Modeling, Control and Simulation of a Prototype Wind Turbine Using S4WT

by

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Modeling, Control and Simulation of a Prototype Wind Turbine Using S4WT

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Abstract

Wind energy is a renewable and sustainable kind of energy that is becoming increasingly important in the last decades. The technologies converting wind energy into usable forms of electricity are developed as alternatives to traditional power plants that rely on fossil fuels. The smallest wind turbines are used for applications such as battery charging or auxiliary power on boats; while large grid-connected wind turbines are designed to generate commercial electricity.

This thesis focuses on modeling, control and simulation of a 500 KW prototype wind turbine that is being developed in the context of the MILRES (National Wind Energy Systems) Project in Turkey. Aerodynamic, mechanical, and electrical models are built in both Samcef for Wind Turbines (S4WT) and Matlab/Simulink environments. S4WT enables to choose each of the turbine components to be used in the composition of prototype wind turbine model, to design their characteristics and the way in which they are connected together and to analyze the behavior of the prototype model. The standard components (tower, bedplate, rotor, rotor shaft, gearbox, generator and coupling shaft) have been used compatible with the IEC 61400-1 in S4WT to perform the simulations. The dynamic equations of aerodynamic, mechanical and electrical models are also modeled in Matlab/Simulink environment.

The main control purpose of the wind turbines is to maximize energy efficiency. However, the turbine must also be protected from excessive loads at different wind speeds. To achieve this goal, generated power curve should be close to the ideal power curve that depicts the optimum energy gathering from the wind depending on the wind speed. The prototype wind turbine

is designed to have a nominal power of 500 KW at a nominal wind speed of around 11 m/s. Ideal power curve has two operating regions: Partial load operating region and full load operating region. Partial load operating region has wind speeds lower than the nominal wind speed and full load operating region has wind speeds above the nominal wind speed. The pitch and torque controllers are used to achieve an actual power curve that is very close to the ideal one. A pitch function and a standard PI controller with gain scheduling have been used to control the pitch angle of the blades to limit the power at the full load operating region in S4WT environment. In Matlab/Simulink environment, a simple Proportional (P) controller is used for the pitch controller. The generator torque which consists of an optimal mode gain method is employed in S4WT environment. A sliding mode controller (SMC) is utilized in Matlab/Simulink environment for controlling the torque. Torque controllers which are designed in both environments are used to control the power at both partial and full load operating regions.

Kaimal turbulence model has been used to generate realistic wind profiles in TurbSim that can be integrated with S4WT. The performance analysis of 500 KW wind turbine prototype is done for both the partial load and full load operating regions under the power production scenario in S4WT environment. A similar analysis is also carried out in Matlab/Simulink environment using the models and controllers developed in this environment. The prototype turbine is tested under several other scenarios including start up, emergency stop, shut down and parked in S4WT. Simulation results both in S4WT and Matlab are quite successful.

Prototip Bir Rüzgar Türbininin S4WT Ortamında Modellenmesi, Denetimi ve Benzetimi

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Özet

Yenilenebilir ve sürdürülebilir bir kaynak olan rüzgar enerjisine verilen önem son birkaç on yılda gittikçe artmaktadır. Rüzgar enerjisini elektriğe dönüştüren teknolojiler, fosil yakıtlara dayanmakta olan geleneksel elektrik santrallerine alternatif olarak geliştirilmektedir. Büyük ölçekli ve şebeke bağlantılı rüzgar türbinleri, ticari elektrik üretimi için tasarlanmaktayken, küçük ölçekli rüzgar türbinleri; batarya şarj etme, teknelerde yedek güç üretimi sağlama gibi uygulamalarda kullanılmaktadır.

Bu tez çalışması, MİLRES (Milli Rüzgar Enerjisi Sistemleri) projesi kapsamında geliştirilen 500 KW nominal güce sahip prototip rüzgar türbininin modellenmesine, denetimine ve benzetimine odaklanmaktadır. Aerodinamik, mekanik ve elektriksel alt sistemler S4WT (Samcef for Wind Turbines) ve Matlab/Simulink ortamında tasarlanmıştır. S4WT; prototip rüzgar türbininin birleşiminde kullanılan herbir mekanik aksamı seçmeyi, bu aksamların karakteristiklerini ve birbirleriyle olan bağlantılarını tasarlamayı ve prototip modelin analizlerinin yapılmasını sağlamaktadır. IEC 61400-1 ile uyumlu standart aksamlar (kule, şasi, rotor, rotor şaftı, dişli kutusu, generatör, generatör şaftı) S4WT ortamında kullanılmaktadır. Matlab/Simulink ortamında ise aerodinamik, mekanik ve elektriksel modellerin dinamik denklemleri modellenmiştir.

Rüzgar türbinlerinin ana denetleme amacı, rüzgardan maksimum verimle yararlanmaktır. Ancak rüzgar türbini farklı rüzgar hızlarında aşırı yüklenmelerden de korunmalıdır. Bu denetleme amacını gerçekleştirebilmek için üretilen güç eğrisi, ideal güç eğrisine yakınsamalıdır. İdeal güç eğrisi,

rüzgar hızına bağlı olarak rüzgardan elde edilebilecek optimum enerjiyi göstermektedir. Prototip türbin, 11 m/s nominal rüzgar hızında 500 KW nominal güce ulaşabilmektedir. İdeal güç eğrisinde, kısmi yük bölgesi ve tam yük bölgesi olmak üzere iki farklı çalışma bölgesi mevcuttur. Kısmi yük bölgesinde, rüzgar hızları nominal rüzgar hızından düşüktür. Tam yük bölgesindeki rüzgar hızları ise nominal rüzgar hızından yüksektir. İdeal güç eğrisini sağlamak için kanat açısı ve moment denetleyicileri tasarlanmıştır. Tam yük bölgesinde, rüzgardan elde edilen gücü nominal değerinde sınırlamak için kanat açısı fonksiyonu ve kazanç çizelgelemeli PI denetleyicisi S4WT ortamında birlikte kullanılmıştır. Matlab/Simulink ortamında ise oransal denetleyici (P), kanat açısını denetlemek için tasarlanmıştır. En uygun kazanç modu sabiti, S4WT ortamındaki moment denetlemesi için kullanılmıştır. Kayan kipli denetleyicisinden ise Matlab/Simulink ortamında moment denetiminde yararlanılmıştır. Her iki ortamdaki moment denetleyicileri, hem kısmı yük bölgesinde hem de tam yük bölgesinde uygulanmıştır.

Gerçekçi rüzgar profilleri oluşturmak için, S4WT ile entegre edilebilen Turbsim ortamında tasarlanan Kaimal türbülans modeli kullanılmıştır. 500 KW prototip türbinin performans analizleri, güç üretim senaryosunun kısmi ve tam yük çalışma bölgeleri için S4WT ortamında yapılmıştır. Benzer analizler, Matlab/Simulink ortamında geliştirilen denetleyiciler kullanılarak gerçekleştirilmiştir. Prototip türbin, S4WT ortamında başlatma, acil durum, kapatma ve park etme gibi farklı senaryolarda kullanılarak test edilmiştir. Her iki ortamda gerçekleştirilen benzetim sonuçları oldukça başarılıdır.

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Chapter I

1 Introduction

Energy exists in many different forms; light energy, heat energy, mechanical energy, gravitational energy, electrical energy, sound energy, chemical energy, nuclear or atomic energy and so on. These forms of energy can be transferred and transformed between one another. Energies are broadly classified into two main groups: non-renewable and renewable energies as shown in Table 1.1.

Non-Renewable Energy	Renewable Energy
Fossil Fuels	Wind Energy
Nuclear Power	Solar Energy
Aquifers	Hydraulic Energy
	Wave energy
	Geothermal Energy
	Bioenergy
	Tidal Energy

Table 1.1: Energy Classification

Non-renewable energy relies on a non-renewable resource. Non-renewable sources are limited. They are natural resources which cannot be produced, grown, generated, or used on a scale which can sustain their consumption rates. This explains why these sources are called non-renewable. Fossil fuels (such as coal, petroleum, and natural gas), nuclear power (uranium) and certain aquifers are examples. These resources have a harmful effect on the environment. Burning fossil fuels produces photochemical pollution from nitrous oxides, and acid rain from sulphur dioxide. Burning fuels also emit greenhouse gases including vast amounts of carbon dioxide that may be causing the phenomenon of global warming.

Besides the greenhouse effect of non-renewable sources, they lead to another common concern. Once this type of sources are depleted, there are no more available for future needs. Non-renewable resources are consumed much faster than the nature can create them. It is expected that the uranium will be depleted in 50 years, petroleum in 44 years and natural gas in 64 years. All types of the non-renewable resources will be totally consumed 185 years later.

Renewable or alternative energy is any energy that is produced from sources other than fossil fuel energy. Renewable energy is any source of energy that doesn't consume the finite resources of the earth. It can be easily and quickly replenished. Renewable energy sources are natural sources i.e. sun, wind, rain, tides and can be generated again and again when required. They are available in plenty and the cleanest sources of energy available on this planet. For example, energy that is received from the sun can be used to generate electricity. Similarly, energy from wind, geothermal, biomass from plants, tides can be used for electricity generation.

1.1 Motivation

Considerable attention has been paid to the utilization of renewable energy sources because the non-renewable energy sources are limited and have pollution to the environment. Renewable energies are wind, solar, geothermal, bioenergy, wave, hydraulic, tidal energies. All types of renewable energies have important advantages:

- The primary sources of the renewable energy are the sun, wind, bioenergy, geothermal, tidal and ocean energy sources which are available in the abundant quantity and free to use.
- Renewable sources have low carbon emissions, therefore they are considered as green and environment friendly.
- Renewable helps in stimulating the economy and creating job opportunities. The money that is used to build these plants can provide jobs to thousands of people.
- The governments don't have to rely on any third country for the supply of renewable sources as in the case of non-renewable sources.
- Renewable sources can cost less than consuming the local electrical supply. In the long run, the price of electricity are expected to soar because they are based on the price of crude oil. However, using renewable sources can cut the electricity bills.
- Various tax incentives in the form of tax waivers, credit deductions are available for individuals and businesses who want to invest in green energy area.

The wind energy is the fastest growing source of electricity production among all types of renewable energies. When the wind energy is compared to other renewable energy types, these energies face some important problems.

The biggest problem with the solar energy is that solar panel systems lead to high cost of entry. Solar panels are relatively new technologies, and are still quite expensive in comparison to wind power. Another disadvantage of solar panel systems is the lack of efficiency due to the nature of sunlight. Solar power does not produce energy if the sun is not shining. Nighttime and cloudy days seriously limit the amount of energy produced [1].

The dams are very expensive to build for hydraulic energy. There needs to be a sufficient, and powerful enough, supply of water in the area to produce energy.

If the geothermal energy is implemented incorrectly, it can produce pollutants. Geothermal sites are prone to running out of steam. Improper drilling into the earth, can release hazardous minerals and gases [2].

Biomass has a smaller energy content for its bulk. Therefore, costs of labor, transportation, and storage are higher. Potential disadvantages of bioenergy projects include unsustainable impacts on soil and water resources. The inappropriate selection of species or management strategies, for example, can lead to land degradation. Water and nutrients, which are in short supply in many areas, must be used to grow biomass crops [3].

Tidal energy is expensive to construct and the power is often generated when there is little demand for electricity. There are limited construction locations for tidal energy. Dams may block outlets to open water. Although locks can be installed, this is often a slow and expensive process. Large dams are needed to make the water flow through the generators. Therefore, dams affect fish migration and other wildlife; many fish like salmon swim up to the dams and are killed by the spinning turbines. Fish ladders may be used to allow passage for the fish, but these are never 100% effective. Dams may also destroy the habitat of the wildlife living near it. Dams may affect the tidal level. The change in tidal level may affect navigation, recreation, cause flooding of the shoreline and affect local marine life [4].

Generated electricity from the wave energy depends on the size of waves. Sometimes loads of energy are gained, sometimes almost nothing. The wave energy generator can cause noise pollution. It becomes a nuisance to those living close to them. Because of their large nature, wave energy generators may cause problems with commercial shipping and other boats in the ocean, according to the OSC Alternative Energy Program [5]. Boats do not able to see the generators. This could cause a potential collision hazard and pose problems for the safety of both those on board and to the wave energy generator. A collision could cause a hydraulic spill or leak and become an environmental hazard. Wave energy needs a suitable site, where waves are consistently strong. This energy must be able to withstand very rough weather. It is not a common practice to generate electricity this way so the equipment is expensive.

Despite these disadvantages of renewable energies, they are widely used all over the world. In Figure 1.1, the hydraulic energy is the mostly consumed renewable energy with 58%. Biomass and solar energies follow it. The wind energy consumption is small when compared to other source of renewable energy in 2005 [6].

The big picture is different five years later. The biomass energy is the leading one and the hydraulic energy takes the second place overall the world. For

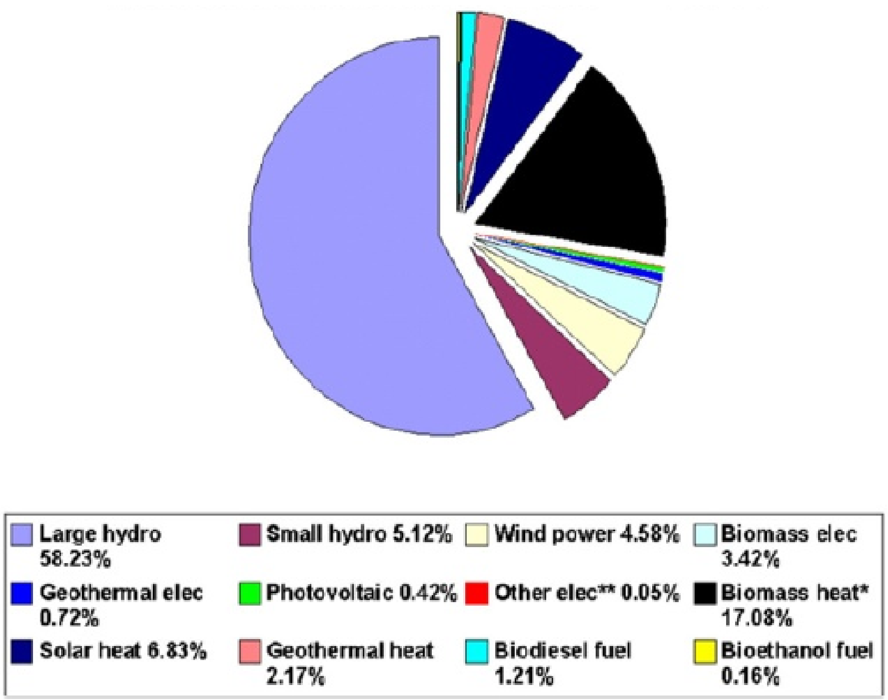

Figure 1.1: World Renewable Energy Chart 2005 [6]

example, Australia meets almost total of its required energy from biomass in 2010. The wind energy consumption increases as it is expected in Figure 1.2.

