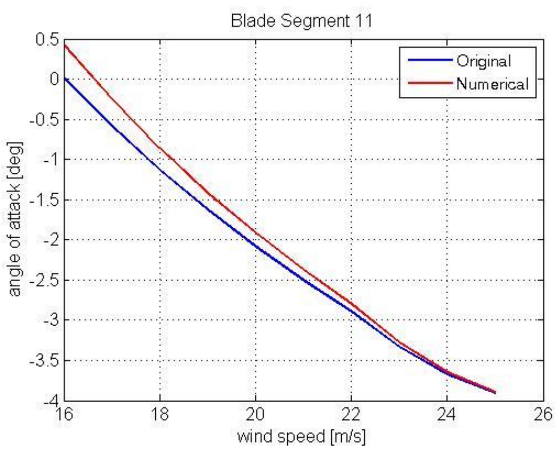


Figure 5.27: Angle of attack obtained for the iterative and numerical BEM

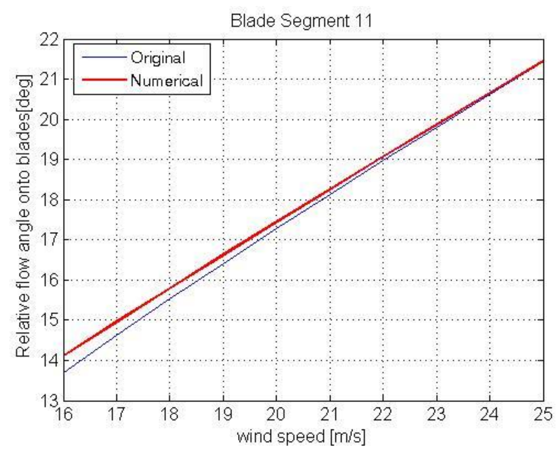


Figure 5.28: Relative flow angles onto blades obtained for the iterative and numerical BEM

Figure 5.25 shows the torque contribution provided by the 11th blade segment. Figure 5.26 represents the lift and drag coefficients obtained from this operation. Here the solid curves show the iterative and the dashed curves show the numerical calculation results. Figure 5.27 shows the angle of attack calculated on the 11th segment of the blade while Figure 5.28 shows the relative flow angle onto the blade. All the results are obtained by two ways, the iterative and the numerical. From these figures above, it can be seen that both iterative and numerical results at each figure follows the same path and have similar values. But in order to see exactly how accurate the numerical method is, the error between the original parameters and analytically obtained parameters must be studied.

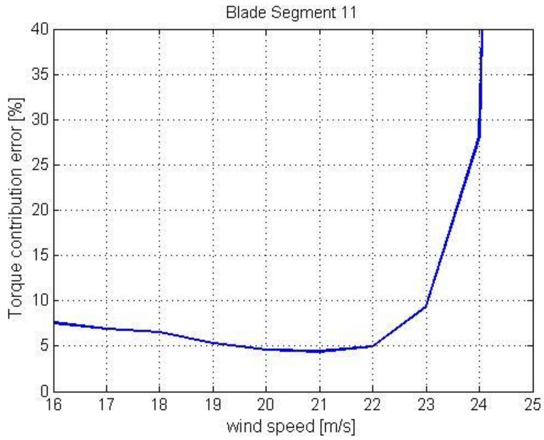


Figure 5.29: Torque difference between the iterative and numerical calculations at 11th blade segment

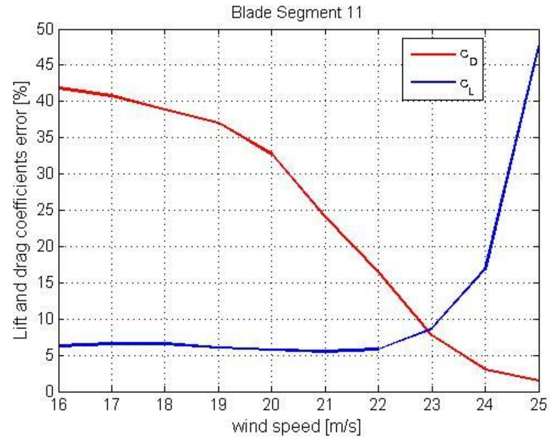


Figure 5.30: Lift and drag coefficients difference between the iterative and numerical calculations at 11th blade segment

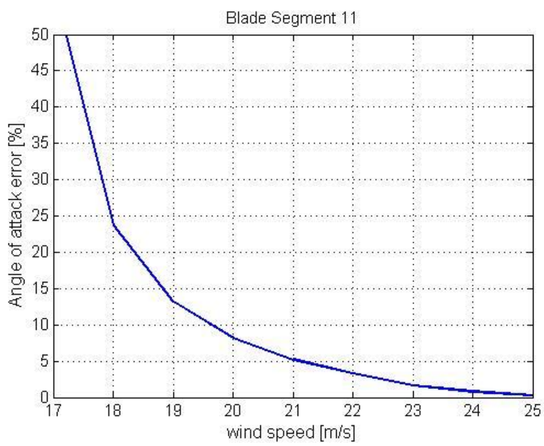


Figure 5.31: Angle of attack difference between the iterative and numerical calculations at 11th blade segment

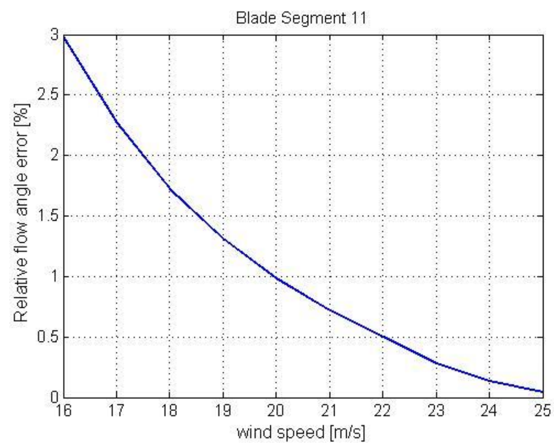


Figure 5.32: Relative flow angle difference between the iterative and numerical calculations at 11th blade segment

Figure 5.29, Figure 5.30, Figure 5.31 and Figure 5.32 shows the difference in torque output, lift and drag coefficients, angle of attack and relative flow angle calculated by iterative and numerical methods in percentage, respectively.

It can be observed from Figure 5.29 that for very high wind speeds, the torque difference is rather much in percentage. But as it can be seen from the Figure 5.25 the torque value is very low, therefore the controller would be able to take care of this big difference. Since the torque is determined by lift coefficient mainly, it is not surprising to see that the lift coefficient difference has a similar behavior as the torque output. From the figures above, it can be said that the angle of attack and relative flow angle values calculated by the iterative and the numerical ways match reasonably.

Overall, it can be observed that the numerical BEM is quite accurate, when it is tested only on the 11th blade segment. But of course, it should also be tested for each blade segment in order to understand the accuracy of this method deeply. Therefore, secondly the numerical calculation is tested for the whole blade.

For simplicity, results will be shown for only one wind speed value. The wind speed chosen is 20 m/s while the pitch angle is 19.05°. This pitch angle value gives the desired operation for this wind speed.

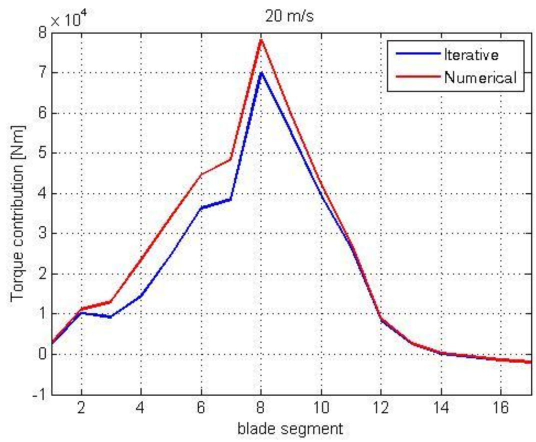


Figure 5.33: Torque contribution of each blade segment calculated by iterative and numerical methods

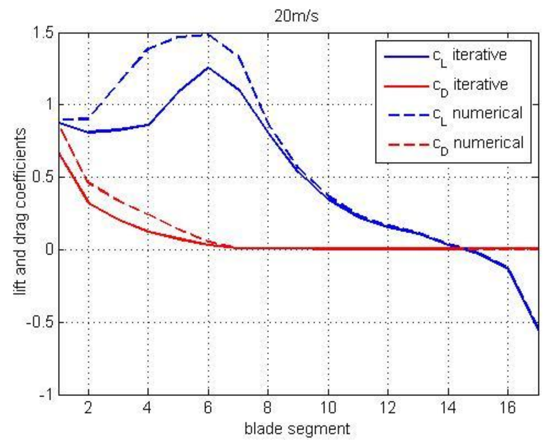


Figure 5.34: Lift and drag coefficients of each blade segment calculated by iterative and numerical methods

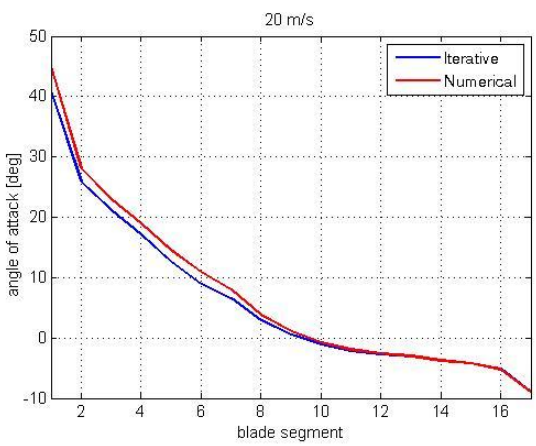


Figure 5.35: Angle of attack of each blade segment calculated by iterative and numerical methods

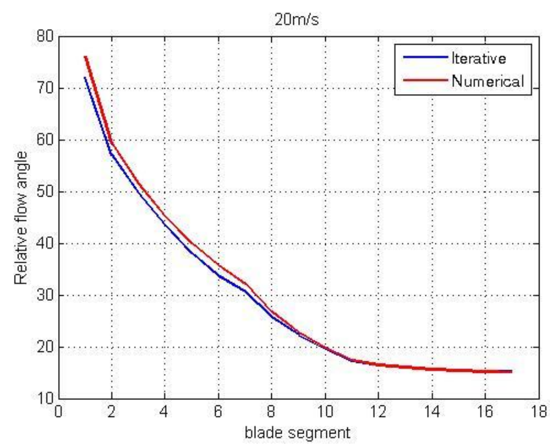
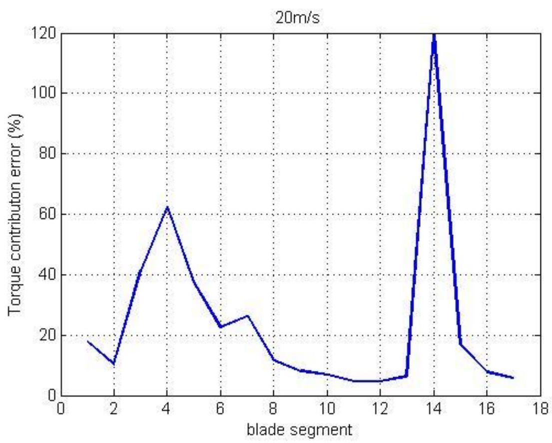


Figure 5.36: Relative flow angle of each blade segment calculated by iterative and numerical methods

Figure 5.33 shows the torque contributions of the blade segments. As it can be observed from this figure, both iteratively and numerically calculated torque outputs follow a similar path, even though there is a difference in values. The numerical torque outputs are higher than the iteratively calculated ones and this can be explained by the results obtained in Figure 5.34.

Figure 5.34 shows that the numerically calculated lift coefficients are higher than the original ones, the output torque which has been calculated numerically would naturally be higher in value than the original value.

Figure 5.35 and Figure 5.36 shows the angle of attack and relative flow angle onto blades, respectively. As it can be seen from these figures, both angles have very similar values and the differences between the two methods are almost zero.



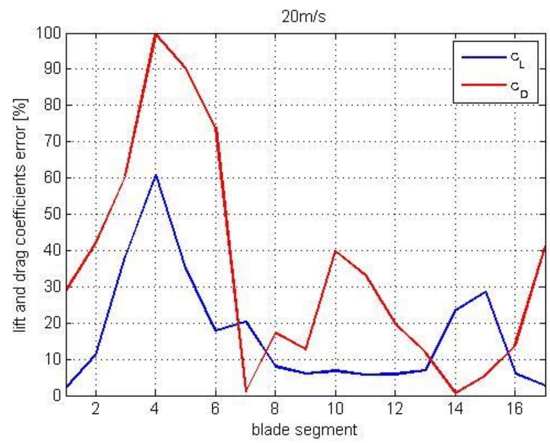


Figure 5.37: Torque difference between the iterative and numerical calculations at each blade segment

Figure 5.38: Lift and drag coefficients difference between the iterative and numerical calculations at each blade segment

Figure 5.37 shows the difference in the torque contributions obtained from each blade segments for 20 m/s wind speed and the corresponding optimal pitch angle. At the 14th blade segment, a very high torque difference is shown, but in reality this is cause by the huge difference between very low values, therefore is not important.

Figure 5.38 represents the error between iteratively and numerically obtained lift and drag coefficients, in percentage. It can be observed that the behavior of the lift coefficient difference is almost identical with the behavior of the torque contribution difference, as expected.

As explained in this section and proved with the help of the figures, one can say that numerical BEM is very accurate and can be used instead of the iterative BEM while deriving the pitch regulator system.

6. BEHAVIOUR OF THE PITCH REGULATED WIND TURBINE SYSTEM AT HIGH WIND SPEEDS

In previous chapters, a controller system which is valid for all the wind speed values was developed. However, by using the pitch angle dependence of the output torque, another control system can be designed. This control system, obviously, can only be valid at high wind speeds since the pitching is only performed at this wind speed range.

A key relation that can be utilized when designing the pitch regulated system is that the output torque can be expressed as a function of the pitch angle. Therefore, if output torque is expressed as,

$$T = f(\beta) = K\beta \tag{6.1}$$

According to that, the controller can be planned as a pitch regulator, a constant which represent the relation between the pitch angle and the output torque and the inertia effect.