Solar energy consumption is even less than the wind energy due to its expensive cost and the limited amount of energy production as it was previously said [7] .

Wind turbines of all sizes have been developed dramatically for a wide variety of reasons, including their economic, environmental and social benefits. Economical, social and environmental advantages are presented in Sections 1.1.1 and 1.1.3 [8].

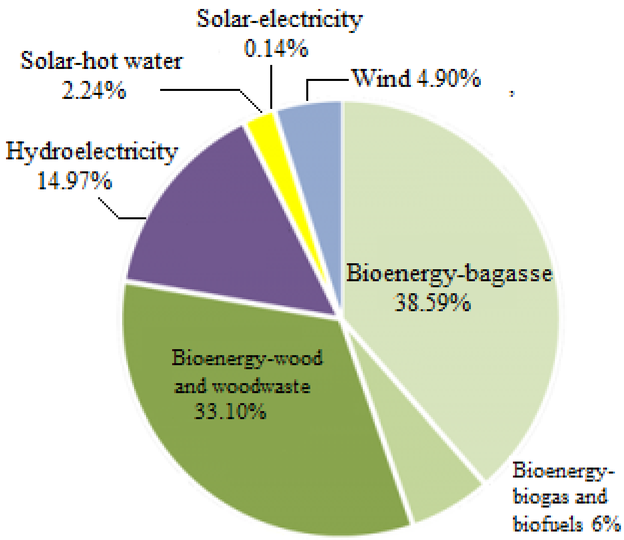

Figure 1.2: Australia Renewable Energy Consumption Chart [7]

1.1.1 Economical Advantages

Wind energy can diversify economies of rural communities, by adding a new source of property value in rural areas. This property value is attractive for the new industry. All energy systems including the wind are subsidized. However, wind receives considerably less than other forms of energy.

For the wind energy, the generating station, or wind turbine, is installed at the source of wind unlike other forms of electrical generation where fuel is shipped to a processing plant. Wind does not need to be mined or transported, thus long-term energy costs are not considered.

The cost of wind-generated electricity has fallen from nearly 30 cent per kWh in the early 1980s to 3-5 cent per kWh today depending on wind speed and project size. Wind energy projects create new short and long-term jobs. Related employment ranges from meteorologists and surveyors to structural engineers, assembly workers, lawyers, bankers, technicians, and operators. Wind energy creates 30% more jobs than a coal plant and 66% more than a nuclear plant per unit of energy generated.

1.1.2 Social Advantages

Wind turbines diversify the energy portfolio and reduce the dependence on foreign fossil fuel. Wind energy is homegrown electricity, and can help control spikes in fossil fuel costs.

A new crop rarely emerges from the thin air. Wind turbines can be installed amid cropland without interfering with people, livestock, or production. A significant contribution to the worldwide energy mix can be made by small clusters of turbines or even single turbines that are operated by local landowners and small businesses. Developing local sources of electricity means less fuel import from other states, regions, and nations.

1.1.3 Environmental Advantages

Wind energy also conserves water resources. For example, producing the same amount of electricity can take about 600 times more water with nuclear power than wind, and about 500 times more water with coal than wind. Other sources of electricity produce harmful particulate emissions that contribute to global climate change and acid rain. Wind energy production is pollution free.

Wind farms are spaced over a large geographic area, but their actual "footprint" covers only a small portion of the land resulting in a minimum impact on crop production or livestock grazing. Large buildings cannot be created near the turbine. Thus, wind farms preserve open spaces.

Despite these economical, environmental and social advantages of wind turbines, there are misconceptions with turbines. The first one is that turbines make huge noises. It is known that wind turbines are not silent. However, as turbine technology has improved over the years, the amount of noise has fallen considerably. Sounds of wind turbines do not interfere with normal activities, such as quietly talking to one's neighbor like in Figure 1.3.

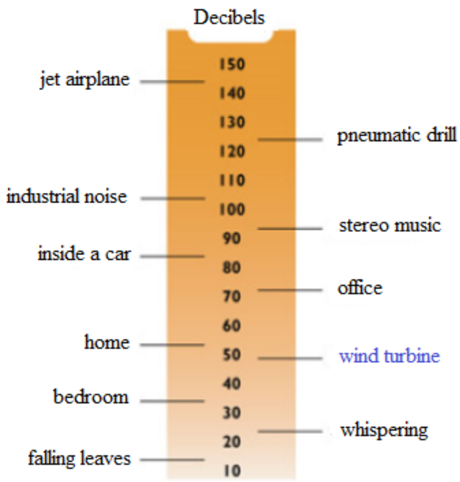

Figure 1.3: Sound Chart [9]

Another misconception about wind turbines is the wildlife habitat, especially birds. According to extensive environmental impact analysis of Erickson, wind turbines are not the dominant factors of the bird mortality in Figure 1.4.

Wind power can be a cornerstone of the sustainable energy in the future. It is affordable, provides jobs, substantial and distributed revenue, and treads lightly on the environment without causing pollution, generating hazardous wastes, or depleting natural resources. Embracing wind energy today will lay the foundation for a healthy tomorrow.

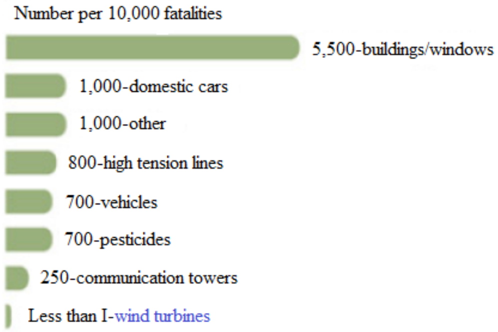

Figure 1.4: Causes of Bird Fatalities [10]

1.2 World Wind Energy Demand and Consumption

According to the half year report of 2011 of World Wind Energy Association (WWEA); the world market for wind energy saw a sound revival in the first half of 2011 and regained momentum after a weak year in 2010. The worldwide wind capacity reached 215,000 MW by the end of June 2011, out of which 18,405 MW were added in the first six months of 2011. This added capacity is 15% higher than in the first half of 2010 when only 16,000 MW were added as shown in Figure 1.5 and Figure 1.6.

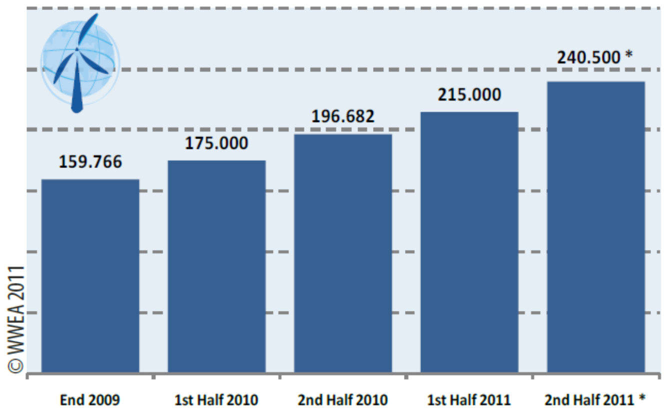

Figure 1.5: Total Installed Capacity 2010-2011 [MW] [11]

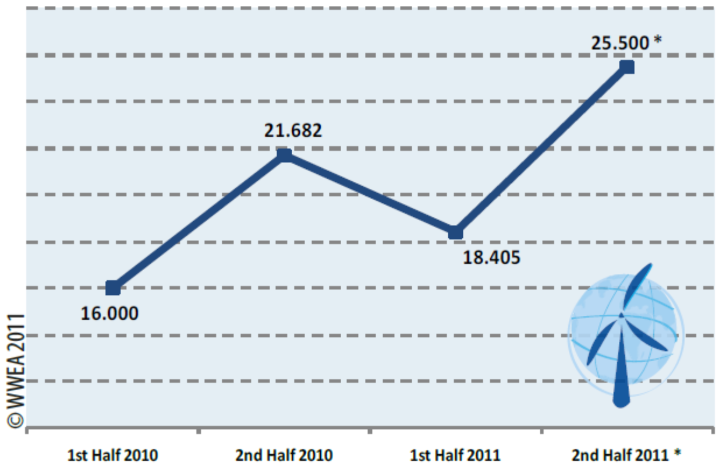

Figure 1.6: New Installed Capacity 2010-2011 [MW] [11]

Still the five leading countries stand for the main share of the world capacity of wind turbines: China, USA, Germany, Spain and India, together representing a total share of 74% of the global wind capacity.

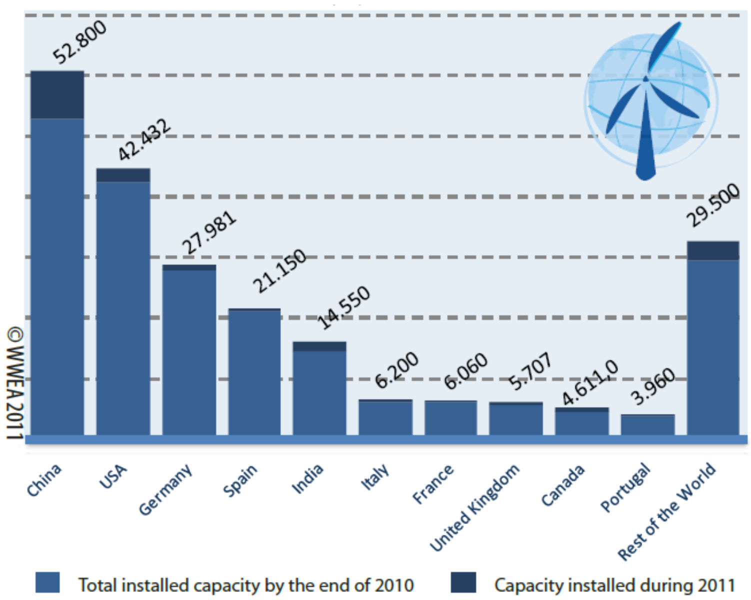

Figure 1.7: Total Installed Capacity by end of 2010 and 2011 [MW] [11]

Position	Country	Total Capacity by June 2011 [MW]	Added Capacity first half 2011 [MW]	Total Capacity end 2010 [MW]	Added Capacity first half 2010 [MW]	Total Capacity end 2009 [MW]
1	China	52.800	8.000	44.733	7.800	25.810
2	USA	42.432	2.252	40.180	1.200	35.159
3	Germany	27.981	766	27.215	660	25.777
4	Spain	21.150	480	20.676	400	19.149
5	India	14.550	1.480	13.065	1.200	11.807
6	Italy	6.200	460	5.797	450	4.850
7	France	6.060	400	5.660	500	4.574
8	United Kingdom	5.707	504	5.203	500	4.092
9	Canada	4.611	603	4.008	310	3.319
10	Portugal	3.960	260	3.702	230	3.357
	Rest of the World	29.500	3.200	26.441	2.750	21.872
	Total	215.000	18.405	196.682	16.000	159.766

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Figure 1.8: The Capacity 2010-2011 [MW] [11]

In 2011, China continues to dominate the world wind market like the previous year, adding 8 GW in only 6 months. This is the highest number ever within the first half year in Figure 1.8. For the first 6 months in 2011, China accounted for 43% of the world market for new wind turbines. However, it was 50% in the first half year of 2010.

By June 2011, China had an overall installed capacity of around 52 GW. The US market added 2,252 MW between January and June 2011, about 90% more than 1,200 MW of the weak period which is between January and June 2010. However, it is questionable whether the US market can regain the strength it had in 2009 when a total capacity of almost 10 GW higher than 25,810 MW installed capacity of China in 2009.

Most of the European markets showed stronger growth in 2011 than in the previous year. The top markets in Europe continue to be Germany with a new capacity of 766 MW and reaching a total of 27,981 MW, Spain (484 MW, 21,150 MW in total), Italy (460 MW, 6,200 MW in total), France (400 MW, 6,060 MW in total), the United Kingdom (504 MW, 5,707 MW in total) and Portugal (260 MW, 3,960 MW in total). Only France and Denmark showed a decrease in their new installed capacity compared to the first half of 2010 and Denmark even dropped out of the list of the top 10 markets, while Portugal became the new number 10.

A number of new markets are arising around the world. During the first half of 2011, three countries were added to the list of countries that are using wind energy, increasing the number from 83 to 86: Venezuela, Honduras, and Ethiopia. Also the Dominican Republic installed its first major wind farm and increased its capacity from 0,2 MW to 60,2 MW.

Within Europe, again the emerging markets in Eastern Europe showed the highest growth from January to June 2011. For example, Romania with 10% growth (59 MW added), Poland with 22% (245 MW added), Croatia with 28% (20 MW added) and Estonia with 32% (48 MW added).

In the second half of 2011, an additional capacity of 25,500 MW is expected to be erected worldwide, which would bring new annual installations to 43,905 MW, compared with 37,642 MW in the year 2010. The total installed wind capacity is projected to reach 240,500 MW by the end of this year. This capacity can cover almost 3% of the electricity demand all over the world [11].

Increasing the usage of renewable energy sources is important in Turkey and the motivation is concentrated on the wind energy because of its economical, social and environmental advantages. YEGM (Turkey's Renewable Energy General Management) designs Turkey Wind Energy Potential Map (REPA) in order to define the characteristics and distribution of the wind sources in 2006. This map provides the candidate regions which are suitable for electricity production from wind energy. It is understood that the most proper regions are coastal areas and high hills. The Aegean, the East Mediterranean and Marmara regions have high potentials for wind energy. The total potential of Turkey is 47,849 MW by considering wind speeds above the 7 m/s.

Turkey's total installed wind capacity have increased between years 1998 and 2010 as shown in Figure 1.9. Balıkesir, İstanbul, Çanakkale in Marmara region, İzmir, Manisa in Aegean region and Hatay in East Mediterranean region make the highest contributions to this installed wind capacity.

The total installed wind capacity has reached 1405,95 MW with the addition of the three new stations since May 2011. Turkey's installed wind capacity has the rank of 7 in the Europe and 17 in the Worldwide [12].

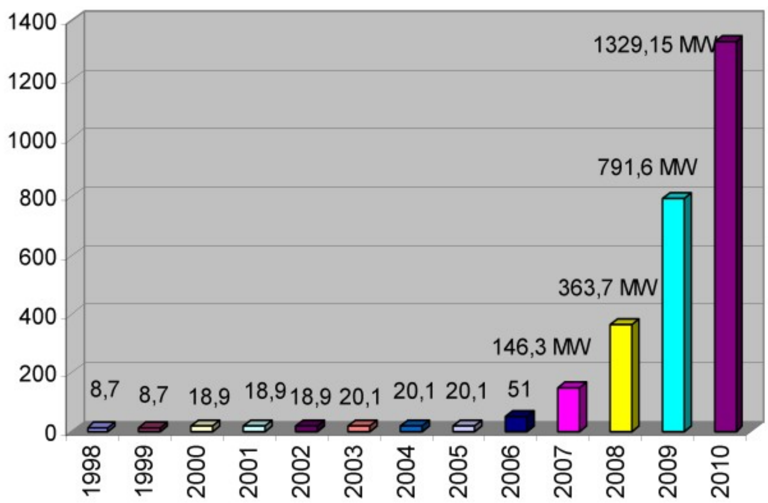

Figure 1.9: The total installed capacity of Turkey between the years 1998 and 2010 [12]

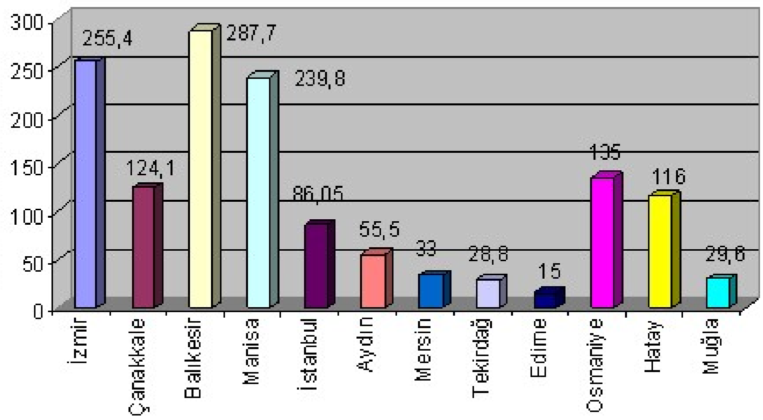

Figure 1.10: The total installed capacity of Turkey depending on the city distribution [12]

1.3 Thesis Organization and Contributions

The purpose of this thesis is to model, control and simulate a 500 KW prototype wind turbine in the context of MILRES project. The prototype turbine is designed as a variable speed variable pitch angle wind turbine due to its advantages in efficiency and structure. The modeling, control and simulation of the prototype turbine is done in both Samcef for Wind Turbine (S4WT) and Matlab/Simulink. The organization of this thesis is as follows:

In chapter II, some background information on wind turbines is presented.

In chapter III, a horizontal axis wind turbine is modeled in S4WT. This model consists of aerodynamic, mechanical and electrical subsystems. The wind that is an input to the aerodynamic subsystem is designed using Turbsim. Turbsim is a stochastic, full-field, turbulent wind simulator that uses a statistical model to numerically simulate time series of three component wind speed vectors. Wind turbine subsystems are modeled using standard components (tower, bedplate, rotor, rotor shaft, gearbox, generator and coupling shaft) of S4WT.

Chapter IV focuses on the design of pitch and torque controllers in S4WT environment. The pitch controller of the prototype turbine is designed using different control methods: Pitch function curve and PI control with gain scheduling. While the pitch function curve depends on the angular speed of rotor, PI controller with gain scheduling uses angular speed of the generator. Torque controller can also be designed in S4WT using two methods: Generator torque curve and optimal mode gain. Optimal mode gain method is utilized for torque control of the prototype turbine in S4WT.

In chapter V, the dynamic equations which belong to the aerodynamic, mechanical and electrical subsystems of the prototype turbine, are modeled in Matlab/Simulink environment. Pitch controller of the prototype turbine is designed using Proportional (P) controller in Matlab/Simulink environment. The sliding mode controller is utilized as the torque controller of the prototype turbine.

Chapter VI presents simulation results of the prototype wind turbine. The performance analysis of prototype turbine is done under the power production, start up, emergency stop, shut down and parked scenarios in S4WT. A similar analysis is also carried out under power production scenario in Matlab/Simulink environment.

Chapter VII concludes the thesis work and indicates possible future directions.

1.4 Notes

This Master Thesis work is carried out in the context of the TUBITAK (Scientific and Technological Research Council of Turkey) project "National Wind Energy Systems" under the Grant 110G010.

Publications:

- Modeling and Simulation of a Horizontal Axis Wind Turbine Using S4WT, Sanem Evren, Mustafa Unel, Omer K. Adak, Kemalettin Erbatur, Mahmut F. Aksit, International Conference on Renewable Energy Research and Applications (ICRERA), 2012 (accepted).

- Prototip Bir Rüzgar Türbininin S4WT Ortaminda Modellenmesi, Denetimi ve Benzetimi, Sanem Evren, Mustafa Unel, Omer K. Adak, Kemalettin Erbatur, Mahmut F. Aksit, TOK'12: Otomatik Kontrol Ulusal Toplantısı, 2012 (accepted).

1.5 Nomenclature

Symbol	Description
P_a	aerodynamic power
ς	air density
R	rotor radius
C_p	power coefficient
C_q	torque coefficient
λ	tip speed ratio
β	pitch angle
V	wind speed
$P_{specific}$	specific gas constant
ρ	absolute pressure
T	absolute temperature
ω_r	angular speed of turbine rotor
ω_g	mechanical angular speed of generator
ω_e	electrical angular speed of generator
T_a	aerodynamic torque
T_{ls}	torque at the low speed shaft
T_{hs}	torque at the high speed shaft
T_{em}	generator electromagnetic torque
T_g	generator torque at the low speed side
J_r	rotor inertia
J_g	generator inertia
J_t	total inertia
B_r	rotor damping
B_g	generator damping
B_t	total damping
K_r	rotor stiffness
K_g	generator stiffness
K_t	total stiffness
n_g	gearbox ratio

Symbol	Description
ψ_{ds},ψ_{qs}	d-q axis stator magnetic fluxes
ψ_{dr},ψ_{qr}	d-q axis rotor magnetic fluxes
i_{ds},i_{qs}	d-q axis stator currents
i_{dr},i_{qr}	d-q axis rotor currents
ω_s	synchronous angular speed
f_s	synchronous frequency
p	number of poles
P_s	active power
Q_s	reactive power
R_s	stator resistance
R_r	rotor resistance
L_s	stator inductance
L_r	rotor inductance
L_m	mutual inductance
K_{opt}	optimal coefficient
z	the height above ground
z_r	the reference height above ground
z_0	the roughness length
α	the wind shear exponent
f	cyclic frequency
L_K	integral scale parameter

Chapter II

2 Wind Turbines

A wind turbine is a device that converts kinetic energy of the wind to the mechanical energy and then to the electrical energy by the generators. The basic operating principle of the wind turbine is a reverse of the operating principle of fans. The wind turbines are classified as horizontal axis wind turbines and vertical axis wind turbines. These wind turbines are presented in Figure 2.1. Vertical axis wind turbines have rotor axes that are perpendicular to wind streamlines. Main components of these turbines such as gearboxes and generators are placed on the foundation. Thus, their maintenances are easier. Horizontal axis wind turbines have rotor axes that are parallel to wind streamlines. They usually have two or three blades.

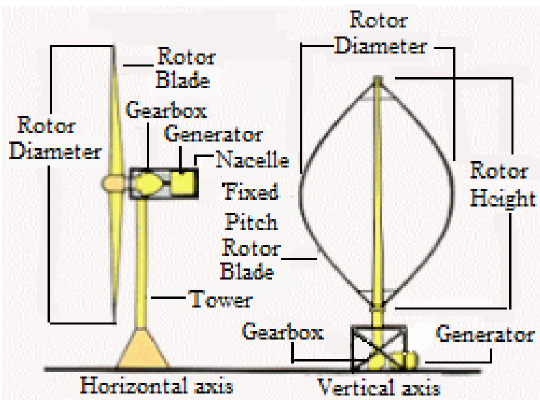

Figure 2.1: Wind turbine configuration [13]

Horizontal axis wind turbines are electromechanical systems that consist of aerodynamic subsystems, mechanical subsystems and electrical subsystems in Figure 2.2. Aerodynamic subsystems include blades and hubs. Drive trains (low speed shafts, high speed shafts, gearboxes) and brakes form mechanical subsystems. Some wind turbines do not have gearboxes; so low speed shafts are directly connected to high speed shafts. Electrical subsystems consist of generators and power converters. Generators convert mechanical power into electrical power. Towers carry wind turbines. There are nacelle mechanisms at the top of the towers. Nacelle includes the gearbox, the drive train, the generator and the controller. A yaw mechanism is a gear mechanism and it can turn the wind turbine depending on the wind direction. Thus, mechanical power extraction from the wind can be increased.

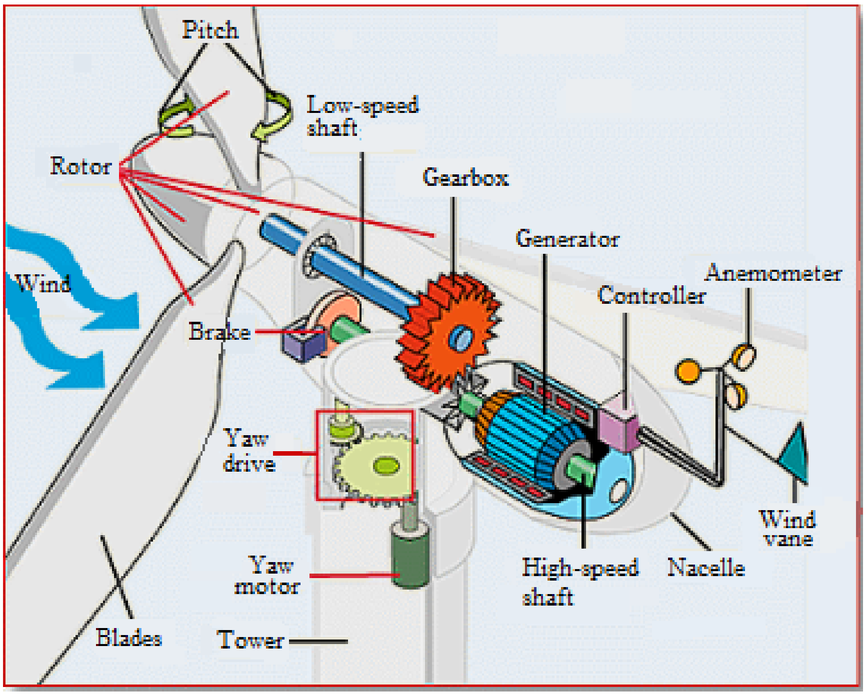

Figure 2.2: The horizontal axis wind turbine [14]

2.1 Wind Turbine Classification and Ideal Power Curve

Wind turbines have different operating principles. They can be designed to be either constant-variable speed or constant-variable pitch angle wind turbines. Consequently, wind turbines are classified as follows:

- Constant Speed Constant Pitch Angle Wind Turbines
- Constant Speed Variable Pitch Angle Wind Turbines
- Variable Speed Constant Pitch Angle Wind Turbines
- Variable Speed Variable Pitch Angle Wind Turbines

The wind turbine capacity is related to the maximum power captured from the wind. The main control purpose of wind turbines is to maximize energy efficiency. However, the wind turbine must also be protected from excessive loads at different wind speeds. To achieve this goal, generated power should be close to the ideal power curve that depicts the optimum energy gathering from the wind depending on the wind speed. All the wind turbines have their own ideal power curves. A typical power curve for the wind turbine is presented in Figure 2.3. The ideal power curve has two operating regions depending on the wind speeds:

- Partial load operating region : The operating region with the wind speeds below the nominal value
- Full load operating region : The operating region with the wind speeds above the nominal wind speeds

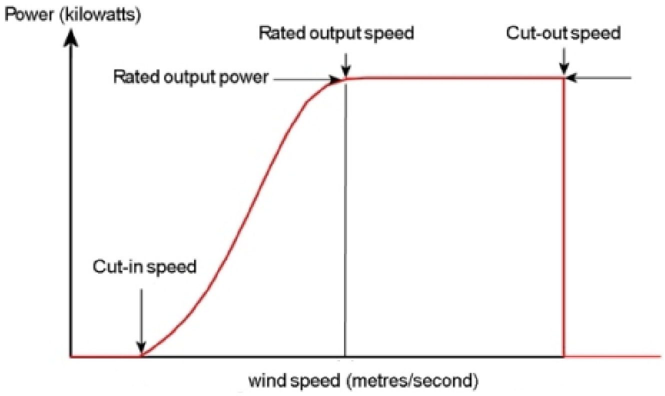

Figure 2.3: Ideal Power Curve

The wind turbine starts to produce electrical energy at cut-in wind speed. The goal at the partial load region is to increase power efficiency and reach the nominal (rated) power at the nominal wind speed. to achieve this, torque control is needed. Above the nominal wind speed, the wind turbine is exposed to aerodynamic loads and it begins to operate at the full load region. The mechanical power captured from the wind must be limited to the nominal power by using pitch controllers. When the wind speed reaches cut-out wind speed, the wind turbine must be shut down since loads become excessive.

2.2 Control of Wind Turbines

A wind turbine control system consists of pitch and torque controllers [15]-[16]. A pitch actuator mechanism is used to physically turn blades around their longitudinal axes [17]-[18]. At low wind speeds, the control system will use this feature to maximize energy extracted from the wind. At high wind speeds, the power can easily be limited to its nominal value by adjusting the pitch angle. Pitch control methods are [19]:

- Passive stall
- Active stall
- Pitch to feather

Passive stall controlled wind turbines have rotors firmly attached to hubs at fixed angles. In the passive stall control method, the pitch angle is always constant, no mechanism is required to turn the blades around their axes. The mechanical power is limited by changing the pitch angle. The pitch angle can be increased or decreased. If it is increased, the method known as pitch to feather is implemented. If the pitch angle is decreased, active stall method is implemented.

Torque control methods of variable speed wind turbines are presented in [20]. A new adaptive torque controller that is designed by NREL (National Renewable Energy Laboratory) to resemble the standard non-adaptive controller used by the wind industry for variable speed wind turbines below the nominal power [21].