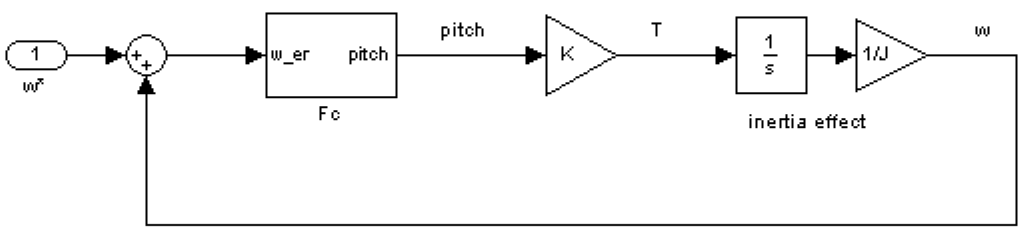


Figure 6.1: the general scheme of the pitch regulated wind turbine system

Figure 6.1 shows the general scheme of the pitch regulated wind turbine system. On this scheme, F_c represents the controller of the wind turbine; K represents the dependence between the pitch angle and the output torque and $\frac{1}{sJ}$ represents the inertia of the turbine. Therefore, the system can be represented as [3]:

$$\frac{\omega}{\omega^*} = \frac{F_c \frac{K}{sJ}}{1 + F_c \frac{K}{sJ}} \tag{6.2}$$

which can also be written as,

$$\frac{\alpha}{\alpha + s} = \frac{F_c \frac{K}{J}}{s + F_c \frac{K}{J}} \tag{6.3}$$

Using (6.3), the controller F_c can be expressed as,

$$F_c = \frac{\alpha J}{K} \tag{6.4}$$

With this design the output torque was assumed to be directly proportional to the pitch angle, which means that the controller could be designed as a P-controller. According to this assumption, the controller parameter k_p can also be expressed as (6.4), where α is the bandwidth of the controller and J is the inertia of the turbine.

Once the controller parameter k_p is expressed as above, the next step of the controller design would be to express the output torque as a function of the pitch angle. This task can be done in several ways, two of which are going to be handled in this project.

6.1. The numerical method

For expressing the output torque as a function of the pitch angle, the first approach to mention is the numerical one. In order to achieve this, the torque difference for a small change of pitch angle is calculated. In this thesis, this small pitch angle variation is assumed as 2°, both increasing and decreasing. Afterwards, the torque behavior of the system has been tested under these circumstances.

All calculations regarding the pitch regulated system would be held in a certain wind speed range. This range is when the wind speed is between 16 m/s and 25 m/s. The reason for this is to create a pre-pitched wind model, which would prevent the oscillations that might occur at instant pitch angle changes.

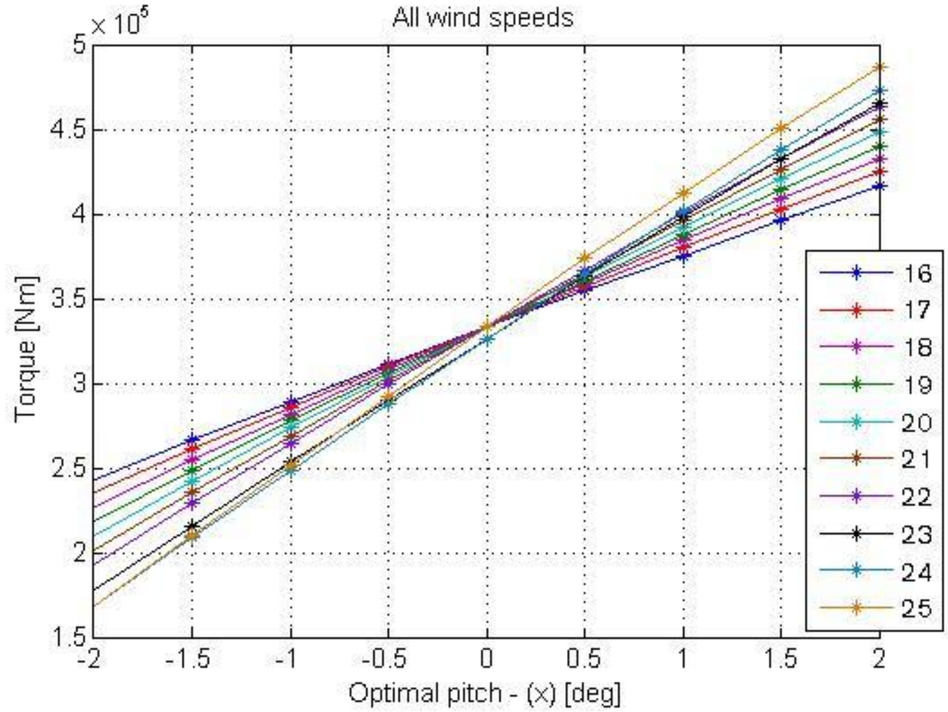


Figure 6.2: Output torque derivation according to small pitch angle changes for high wind speed region

Figure 6.2 shows the output torque behavior of one blade of the wind turbine when the optimal pitch angle is increased and decreased 2°, with 0.5° steps for each wind speed in the corresponding wind speed range. It can be seen from the figure that the relation between the pitch angle and the output torque is linear. Therefore, the output torque can be expressed as

$$T = m\Delta\beta + T_0 \tag{6.5}$$

where T is the output torque, m is the slope of the line, Δβ is the change in the pitch angle and T_0 is a linearization consequence. The pitch angle difference is calculated as:

$$\Delta\beta = \beta_0 - \beta_{ins} \tag{6.6}$$

By forming (6.5) using (6.6), then the output torque can finally be written as:

$$T = K\beta + N \tag{6.7}$$

where K is the constant that represents the linear part of the relation between the output torque and the pitch angle and N is the constant of the expression. With this K value, the controller parameter k_p can be calculated as shown in (6.4). The bandwidth is put equal to 2 rad/s and the inertia is $5.5156 \cdot 10^6$ kgm^2.

Table 6.1 shows the output torque expressions according to pitch angle and the controller parameters derived using them, for different wind speeds in the high speed region.

Table 6.1: Output torque expression and controller parameter values for different wind speeds

Wind speed (m/s)	T=f(β)	Kp=αJ/K
16	-130200β+2.74*10^6	-84.726
17	-141975β+3.12*10^6	-77.7
18	-154050 β+3.52* 10^6	-71.608
19	-166200β+3.95*10^6	-66.372
20	-185925β+4.54*10^6	-59.34
21	-190800β+4.87*10^6	-57.814
22	-202950β+5.37*10^6	-54.354
23	-215925β+5.91*10^6	-51.008
24	-228000β+6.46*10^6	-48.382
25	-239250β+6.987*10^6	-46.1

According to Table 6.1, the controller should be designed as a P-controller with a feed forward term to prevent a large steady state error. However, both parameters change when the wind speed changes. Thereby, in order to prevent a steady state error, the controller should also have an integral part. The controller parameter for the integral part is calculated as an 'active damping' parameter [7]. k_p is chosen as –59.34, which is suitable for the whole high wind speed range.

$$k_i = \frac{\alpha^2 J}{K} = \alpha . k_p = 118.68 \tag{6.8}$$

Figure 6.3 shows the configuration of the high wind speed controller and the wind turbine system.

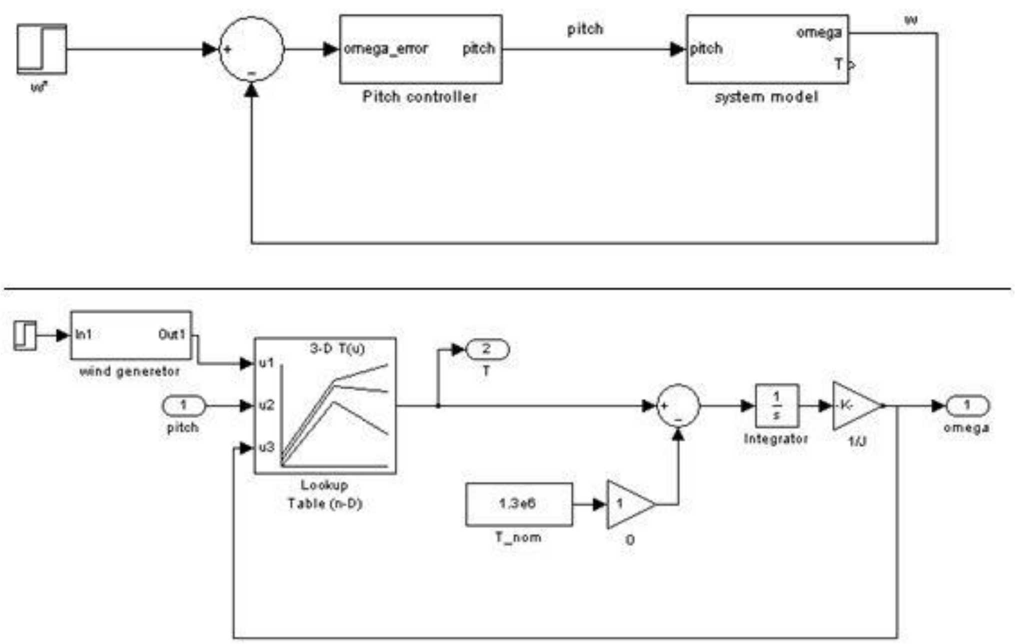


Figure 6.3: Scheme of the pitch regulated high speed control and the wind turbine system model

Figure 6.4, Figure 6.5, Figure 6.6, Figure 6.7, Figure 6.8 and Figure 6.9 show the behavior of the output torque, rotor speed and the pitch angle of the wind turbine system. It can be observed from Figure 6.7 that the rise time is appropriate. According to the figures mentioned above, the pitch regulated wind turbine system works properly for the high wind speeds.

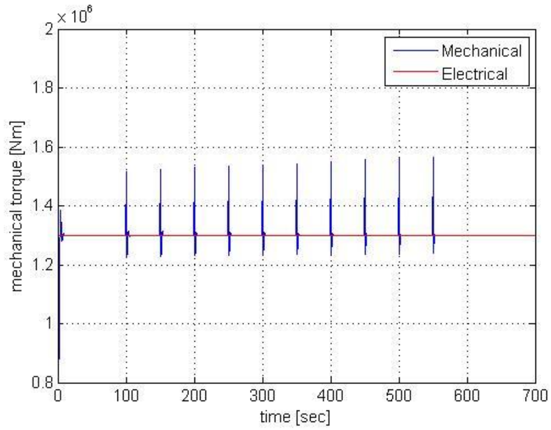


Figure 6.4:Mechanical and electrical torque response of the pitch regulated system

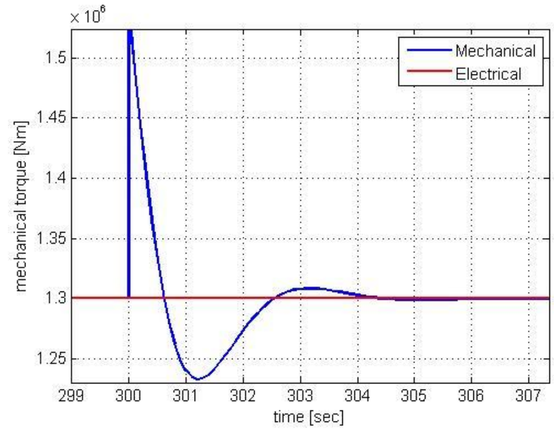


Figure 6.5: Mechanical and electrical torque response of the pitch regulated system (close up)

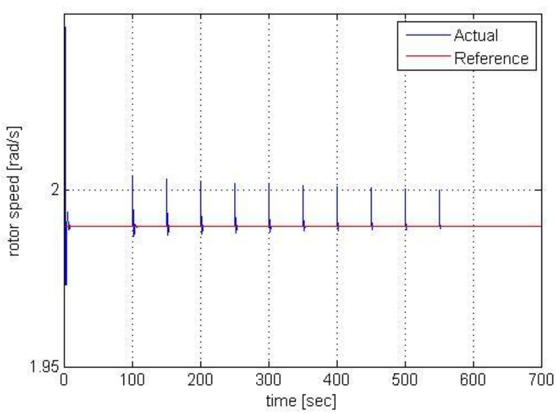


Figure 6.6:Rotor speed response of the pitch regulated system

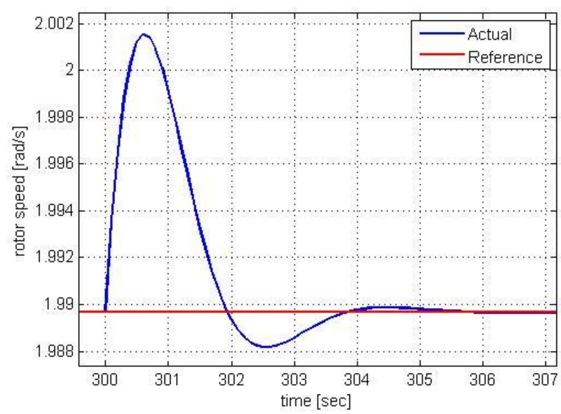


Figure 6.7:Rotor speed response of the pitch regulated system (close up)

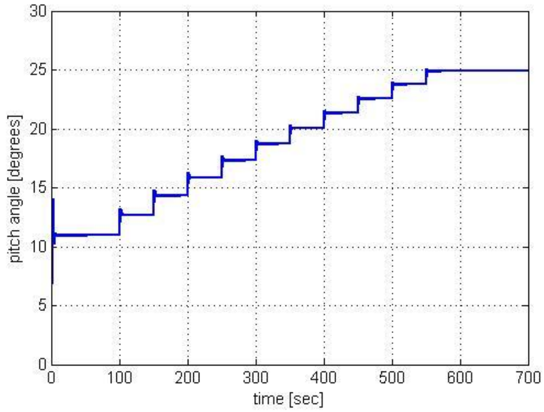


Figure 6.8: Pitch angle response of the pitch regulated system

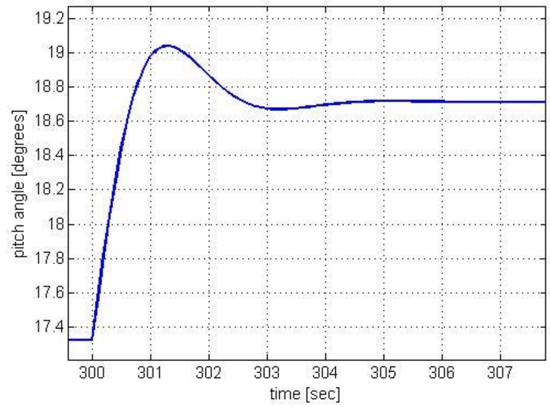


Figure 6.9: Pitch angle response of the pitch regulated system (close up)

6.2. The Partial Derivation method

Another way to express the output torque as a function of the pitch angle is the partial derivation method. This task is achieved by using the torque contribution formula from the BEM theory. The torque contribution is expressed as:

$$\Delta T = \frac{1}{2}\rho W^2 c\Delta r.r(c_L \sin\phi - c_D \cos\phi) \tag{6.9}$$

This method is only valid when the lift and drag coefficients are linear and defined only as one expression. As it is studied at Chapter 5, for the wind speed region used to develop this control system (16-25 m/s), the angle of attack is always between -10° and 10°. In this range, both lift and drag coefficients can be expressed with one formula. Therefore, the partial derivation method can be performed for the corresponding wind speed range.