All wind turbine have different control techniques at the partial and full load operating regions.

Constant speed constant pitch angle wind turbines do not have any torque control because the generator speed is fixed. Pitch angles are stall regulated (Passive Stall control method). These type of wind turbines cannot generate the nominal power. Therefore, the efficiency of the constant speed constant pitch angle wind turbine is low.

Constant speed variable pitch angle wind turbines also do not have torque control; so the efficiency below the nominal wind speed is low. On the other hand, this turbine has high efficiency above the nominal wind speed because of the pitch control. The pitch control increases the efficiency by using Active Stall or Pitch to Feather control method.

Variable speed constant pitch angle wind turbines have the torque control at the partial load operating region so their efficiencies can be increased below the nominal wind speed. However, this turbine type has low efficiency at the full load operating region since it becomes stall regulated [22].

In light of above discussions, wind turbines should be designed as variable speed constant pitch angle wind turbines below the nominal wind speed and as constant speed variable pitch angle wind turbines above the nominal wind speed. However, the pitch actuator dynamics change slowly; so the torque control is needed above the nominal wind speed. As a result, wind turbines should be variable speed variable pitch angle.

At the partial load operating region, pitch angle of the variable speed variable pitch angle wind turbine is kept constant at zero degree. The generator torque is controlled to operate the wind turbine with a maximum power coefficient, C_{pmax}. An optimal *tip speed ratio* (the ratio of the rotational speed of the blade tip to the actual wind speed) is held constant to protect C_{pmax}. Therefore, the wind turbine gains maximum power between V_{cutin} and V_n wind speeds.

At the full load operating region, the maximum energy is limited to the nominal value, P_n between V_n and V_{cutoff} wind speeds using pitch to feather control method. Thus, the wind turbine is protected from excessive loads. The torque control is also used due to the slow pitch mechanism.

2.3 Electrical Machines used in Wind Turbines

In literature, constant speed and variable speed wind turbines differ not only in their efficiencies but also in their structures [23]-[24]. These turbines are variable pitch wind turbines due to low efficiencies of constant pitch wind turbines. Therefore, wind turbines are divided into three depending on the structure as shown in Figure 2.4:

- The constant speed variable pitch angle wind turbine with SCIG
- The variable speed variable pitch angle wind turbine with DFIG
- The variable speed variable pitch angle wind turbine with PMIG

The constant speed wind turbine consists of a directly grid coupled squirrel cage induction generator (SCIG). The wind turbine rotor is coupled to the generator through the gearbox. The rotor is designed in such that its efficiency decreases at high wind speeds. Active power control is not used because there is not any torque control.

Variable speed wind turbines are divided into two; a variable speed wind turbine with doubly fed induction generator (DFIG) and a variable speed wind turbine a direct drive synchronous generator (PMSG). The variable speed wind turbine with DFIG has a stator that is directly coupled to the grid. However, a rotor of the generator is coupled to the power converters.

The variable speed wind turbine with PMSG has a stator and rotor which are coupled directly to the grid via power converters; back to back voltage source converters. The synchronous generator is excited using permanent magnets. The modeling and control of variable speed wind turbines with permanent magnet synchronous generators are presented in [25]-[28].

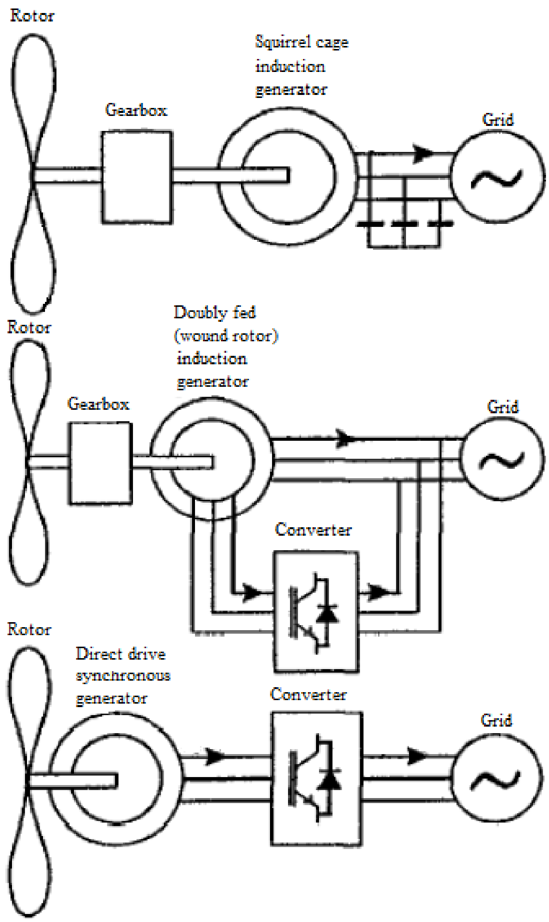

Figure 2.4: Different Wind Turbines [29]

All wind turbines share one important characteristic; the generated power depends on the wind speed. In literature, there are some important differences in the grid connection of constant and variable speed wind turbines [29]-[31]. These differences come from the fact that although variable speed wind turbines have power electronics, constant speed wind turbines do not. The first difference is that constant speed wind turbines do not have energy buffers. Therefore, any change in the wind speed is immediately reflected in the generated power. However, variable speed wind turbines have power electronics which control the generated power based on the actual value of the electrical speed of the generator rotor.

The second difference between constant and variable speed wind turbines is their interaction between grid. A constant speed wind turbine contains a squirrel cage induction generator of which the stator is directly grid coupled. Therefore, electrical properties and mechanical properties propagate to stator terminals and this leads to a harmful effect on the generated power. If a fault occurs, the generator speeds up because of the unbalance between electrical and mechanical powers.

Electrical and mechanical properties of variable speed wind turbines are controlled by power electronics. When a fault occurs, the generated power will not be badly affected. Wind turbines can be disconnected from the grid. Depending on the control algorithm, they can be very quickly reconnected when voltage recovers. During the fault, they accelerate and the rotor speed is controlled by changing the pitch angle of blades. These advantages make variable speed wind turbines more preferable than constant speed wind turbines.

Variable speed wind turbines with DFIG have power electronic converters that use a rating of only about one third of the nominal power of the wind turbine. However, the gearbox is still necessary so this may decrease the reliability. The gearbox is not required for variable speed wind turbines with PMSG. This advantage must be paid for by the disadvantage of a larger power electronic converter and a more complicated and expensive generator.

Chapter III

3 Wind Turbine Model Components in S4WT

The wind turbine has aerodynamic subsystem, mechanical subsystem, electrical subsystem, pitch controller and torque controller. The overall block diagram is presented in Figure 3.1. Wind profiles are modeled in Section 3.1. The wind turbine components which are belong to the aerodynamic, mechanical and electrical subsystems are described in Section 3.2.

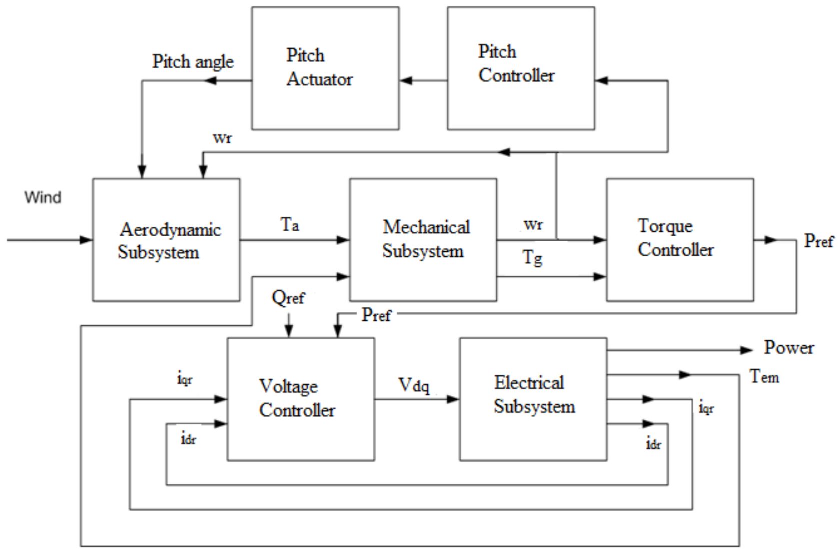

Figure 3.1: Wind turbine block diagram

3.1 Wind Profile Models in S4WT

The wind profile which is an input of the system in Figure 3.1, can be modeled as constant wind speed or turbulent wind speed. There isn't any limitation on wind data since the external inputs can also imported to the wind model.

3.1.1 Constant wind speed profile

The constant wind blows at a constant rate as shown in Figure 3.2. It has components in three axial directions. This type of wind varies in space, but, not in time because of the wind shear coefficient. Wind shear is the variation of the wind speed across a plane perpendicular to the wind direction.

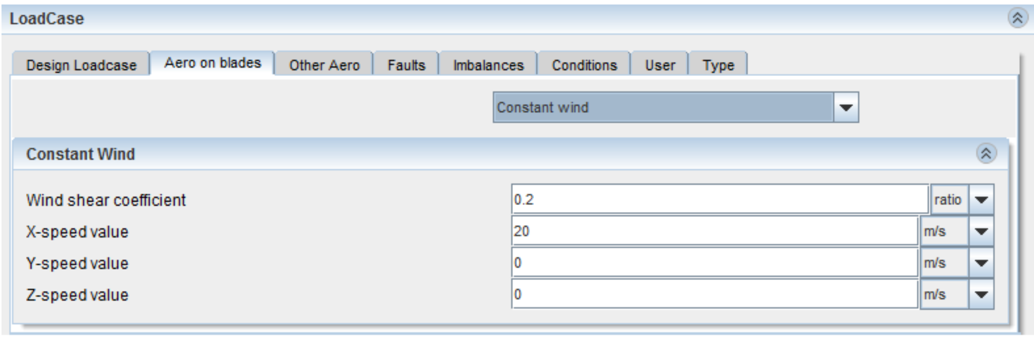

Figure 3.2: The constant wind speed

Mathematical expression for assumed wind speed variation with height above ground can be derived by the logarithmic form in Equation (1) and the power law in Equation (2).

$$V(z) = V(z_r)\frac{\ln(z/z_0)}{\ln(z_r/z_0)} \tag{1}$$

$$V(z) = V(z_r)(\frac{z}{z_r})^{\alpha} \tag{2}$$

where z is the height above ground, $V(z)$ is the wind speed at height z, z_r is a reference height above ground used for fitting the profile, z_0 is the roughness length, α is the wind shear (or power law) exponent. Wind shear coefficient is calculated using Equation (2) in S4WT.

3.1.2 Turbulent Wind Generator/TurbSim

S4WT can be integrated with TurbSim using the Turbulent Wind Generator panel in S4WT. TurbSim is a stochastic, full-field, turbulent-wind simulator. It uses a statistical model to numerically simulate time series of three-component wind-speed vectors at points in a two-dimensional vertical rectangular grid that is fixed in space.

TurbSim can set the spectral model to simulate, determines the mean wind speeds, and sets the boundary conditions for the spectral models defined in the IEC standards. The spectral models are: Kaimal, Von karman, The Risø Smooth-Terrain Model, The NREL National Wind Technology Center Model, The NREL Great Plains Low-Level Jet Model, The NREL Wind Farm, Upwind Model, The NREL Wind Farm, Downwind Model (14 Rotor Diameters), The NREL Wind Farm, Downwind Model (7 Rotor Diameters). The details about these models are given in [32] except the Kaimal Spectrum Model.

The Kaimal spectra for the three wind components, K = u, v, w, are given by

$$S_K(f) = \frac{4{\sigma_k}^2 L_K/\overline{u}_{hub}}{(1+6fL_K)/\overline{u}_{hub}} \tag{3}$$

where f is the cyclic frequency and L_K is an integral scale parameter.

The IEC 61400-1 standard defines the integral scale parameter to be

$$L_K = \begin{cases} 8.10\Lambda_u & , \quad K = u \\ 2.70\Lambda_u & , \quad K = v \\ 0.66\Lambda_u & , \quad K = w \end{cases} \tag{4}$$

where the turbulence scale parameter, Λ_u, is shown in Equation (5). The relationships between the standard deviations are defined in in Equations (6)-(7).

$$\Lambda_u = 0.7 \min(60m, Hub_{Ht}) \tag{5}$$

$$\sigma_v = 0.8\sigma_u \tag{6}$$

$$\sigma_w = 0.5\sigma_u \tag{7}$$

The other required parameters related with IEC standards are the wind speed at the reference height, Ref_{Ht}, and the mean streamwise wind speed at the reference height, U_{ref}. Ref_{Ht} specifies the height (in meters) of the corresponding reference wind speed. This parameter enables to specify the mean wind speed at a height other than the hub height. U_{ref} parameter is the mean value that is calculated based on the time length of the simulation of the u-component wind speed.

The wind turbine classification offers a range of robustness clearly defined in terms of the wind speed and turbulence parameters. Table 3.1 specifies the basic parameters, which define the wind turbine classes. The parameter values apply at hub height and V_{ref} is the reference wind speed average over 10 min. A designates the category for higher turbulence characteristics, B designates the category for medium turbulence characteristics, C designates the category for lower turbulence characteristics. I_{ref} is the expected value of the turbulence intensity at 15 m/s.

Table 3.1: Basic parameters for wind turbine classes

Wind Turbine Class	I	II	III
V_{ref} (m/s)	50	42.5	37.5
A I_{ref}	0.16	0.16	0.16
B I_{ref}	0.14	0.14	0.14
C I_{ref}	0.12	0.12	0.12

A wind turbine shall be designed to safely withstand the wind conditions defined by the selected wind turbine class. The wind regime for load and safety considerations is divided into the normal and extreme wind conditions. Normal wind conditions occur frequently during normal operation of a wind turbine. Extreme wind conditions are defined as having 1-year or 50-year recurrence periods. S4WT uses normal turbulence models from normal wind conditions. For the normal turbulence model, the value of the turbulence standard deviation, σ_1, given by Equation (8);

$$\sigma_1 = I_{ref}(0.75V_{hub} + b) \tag{8}$$

where $b = 5.6m/s$. Values for the turbulence standard deviation σ_1 and the turbulence intensity $\frac{\sigma_1}{V_{hub}}$ are shown in Figures 3.3-3.4. The values for I_{ref} are given in Table 3.1. The details about extreme wind conditions are presented in [33].