Firstly, the lift and drag coefficients are expressed as in (5.6) and (5.7). Therefore, the torque contribution can be written as:

$$\Delta T = \frac{1}{2}\rho W^2 c.\Delta r.r((a\alpha + b)\sin\phi - (d\alpha + e)\cos\phi) \tag{6.10}$$

In (6.9), the only parameter that is a function of the pitch angle is the angle of attack (α). Accordingly:

$$\frac{\partial T}{\partial \beta} = \frac{1}{2}\rho W^2 c.\Delta r.r(a\sin\phi - d\cos\phi) \tag{6.11}$$

The constant that represents the relation between the torque and the pitch angle, K, then becomes (6.11). Here the angle Φ is calculated according to (5.1).

Table 6.2: Relation between the output torque and pitch angle (K) and the controller parameters for different wind speeds

Wind speed [m/s]	K	k_p
16	-186990	-59
17	-200430	-55.034
18	-214170	-51.5
19	-228180	-50.1
20	-242490	-45.49
21	-257100	-42.9
22	-272040	-40.55
23	-287280	-38.4
24	-302880	-36.42
25	-318780	-34.6

Instead of changing the controller parameters for each wind speed, one value which is suitable for the whole range is determined. In this case, the controller parameter at 20 m/s wind is chosen as the controller parameter. As mentioned in Section 6.1, the controller must have an integral part in order to remove a steady state error. Similar to the numerical method, the integral term is derived as (6.8) [7].

The results obtained from the controller which the settings have been discussed above are as such:

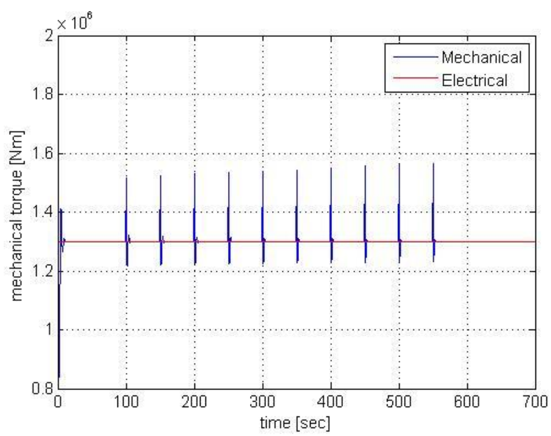


Figure 6.10: Mechanical and electrical torque response of the pitch regulated system

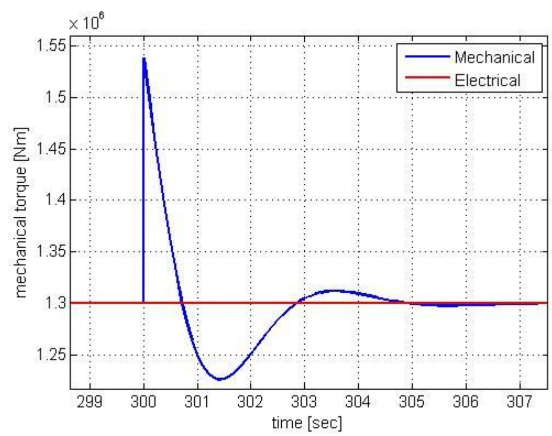


Figure 6.11: Mechanical and electrical torque response of the pitch regulated system (close up)

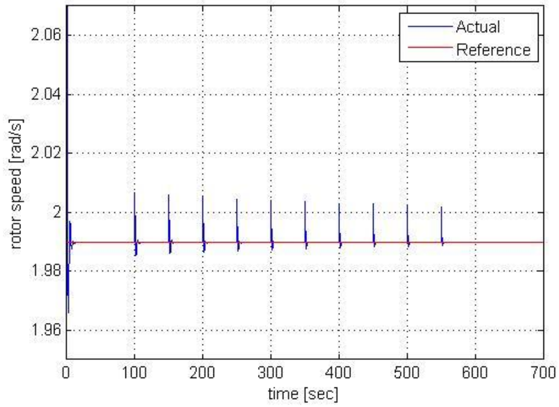


Figure 6.12: **Rotor speed response of the pitch regulated system**

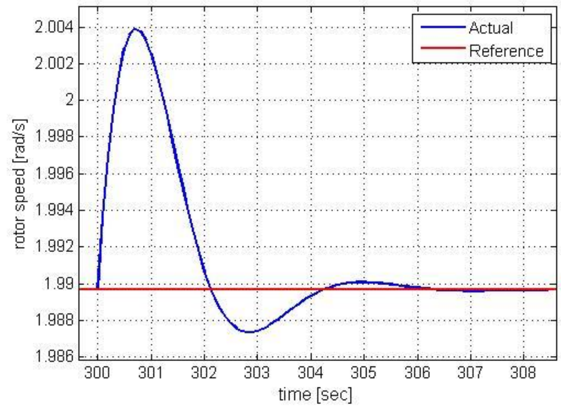


Figure 6.13: Rotor speed response of the pitch regulated system(close up)

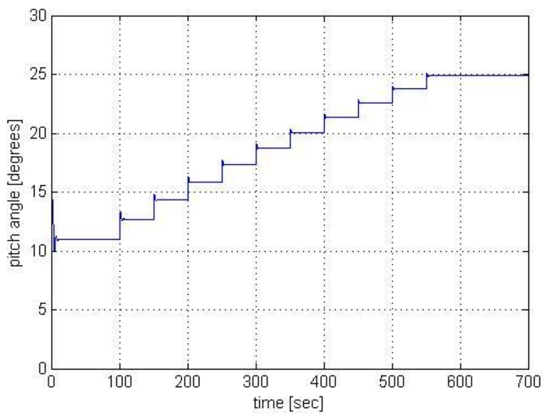


Figure 6.14: **Pitch angle response of the pitch regulated system**

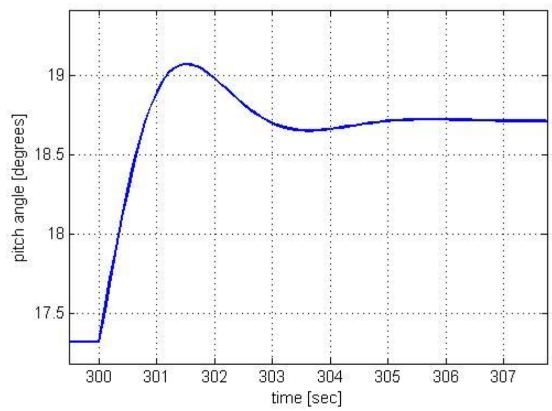


Figure 6.15: Pitch angle response of the pitch regulated system (close up)

Figure 6.10 and Figure 6.11 show the output torque behavior, Figure 6.12 and Figure 6.13 show the rotor speed behavior; Figure 6.14 and Figure 6.15 show the pitch angle behavior of the wind turbine system, as the wind speed increases in steps. It is observed from Figure 6.13 that the rotor speed overshoot is higher than the one predicted using the numerical method, due to the fact that the integral term is smaller than the numerical one. But since the overshoot is within reasonable range and the rise time of the rotor speed is appropriate, the controller system is here assumed to work properly for the high wind speeds.