The wind profile that is designed for prototype turbine is presented in Table 3.2. This wind profile is used in both S4WT and Matlab/Simulink environments.

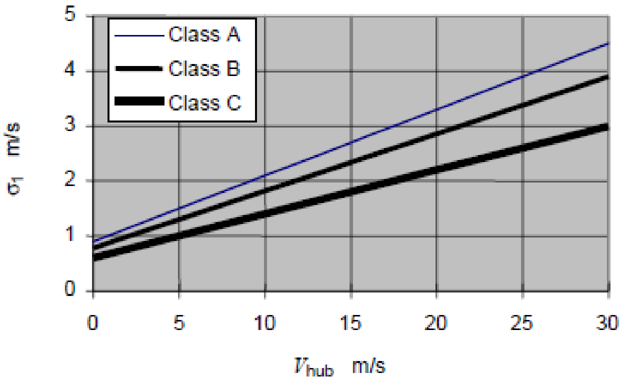

Figure 3.3: Turbulence standard deviation for the normal turbulence model (NTM) [33]

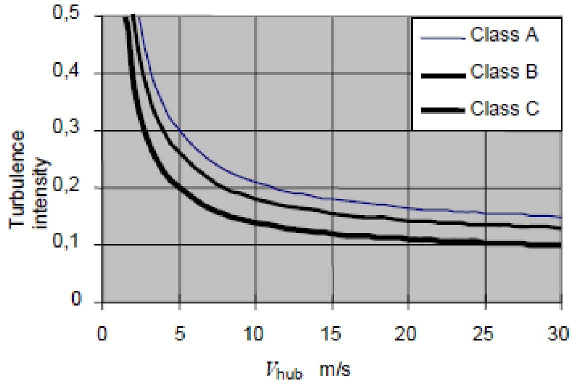

Figure 3.4: Turbulence intensity for the normal turbulence model (NTM) [33]

3.2 Wind Turbine Components in S4WT

S4WT is a tool that provides engineers with an easy access to detailed linear and nonlinear analysis of all relevant wind turbine components. The basic goal of S4WT is to construct a model of a wind turbine from basic components, to connect these together, to assign engineering parameters to the model and then to analyze the model with these parameter values. The basic

Table 3.2: The generated wind profile for prototype turbine

Turbulence model	Kaimal
Wind speed at the reference height	11 m\s for full load operating region 7 m\s for full load operating region
Height of the reference speed	63.5 m
IEC turbulence type	Normal Turbulence
IEC wind turbine class	1
IEC turbulence class	A

wind turbine components are tower, bedplate, blades, gearbox, rotor shaft, nacelle, generator and generator shaft. Aerodynamic, mechanical and electrical subsystems of the wind turbine can also be modeled in S4WT using these components as shown in Figure 3.5. Different wind turbine models can be designed in S4WT:

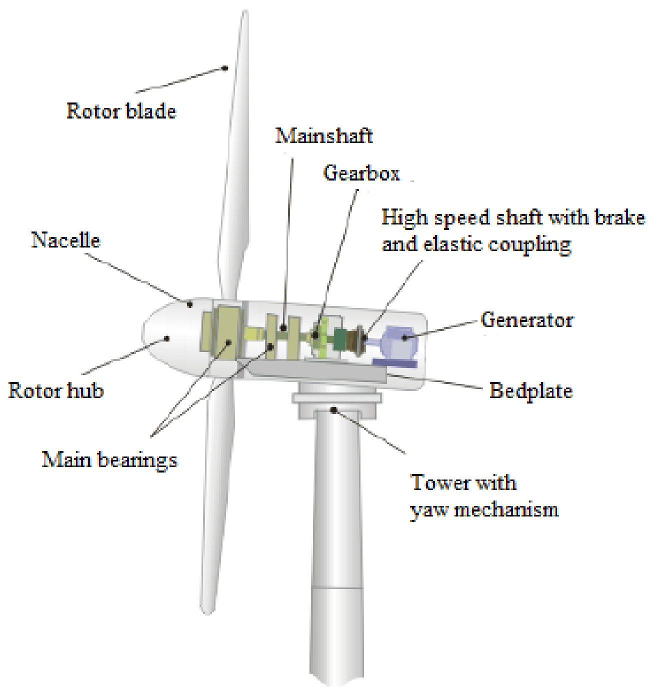

Figure 3.5: Components of the wind turbine [34]

- Simplified Parametric Model
- Standard Parametric Model
- Sample SField Model
- SField Model
- Super Element Model
- Advanced Bacon Model

Simplified and standard parametric models have predefined simple and standard components. In addition to the components that are available in the predefined families, it is possible to add external components to a model. These external components must have been previously defined and be available as a Samcef super element or a model created in Samcef Field (SField). SField model and super element models are examples of this. Also, S4WT uses the bacon language. It is possible to create the wind turbine model with bacon language and this model is called advanced bacon model. Custom creation is also available for designing wind turbines in S4WT. The detailed information on all these models can be found in the Samcef documentation [34].

3.2.1 Tower

The tower component consists of the supporting tower, its foundation and the yaw mechanism. The following tower models are available in S4WT:

- Standard Tower
- Simple Tower

Bottom of the tower is connected to the foundation and the top of the tower is connected to the bedplate. The standard tower is composed of a segmented tower, which is available in two heights; 90 m and 120 m. Towers with different heights can also be designed by changing dimensions of flanged segments. The following data is required for two types of parametric segmented towers:

- The geometry of the tower segments
- The material properties of the segments
- The geometry of the top flange
- The characteristics of the yaw mechanism
- The elastic properties of the foundation

The tower is composed of a number of segments, which includes the bottom flange as shown in the Figure 3.6. There are no limitations on the number of segments in S4WT. The top flange is defined separately.

The lowest point is assumed to be ground level, i.e. this lowest segment does not include the foundations. Data required for top flange is given in Figure 3.7. All segments of the tower are assumed to be made of the same material in Table 3.3. Simple clamp method is used for connecting the tower to its foundation. In this method, the base of the tower is fixed rigidly to the foundation.

The simple tower is composed of a single component, the tower. The simple tower is represented as a single geometrical entity. Dimensions of the simple tower are given in Figure 3.8. The material parameters of the simple tower are the same with the standard tower.

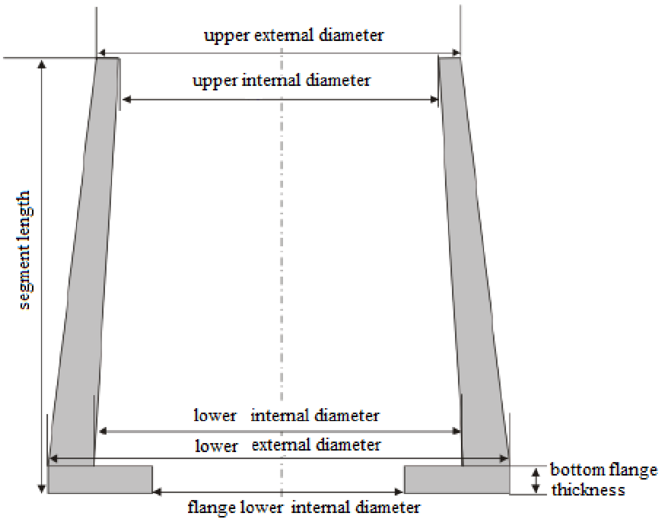

Figure 3.6: Dimensions of flanged segments

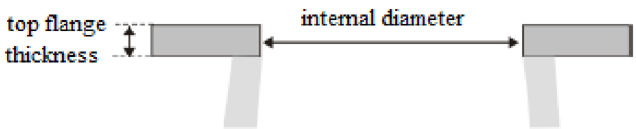

Figure 3.7: Dimensions of the top flange

Table 3.3: The tower material

The density of the material
Young's modulus
Poisson's ratio
Damping

The prototype tower is designed using the standard tower in Figure 3.9. The height of the prototype tower is 63.5 m and it has three segments. Segment order goes from top (0) to bottom (2). Segment(0) has a length of 18.7 m, segment(1) and segment(2) are 22.4 m long. The diameters of the prototype turbine segments are shown in Figures 3.10-3.12.

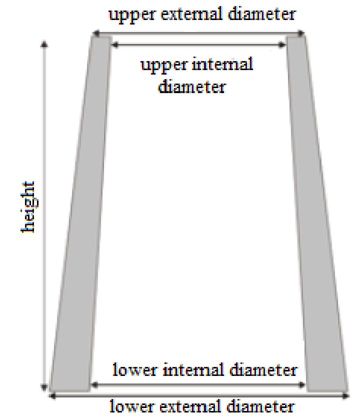

Figure 3.8: Dimensions of the tower SE

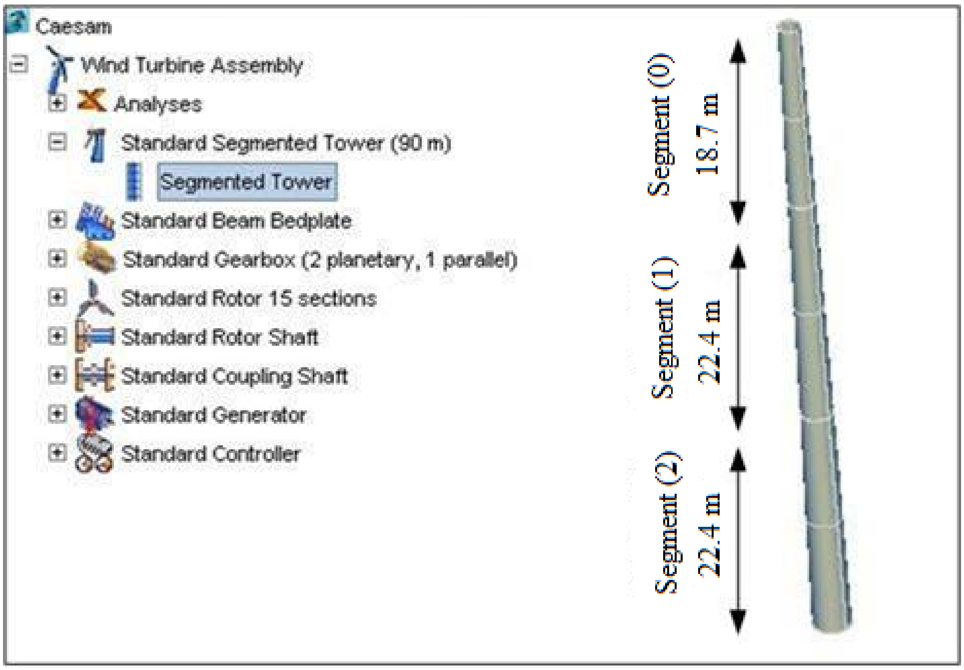

Figure 3.9: The prototype turbine in S4WT

The prototype tower is made up of steel $S235$ and the material data is presented in Figure 3.13. The top flange has an internal diameter of 2.076 m and a thickness of 0.06 m in Figure 3.14.

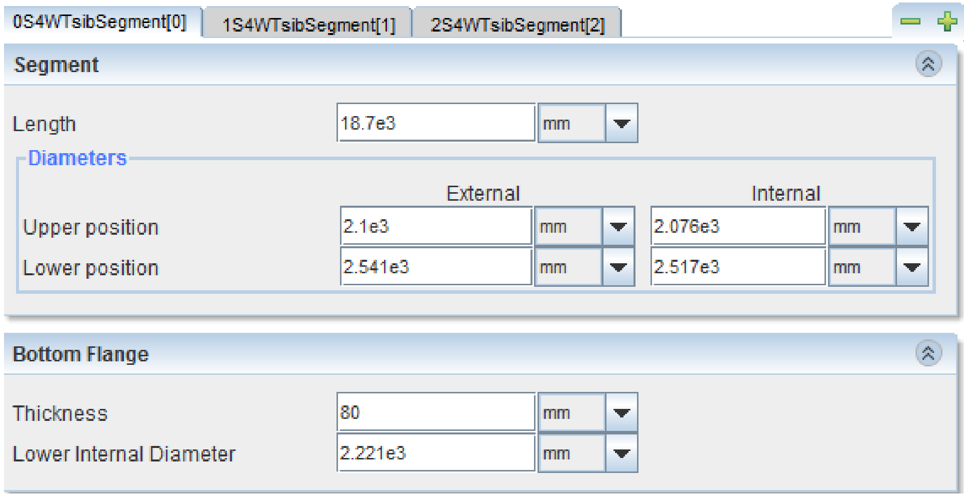

Figure 3.10: The segment(0) geometry of the prototype turbine

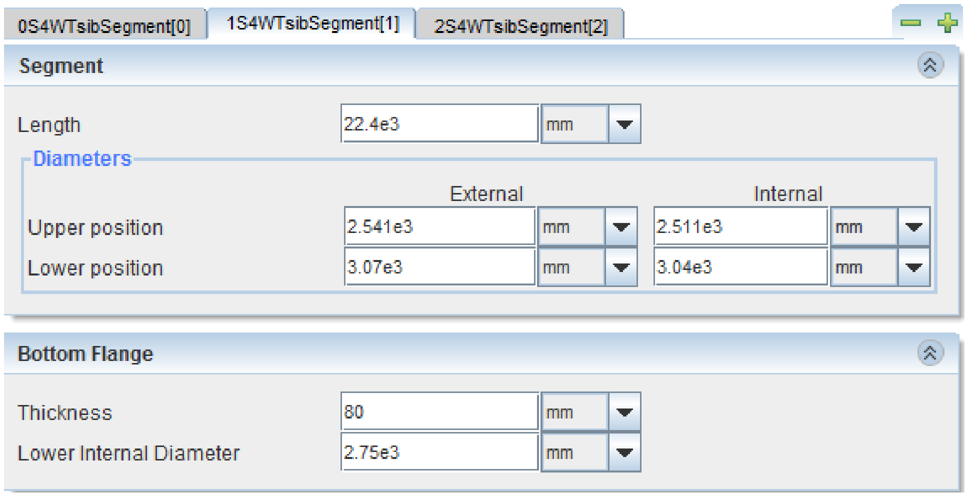

Figure 3.11: The segment(1) geometry of the prototype turbine

3.2.2 Bedplate

The bedplate is the structure that provides support for the main rotor bearings, the torque arms in the gearbox housing (yokes) and the generator frame. The bedplate is connected to the tower, the rotor shaft, the gearbox and the generator.