As mentioned before, both in the numerical and the partial derivation methods, the integral term k_i is calculated using active damping. It is seen from the figures above, that the output parameters of the wind turbine experience an overshoot while reaching the steady state. This can be prevented by choosing a stronger integral term in the controller; however it is not included in this report.

6.3. Behavior of the pitch regulated wind turbine system under grid disturbances

The previous section shows that the pitch regulated system is able to operate as desired while there are no disturbances in the grid. However in real life operations, the grid conditions might not be ideal. Therefore the pitch regulated system can be tested under some grid disturbances in order to observe the real life operation behavior.

The pitch regulated system which has been derived by the partial derivation method is used to test the grid disturbance effects. The pitch regulated model is not based on the electrical system; therefore the voltage dip cannot be introduced directly. However, in the high wind speed region the current limit of the controller is reached. Therefore any change experienced by the grid voltage will directly be reflected on the power of the wind turbine. The power of the wind turbine is determined as,

$$P = T\,\omega_r \qquad (6.12).$$

Therefore, the turbine response to a voltage dip can be formulated as an electrodynamical torque reduction.

6.3.1. Voltage dips

In this thesis, the voltage dips are defined as short time voltage reductions in the grid. More specifically, the voltage dip occurs when the wind turbine system operates in steady state. The duration of the voltage dip investigated here is 500 milliseconds, which corresponds to a fairly difficult case.

Firstly, a 25% voltage dip for 500 ms is subjected to the system and the voltage dip is introduced at the 10th second. Figure 6.16 shows the voltage dip experienced on the grid. As it is mentioned, the voltage dip occurs at the 10th second and lasts for 500 ms. Figure 6.17 shows the behavior of the output torque. The electrical torque experiences the same amount of the reduction as the voltage has. Due to the controller, the mechanical torque follows the electrical torque which is considered the reference. When the dip is over, the mechanical torque is restored fully to its nominal value. Figure 6.18 shows the behavior of the rotor speed of the wind turbine. It is observed that the rotor speed increases with the voltage dip and with the controller action the rotor speed is restored back to its nominal value in about 6 seconds. Figure 6.19 shows the pitch angle behavior. When the voltage dip occurs, the pitch angle increases to reduce the torque, therefore the mechanical torque can follow the electrical torque. When the dip is over, the pitch angle decreases to adjust the output torque level. When the torque reaches steady state, the pitch angle regains its pre-dip value.

The figures which are explained above imply that the pitch regulated wind turbine system is able to work when there is a 25% voltage dip for a short term.

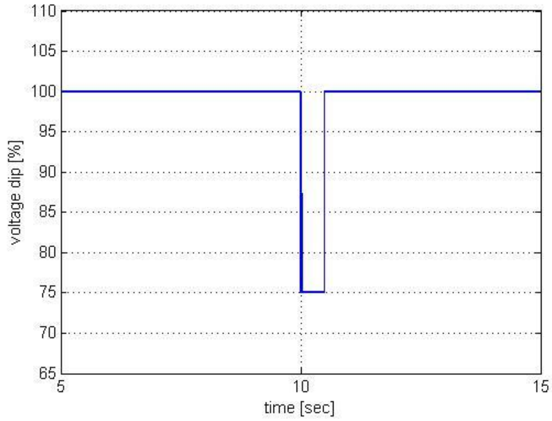


Figure 6.16: The grid voltage (25% dip)

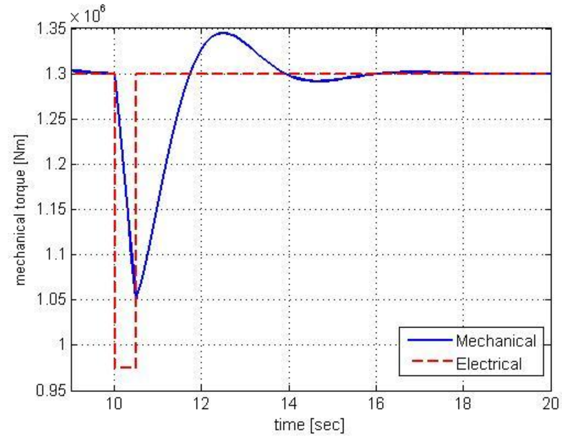


Figure 6.17: The output torque response (25% dip)

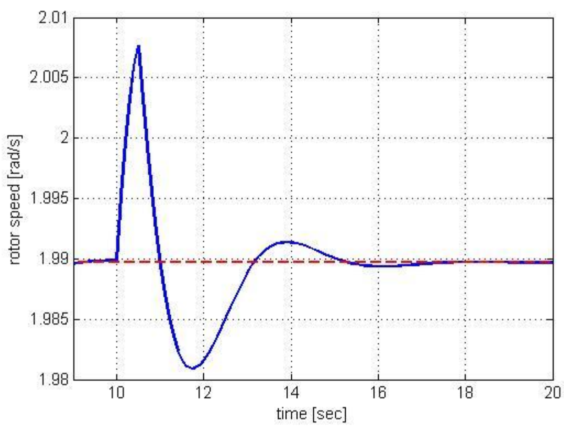


Figure 6.18: The rotor speed response (25% dip)

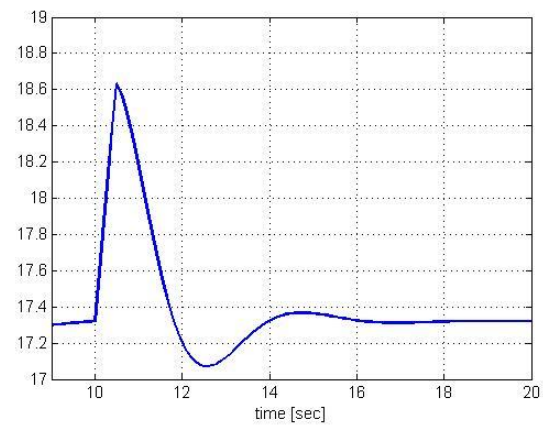


Figure 6.19: The pitch angle response (25% dip)

When the system is verified for the rather low voltage dip, the next step is to test it under extreme circumstances for the worst case. For that, a 90% loss on the grid voltage is experienced. Figure 6.20, Figure 6.21, Figure 6.22 and Figure 6.23 shows the behavior of the pitch regulated system for this grid condition and it is as explained for the previous case. However an important point is that the rotor speed increases more than it did for the 25% dip. This is due to much lower voltage level, which means that the electrical load is reduced even more. Another point is that since the mechanical torque has decreased even more, there is a bigger pitch angle difference in order to compensate for that as it is seen from Figure 6.23.

The figures which are explained above imply that the pitch regulated wind turbine system is able to operate when there is a 90% voltage dip for a short term.

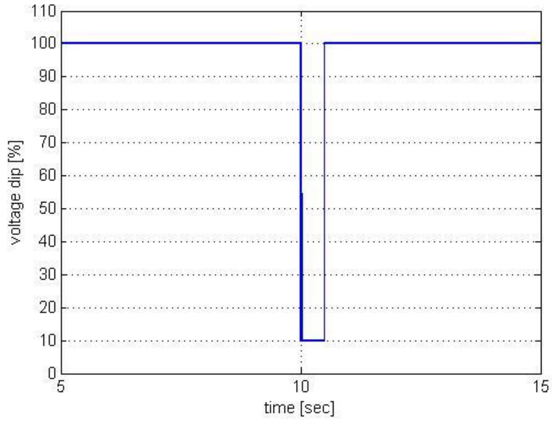


Figure 6.20: The grid voltage (90% dip)

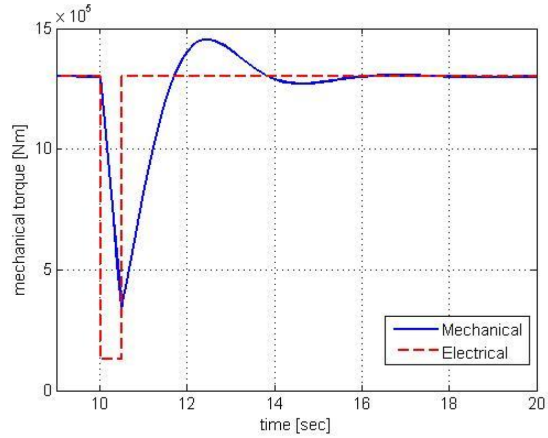


Figure 6.21: The output torque response (90% dip)

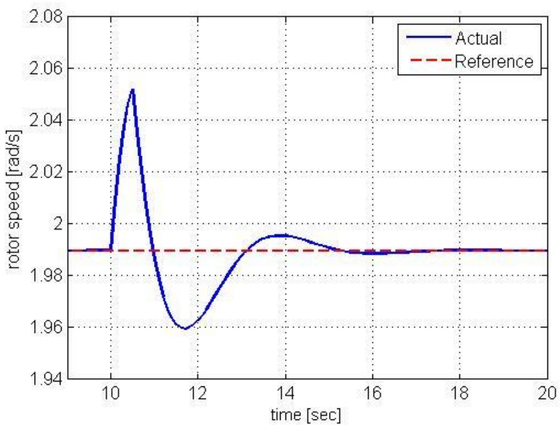


Figure 6.22: The rotor speed response (90% dip)

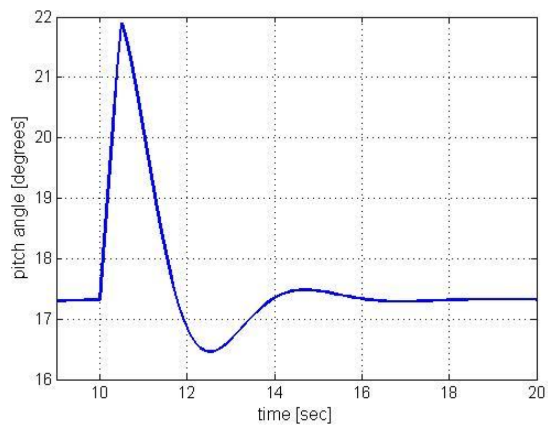


Figure 6.23: The pitch angle response (90% dip)

6.3.2. Spinning Reserve Ability

In this thesis, spinning reserve action is simulated as a power dip that lasts for 10 seconds. The partial derivation based pitch regulated model is used in order to obtain the following results.

The first case of the spinning reserve action is when the rated power is reduced 25% for 10 seconds, in order to feed out energy to the grid. The power down is initiated at 10th second and the power level of the wind turbine is as observed from Figure 6.24. Figure 6.25 shows the torque behavior of the pitch regulated system. As voltage dip, the electrical torque is set as the reference. Therefore, the mechanical torque decreases and reaches steady state in approximately 5 seconds for the new reference. When the power down is finalized, the mechanical torque increases and reaches its nominal value.

Figure 6.26 shows the behavior of the rotor speed of the wind turbine. With the power reduction, the rotor speed increases as expected but since the duration of this situation is more than the time needed for reaching the steady state, the rotor speed reaches the steady state at this power level. Therefore, when the voltage is restored to the nominal value, the rotor speed experiences it as an increase at the power level and starts slowing down. With the controller action, at the 25th second the rotor speed reaches the nominal one for the ideal grid condition.

Figure 6.27 represents the pitch angle behavior of the wind turbine system. As described for the voltage dip case, the pitch angle changes are made in such a way to keep the output torque as desired.

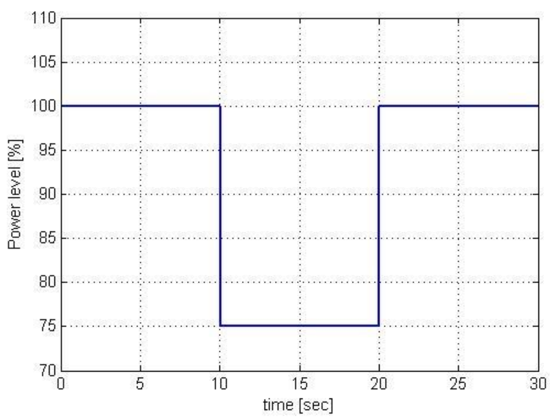


Figure 6.24: The power level of the turbine (25%)

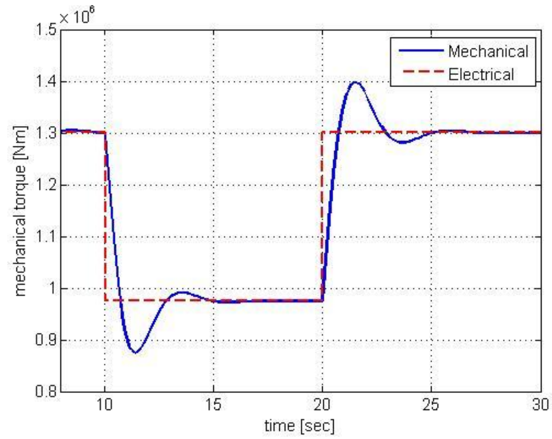


Figure 6.25: The output torque respond during power down (25%)

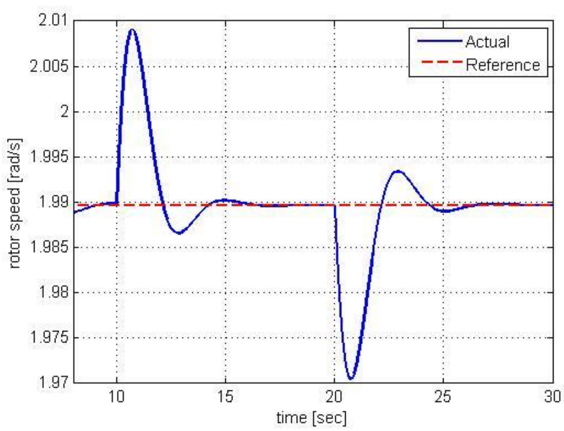


Figure 6.26: The rotor speed response during power down (25%)