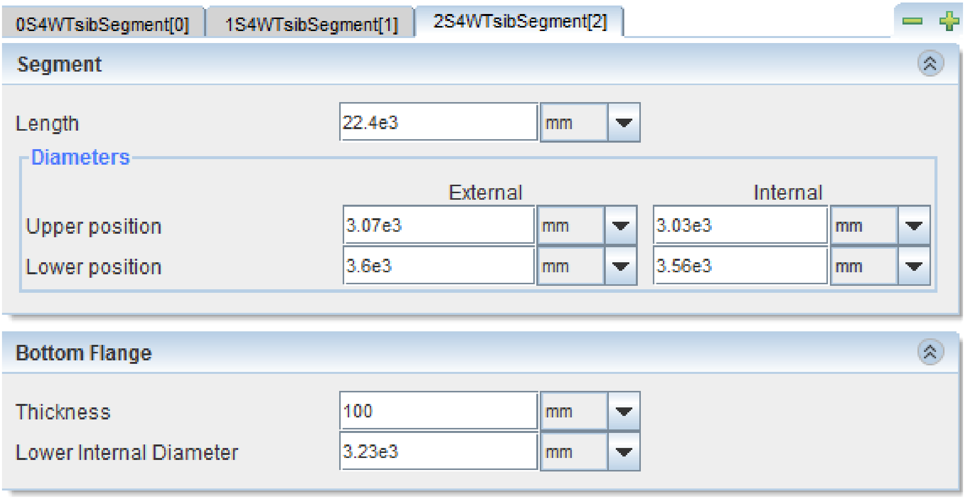

Figure 3.12: The segment(2) geometry of the prototype turbine

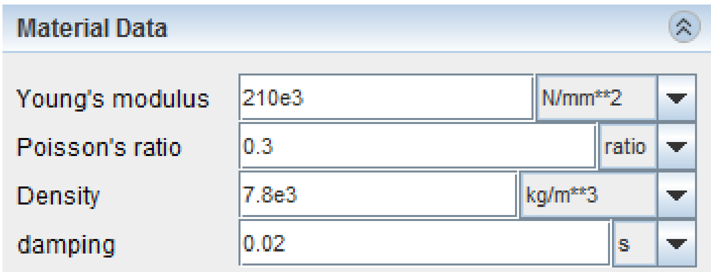

Figure 3.13: The material data of the prototype turbine

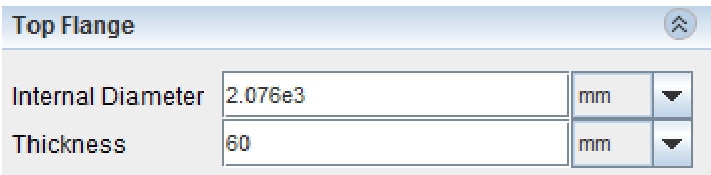

Figure 3.14: The top flange geometry of the prototype turbine

The following bedplate models are available in S4WT:

- Standard Bedplate
- Simple Bedplate

Standard bedplate is defined using two components; the bedplate and the yokes supporting the gearbox torque arms in Figure 3.9. Three levels are defined relative to a chosen reference (0). Dimensions are defined in a direction perpendicular to the rotor axis (not vertical). The levels are indicated in Figure 3.15:

- Rotor Axis Level: The axis of the rotor
- Tower Yaw Level: The centre of the top of the tower (yaw mechanism)
- Yokes Level : Level to the axis of the arms in the yokes.
- Generator Support Level : The level of the generator support.

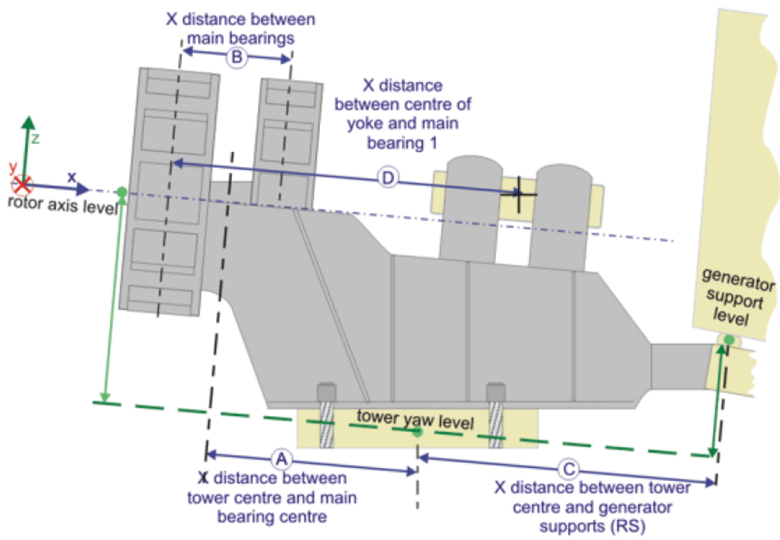

Figure 3.15: Bedplate levels

The simple bedplate is composed of a single component, the bedplate. The prototype bedplate is designed using the standard bedplate in Figure 3.16. The prototype turbine has one main bearing.

The parameters which are related to the levels of the prototype turbine, are presented in Figures 3.17.

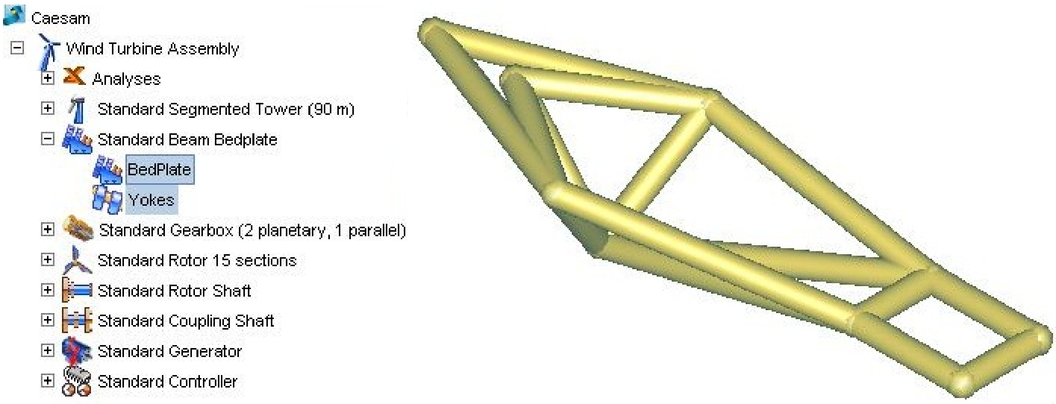

Figure 3.16: The prototype bedplate in S4WT

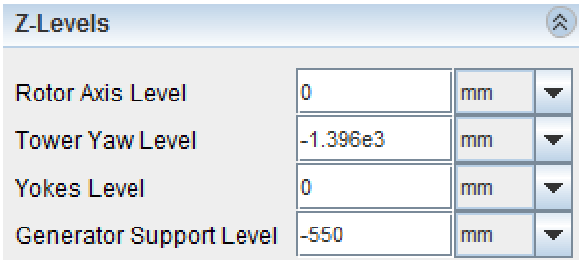

Figure 3.17: The levels of the prototype bedplate

3.2.3 Gearbox

The following gearbox models are available in S4WT:

- Standard Gearbox
- Simple Gearbox

The standard gearbox is composed of three (planetary and helical) stages. The following configurations can be designed:

- two planetary stages and one helical stage
- one planetary stage and two helical stages (two versions A and B are provided with slightly different dimensions)

Depending on the selected combination, the definition of the required parameters can vary to some extent. Each gearbox model has the housing stage which is related with the connection point of the casing to the bedplate yokes. The planetary stages are composed of the fixed outer gear wheel, the planets gears and the sun gear. The planet gears rotating about the sun gear are shown in Figure 3.18. The helical stage is defined including input and output gear wheels. The number of teeth on the sun gears, planet gears and fixed wheel gears of both planetary stages and the number of teeth on the input and output gear wheels define the gearbox (reduction) ratio.

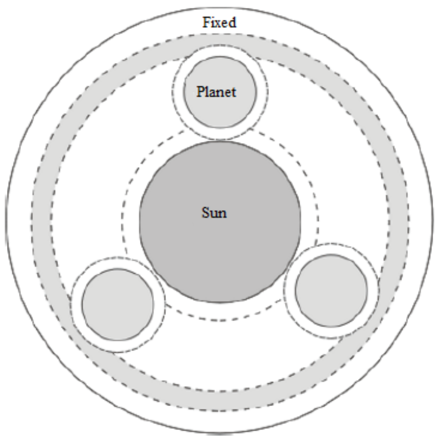

Figure 3.18: Sun, planets and fixed gears in the planetary system

The simple gearbox can be used as a part of a simple model in S4WT. The simple gearbox has two components; the housing and the gears. The global signed reduction ratio of the gears component is the value for the overall reduction performed by the gearbox. This should be a positive value if shafts are rotating in the same direction and negative if shafts are rotating in opposite directions.

The prototype gearbox is designed using the standard gearbox with two planetary and one helical stages. The prototype gearbox has four components; the housing stage, two planetary stages and a helical stage in Figure 3.19. Both planetary stage 1 and 2 have three planet gears around the sun gear. Teeth numbers of all stages are presented in Figures 3.20-3.22. The prototype gearbox has the reduction ratio of 33.5.

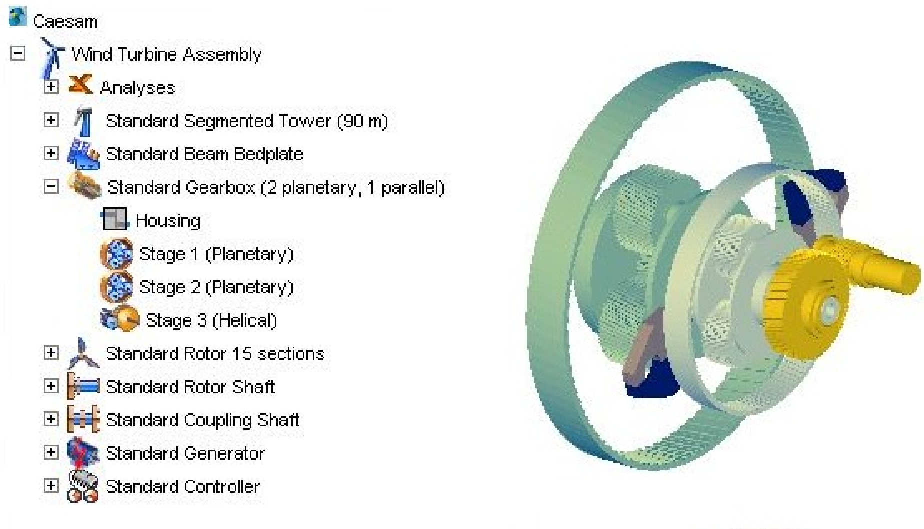

Figure 3.19: The prototype gearbox in S4WT

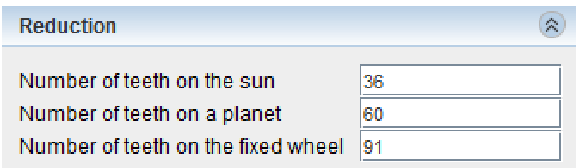

Figure 3.20: The gearbox ratio of the planetary stage 1 of the prototype gearbox

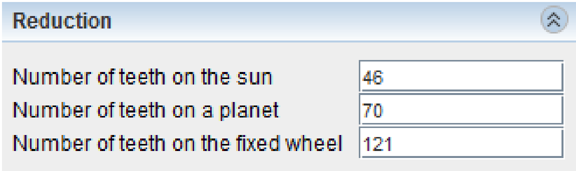

Figure 3.21: The gearbox ratio of the planetary stage 2 of the prototype gearbox

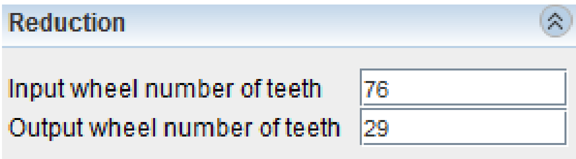

Figure 3.22: The gearbox ratio of the helical stage of the prototype gearbox

3.2.4 Rotor Blades

The rotor component consists of three rotating blades. When defining geometric dimensions of a wind turbine, the geometry of the rotor assembly is assumed to be defined in the system shown in Figure 3.23. The parameters of chord and pitch in Figure 3.24 are related to the blades. The chord is the characteristic length of the section between the leading and the trailing edges. The pitch is the angle of rotation of the complete blade.

The following rotor blades models are available in S4WT:

- Standard Rotor
- Simple Rotor Blade

Standard rotor consists of the rotor blades. It is assumed that three identical rotor blades are used. Two standard rotor models are provided; one with seven predefined sections and one with fifteen predefined sections. The standard rotor has a single component; the blades.

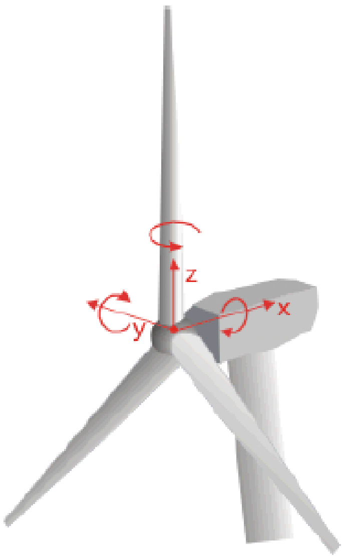

Figure 3.23: Coordinate system of the rotor assembly

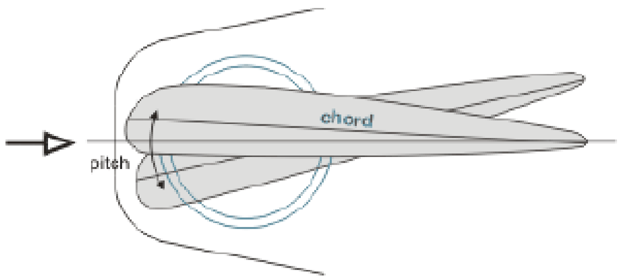

Figure 3.24: Blade parameters

The blade is divided into a number of sections upon which the aerodynamic loads are applied. The section with the lowest number is next to the pitch mechanism and the one with the highest is at the tip.

Each section has the parameters in Table 3.4. Moment, drag and lift coefficients are defined as functions of the angle of attack. It is the angle between the chord and the relative wind direction. The mechanical properties of the rotor are defined with blade data and blade material.