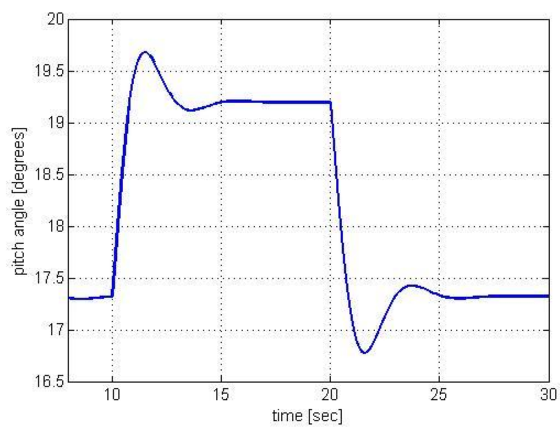


Figure 6.27: The pitch angle response during power down (25%)

Secondly, the spinning reserve ability is tested as a power reduction of 90%. The duration of the power down is 10 seconds. The output power of the wind turbine is shown on Figure 6.28. Figure 6.29 represents the output torque behavior of the wind turbine. As before, the mechanical torque can keep up with the reference torque when the spinning reserve is used. Figure 6.30 shows the rotor speed response and Figure 6.31 shows the pitch angle behavior for this case of spinning reserve ability test. All of the three parameters mentioned above, experiences the same behavior as it did in the 25% power down case, but since the power reduction is much more drastic than the first case, generally it takes longer time for these parameters to reach steady state during the power down. This is due to that when the power down started, the reference and the actual values sensed by the controller are too different from each other and this causes overshoots. When the power is restored, all three parameters can regain steady state in a shorter time.

According to the spinning reserve tests, the pitch regulated wind turbine model is capable of operating when its spinning reserve capacity is 90%.

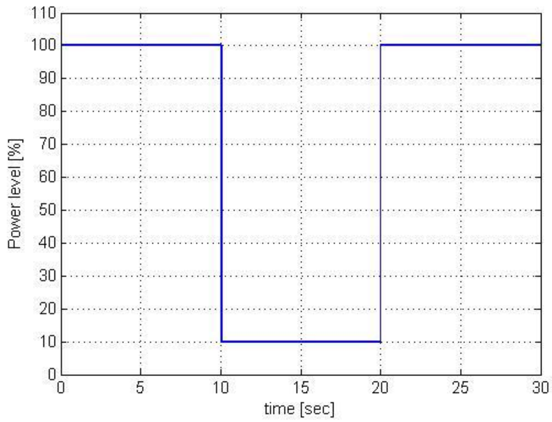


Figure 6.28: The power level of the turbine (90%)

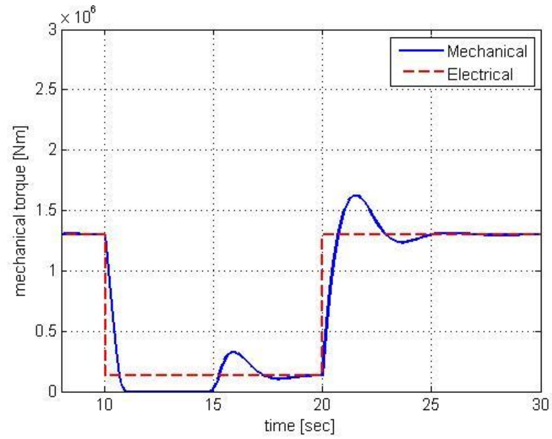


Figure 6.29: The output torque respond during power down (90%)

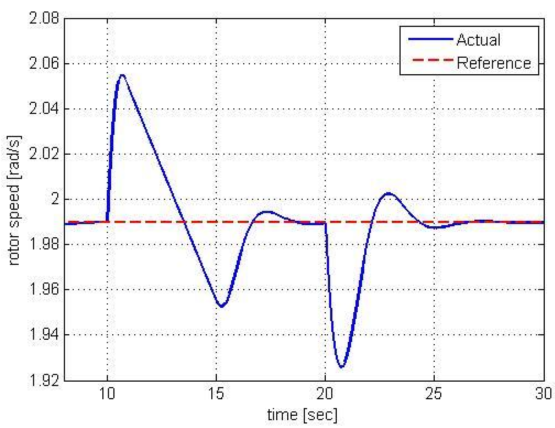


Figure 6.30: The rotor speed response during power down (90%)

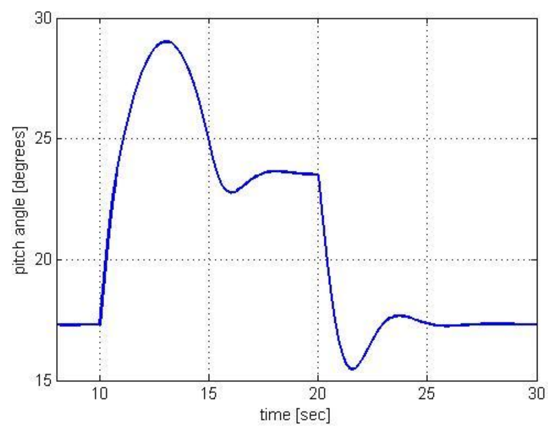


Figure 6.31: The pitch angle response during power down (90%)

7. CONCLUSION

In this thesis, the pitch regulator for a variable speed wind turbine is derived by using three different methods. The main purpose is to develop an analytically expressed pitch regulator for a wind turbine.

After using different methods, the analytically derived pitch regulated system is achieved. It seems that in order to achieve this goal, the blade profile of the wind turbine should be expressed linearly. The fitting of the lift and drag coefficients has been done is such a way that, the difference between the original data and the linear one is less than 1%.

While designing the controller, it is shown that one needs an active damping parameter in order to eliminate the steady state error. Therefore the pitch regulator consists of both proportional and integral parts. With the pitch regulator design according to the active damping method, the output parameters experience overshoots, however the regulator parameters can easily be enhanced in order to achieve a smoother performance. The overshoot in the rotor speed is approximately 0.5%, which is well inside the safe operating margin. According to that, the results obtained using the active damping method are quite correct, even though it consists overshoots.

The behavior of pitch regulated wind turbine systems is investigated under grid disturbances; in order to have a better understanding of the controller's performance. It is observed that the system can operate under voltage dips and power dips up to 90% and also can regain steady state after the conditions come back to normal. For the worst case, the rotor speed of the turbine experiences an overshoot, which is approximately 3%. This overshoot is acceptable and has no negative effect to the system. The turbine control is robust for all high wind speed regions, for both voltage dips and spinning reserve experiences.

7.1. Future Work

This work has been about developing a pitch regulator by analytical methods for the high wind speed region. However, a wind turbine operates at low and middle wind speeds as well as the high speed. Therefore, as a future research suggestion, an analytically derived speed controller for the whole wind speed region could be studied.

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