Table 3.4: Aerodynamic parameters of blades

Chord length	the (average) length for the line joining the leading edge to the trailing edge as shown in Figure 3.25
Twist angle	this is the angle about which the chord of the section is rotated relative to the tip (which is at 0 degrees) in Figure 3.25
Moment, Drag and Lift coefficient functions	The orientation of these functions is shown in Figure 3.26

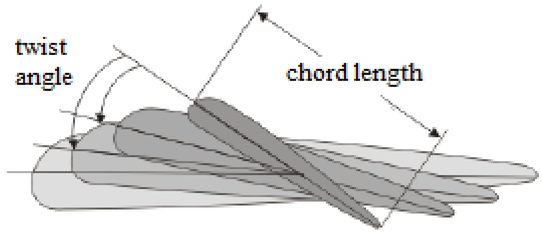

Figure 3.25: Chord length and angle of twist

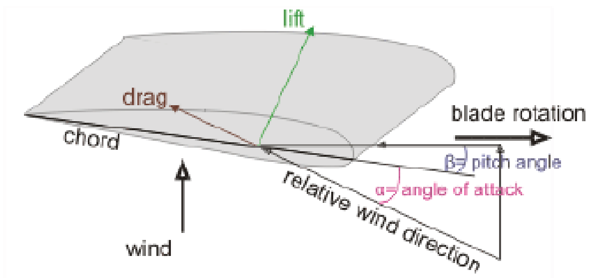

Figure 3.26: Aerodynamic orientations

Blade data includes the blade length, rotor conicity and hub diameter. Blade length is the length of the blade, from the pitch mechanism flange to the tip. Rotor conicity is the angle that the blades make with the vertical plane. Young's coefficient, Poisson's coefficient, density and damping define the blade material data.

The parameters used to define the simple rotor blade are exactly the same as the standard one. The simple rotor blade contains only four predefined sections.

The prototype rotor is designed using the standard rotor with 15 sections in Figure 3.27. Each blade length is 21.5 m and rotor diameter is 45 m. The blade has 15 sections with the aerodynamic data given in the Figure 3.28. The mechanical properties and material data are given in Figures 3.29-3.30.

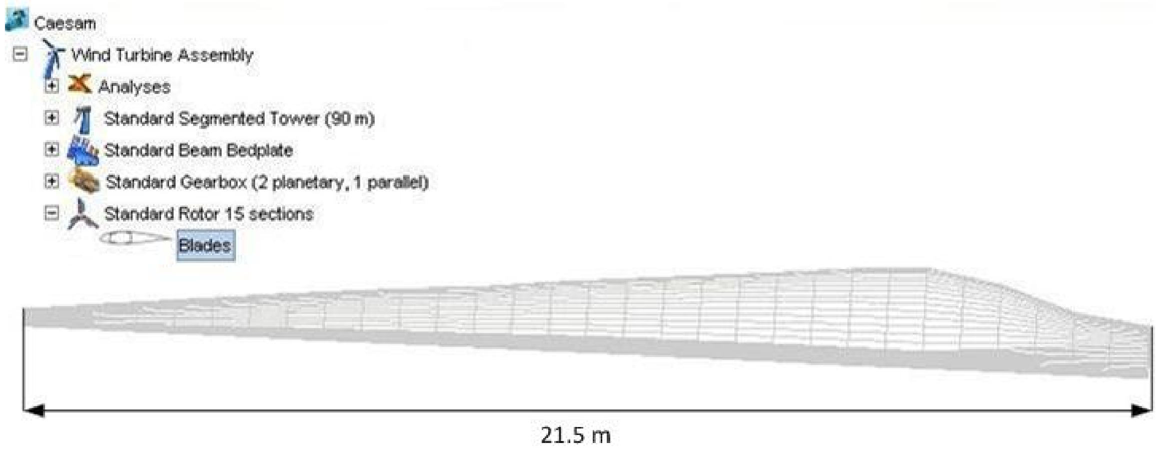

Figure 3.27: The prototype rotor in S4WT

3.2.5 Rotor Shaft

The rotor shaft has components including the hub, main bearings and the shaft itself. The following rotor shaft models are available in S4WT:

- Standard Parametric Rotor Shaft
- Simple Rotor Shaft

There are two types of standard rotor shafts depending on the number of main bearings. The rotor shaft can have one or two main bearings.

	Twist Angle	Chord Length
1	-20 deg	1.215 m
2	-20 deg	1.725 m
3	-20 deg	1.99 m
4	-16.661 deg	1.948 m
5	-12.28 deg	1.855 m
6	-9.135 deg	1.753 m
7	-6.834 deg	1.641 m
8	-5.22 deg	1.519 m
9	-3.991 deg	1.338 m
10	-3.038 deg	1.247 m
11	-2.226 deg	1.097 m
12	-1.504 deg	0.937 m
13	-0.861 deg	0.767 m
14	-0.326 deg	0.589 m
15	0 deg	0.4 m

Figure 3.28: The aerodynamic properties of the prototype rotor

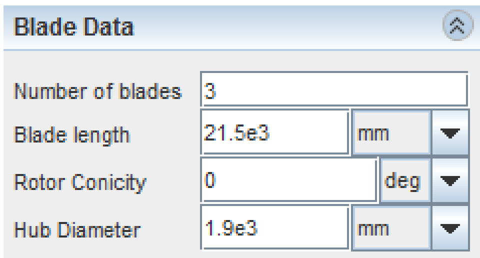

Figure 3.29: The mechanical properties the prototype rotor

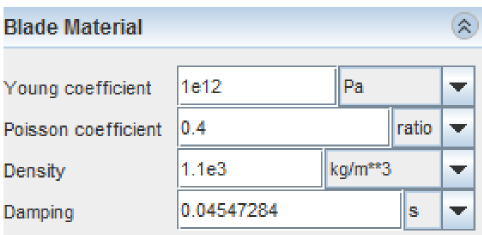

Figure 3.30: The material data of the prototype rotor

When there are two, they are referred to as the bearing on the rotor side or the generator side. When there is only one main bearing, this is regarded as the rotor side bearing. The number of bearings defined for the rotor shaft must correspond with the number of bearings defined on the bedplate. Standard rotor shaft with one and two bearings in which all the loads are carried by the rotor shaft are presented in Figures 3.31 and 3.32. The hub length and the hub external diameter parameters define hub dimensions.

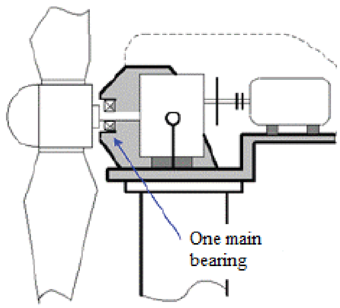

Figure 3.31: Rotor shaft with one main bearing

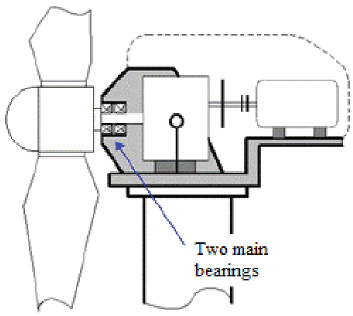

Figure 3.32: Rotor shaft with two main bearings

Hub length is the length in X dimension which corresponds to the axis of rotation of the shaft as shown in Figure 3.33. Flanges which connect blades are attached to the hub external diameter.

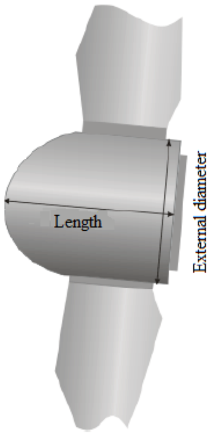

Figure 3.33: Dimensions of the hub

The simple rotor shaft provides a simple model of the rotor shaft. It has two components; the shaft and the hub. Hub dimensions including the hub length and the hub external diameter are given in Figure 3.34.

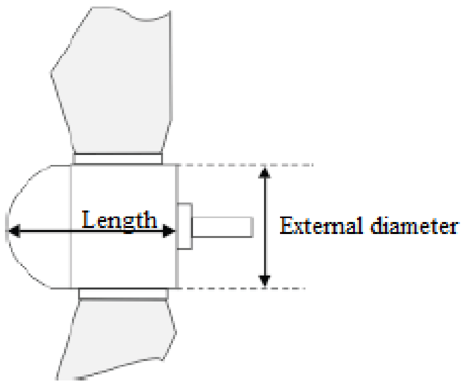

Figure 3.34: Simple rotor hub dimensions

The prototype rotor shaft is designed using the standard rotor shaft. It consists of the shaft and the hub in Figure 3.35. In this design, main bearing is regarded as the rotor side. The prototype rotor shaft has the hub parameters in Figures 3.36-3.37.

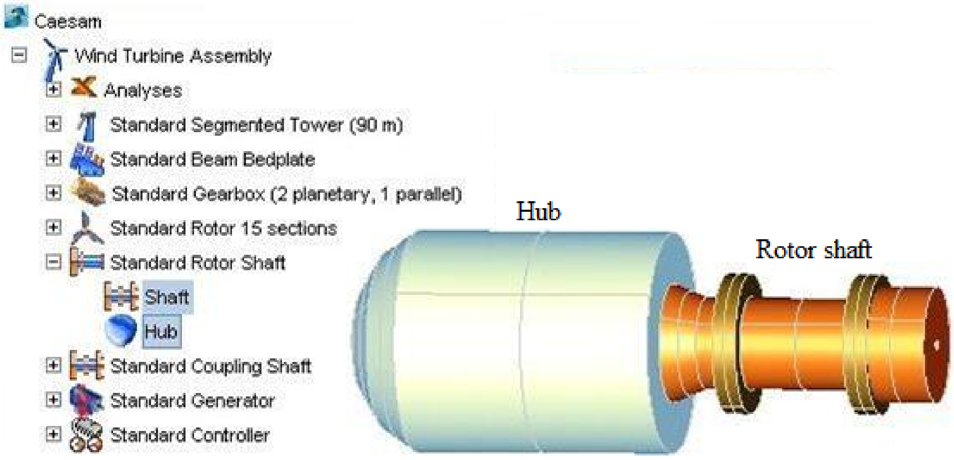

Figure 3.35: Simple rotor hub dimensions

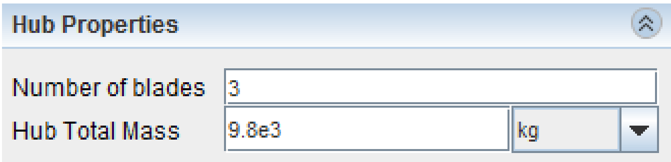

Figure 3.36: The hub properties of the prototype rotor shaft

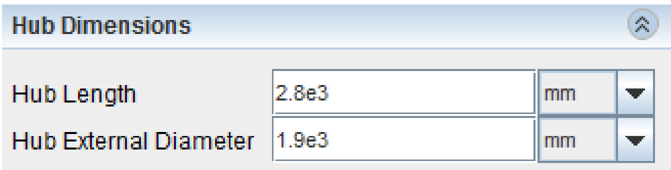

Figure 3.37: The hub dimensions of the prototype rotor shaft

3.2.6 Coupling Shaft

The following coupling shaft models are provided in S4WT:

- Standard Coupling Shaft
- Simple Coupling Shaft

The standard high speed coupling shaft extends from the gearbox to the generator. It consists of the brake, and the shaft itself in Figure 3.38.

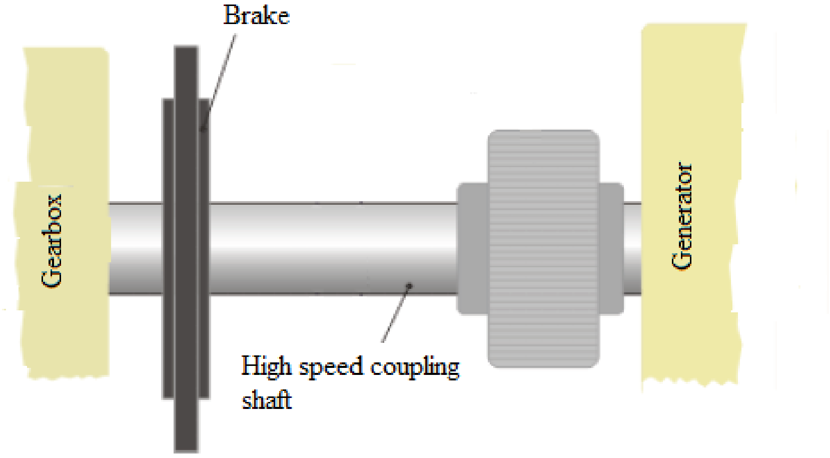

Figure 3.38: Components associated with the high speed coupling shaft

The simple coupling shaft forms part of the simple model family. The prototype high speed coupling shaft is designed using the standard coupling shaft. The prototype coupling shaft consists of a single component; coupling shaft in Figure 3.39. Parameters which are related with brake properties of the prototype high speed coupling shaft are shown Figure 3.40.

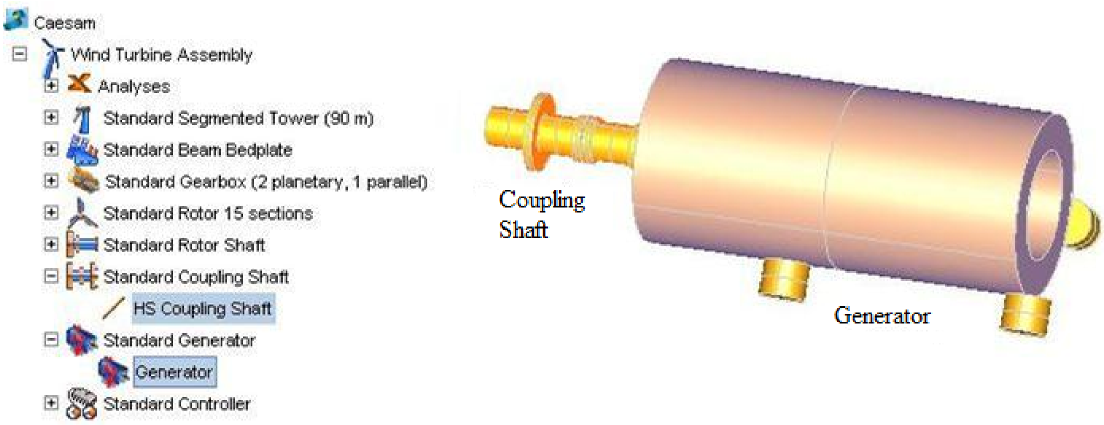

Figure 3.39: The prototype high speed coupling shaft in S4WT

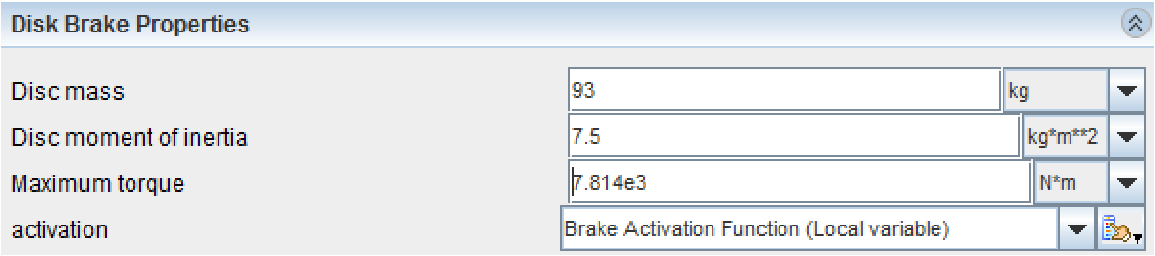

Figure 3.40: The brake properties of the prototype high speed coupling shaft

3.2.7 Generator

The following generator models are available in S4WT:

- Standard Generator
- Simple Generator

The standard generator has only a single component; the generator. Rotor, stator, bearings and generator support bushings are the main components of the generator as shown in Figure 3.41.

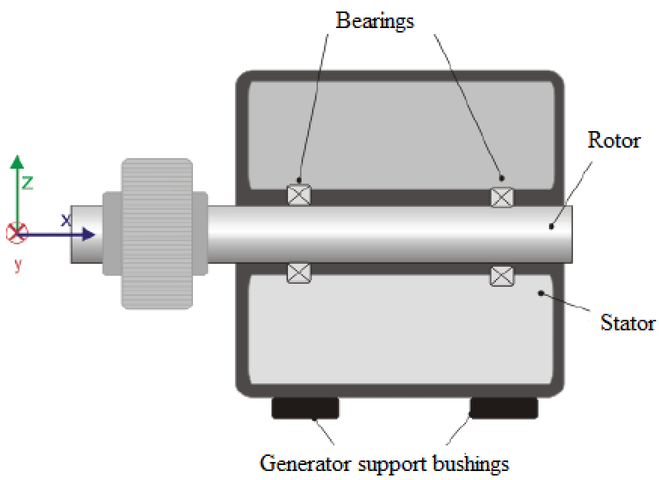

Figure 3.41: Components of the generator

Electrical power losses can also be simulated in S4WT. The mechanical power is reduced by the generator efficiency. The power loss is described using Equation (9). The simple generator is composed of a single component; the generator. The power losses are modeled similar to the standard generator.

$$P_{elec} = Z(P_{elec} - L_0) \tag{9}$$

The prototype generator is designed using the standard generator in Figure 3.39. The prototype generator has an efficiency of 90% in Figure 3.42.

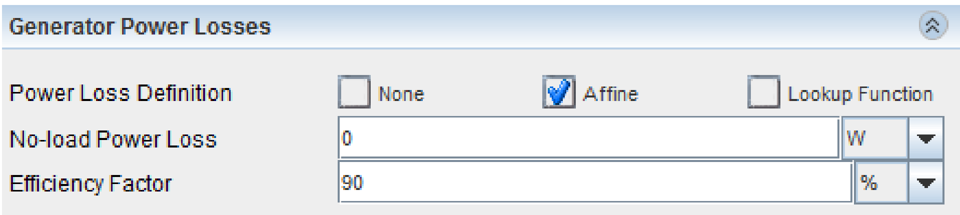

Figure 3.42: The efficiency of the prototype generator

Chapter IV

4 Wind Turbine Control in S4WT

S4WT Samtech Controller is designed for variable speed and variable pitch angle wind turbine. S4WT Samtech control system is composed of two controllers:

- The pitch angle controller
- The torque controller

During power production conditions, the principal tasks of the S4WT SAMTECH Controller are:

- below nominal wind speed conditions: achieving the optimal tip speed ratio (TSR) in the stationary regime (constant TSR control)
- above nominal wind speed conditions: achieving the nomianal speed (constant speed control)

The pitch angle is prescribed either according to a look-up table (the pitch function) or according to a scheduled PI control law. The generator torque control is based either on a lookup table, which will be called generator torque curve. The another method is an optimal mode gain mode, which will be set between a maximum and a minimum generator torque.

Figure 4.1 shows the basic scheme of the S4WT Samtech controller. Inputs of the control system are the measured and the nominal generator speed. Outputs of the control system are the pitch angle and the demanded generator torque. While torque control regulates the generator speed, pitch control regulates the aerodynamic torque.

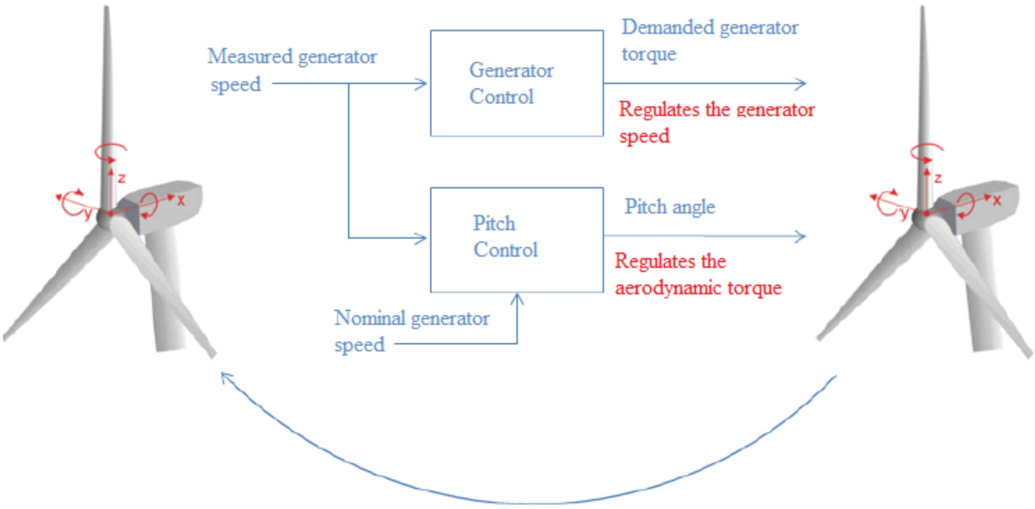

Figure 4.1: Schematic representation of the control algorithm [34]

4.1 Pitch Control

The pitch controller consists of

- Pitch function
- PID controller
- Gain scheduling

The pitch function is the curve defined through the specification of the interpolation points. This curve controls the pitch angle depending on the turbine rotor speed. The unit of the abscissa inputs of the typical pitch function curve is [rad/s] and its unit of the ordinate inputs is [rad].

S4WT Samtech controller enables another control method to control the pitch angle. This method is the PID controller. However, PID controller uses an input of the generator speed, not the turbine rotor speed. The error variable for the PID feedback controller is given by

$$e = \max(\omega_g - \omega_{nom}, 0) \tag{1}$$

where ω_g is the (filtered) measured generator speed and ω_{nom} is the nominal generator speed. The nominal generator speed is not explicitly defined inside the list of control parameters; it is calculated as the product of the nominal turbine rotor speed and the gearbox ratio.

There is a PID starting time parameter which is a threshold time for distinguishing how to control the pitch angle. Before reaching this time, the pitch function is used, and after that the PID algorithm is activated.

Proportional, integral and derivative gains of PID controller are given as inputs to the model. The constant proportional gain, K_P is the weighting factor of the PID controller considering the current control error. The constant integral gain, K_I is the weighting factor of the PID controller considering the accumulated control error. The constant derivative gain, K_D is the weighting factor of the PID controller considering the rate of change of the control error.

S4WT Samtech controller also provides gain scheduling. It means that the already defined PID values K_P, K_I,K_D can change when they are multiplied by a weight function which depends on the instantaneous blade pitch. The argument of the weight function is the instantaneous pitch angle and its output is the corresponding gain factor. The weight function is defined through the specification of the interpolation points.

The pitch behavior of the wind turbine can be adjusted by means of characteristic actuator limits. These impose restrictions that affect both the allowed pitch speed and the pitch acceleration values. The effective parameters are:

- Pitch Speed Limit : Limits value of the achievable pitch speed
- Pitch Acceleration Limit : Limits value of the achievable pitch acceleration
- Pitch Speed Reduction Threshold : The speed limit for the pitch actuator is decreased when the difference between the demanded pitch angle and the measured pitch angle is lower than this threshold.

The pitch control of the prototype turbine is designed such that both the pitch function and the PI controller with gain scheduling are used together. The pitch control parameters are presented in Figure 4.2. The derivative gain, K_D, is designed as zero. During the first four seconds, pitch function is used and the PI controller with gain scheduling is activated afterwards.

4.2 Generator Torque Control

The dynamical behavior of the generator is represented in terms of one dimensional, linear time invariant (LTI) system with bounded output.

The generator torque control is achieved by two methods; the optimal mode gain method and look up table method. The optimal mode gain, $K_{optimal}$ is a constant parameter, needed to define the demanded generator

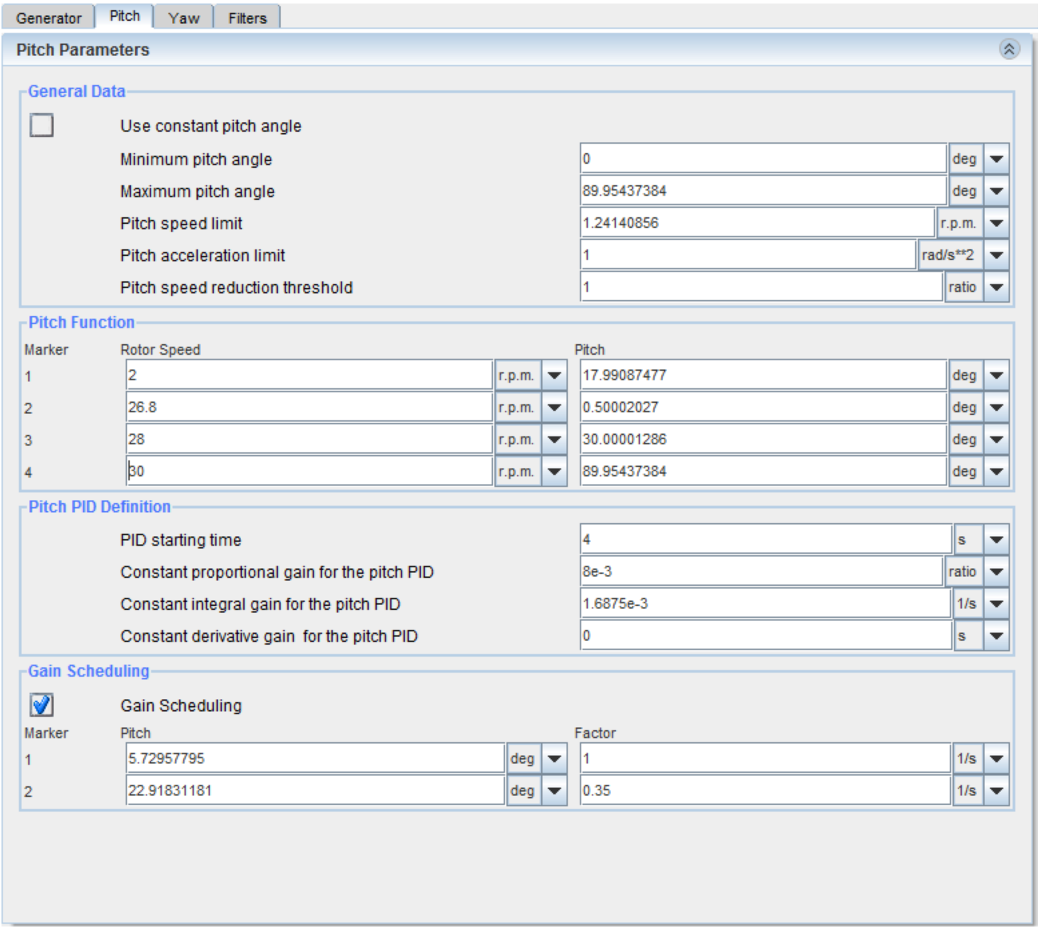

Figure 4.2: The pitch control of the prototype turbine

torque T_{demand}. If $K_{optimal}$ is designed appropriately, it ensures that the wind turbine achieves the condition of optimum tip speed ratio (TSR). When the optimal mode gain method is used, the demanded generator torque T_{demand} is given by:

$$T_{demand} = K_{optimal}{\omega_g}^2 \tag{2}$$

where ω_g is the measured generator speed. In this method, the parameters of maximum and minimum generator torques are used to limit the upper and lower of the torque the generator can provide.

As an alternative to the optimal mode gain method, the generator torque curve can be used to define the demanded generator torque. This curve defines the required generator torque T_{demand} depending on the generator instant speed. The generator torque curve is defined through the specification of interpolation points. The unit of the abscissa inputs of the typical generator torque curve is [rad/s] and its unit of the ordinate inputs is [N.m].

The prototype turbine has torque controller that is designed with the optimal mode gain method in Figure 4.3.

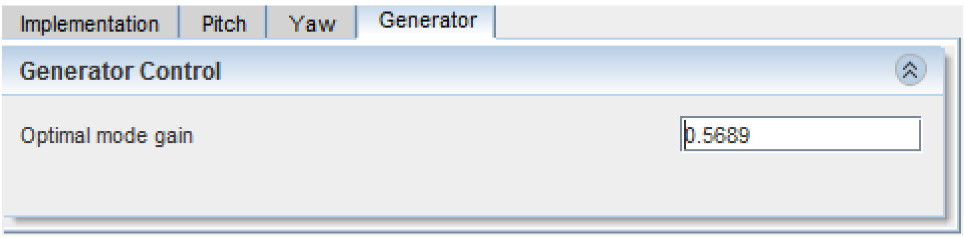

Figure 4.3: Optimal mode gain used for the prototype turbine

Chapter V

5 Modeling and Control in Matlab/Simulink Environment

Wind turbine model which is designed in Matlab/Simulink environment is composed of aerodynamic subsystem, mechanical subsystem, electrical subsystem, voltage controller, pitch controller and the torque controller.

5.1 Aerodynamic Subsystem

The aerodynamic power that is extracted from the horizontal axis wind turbines is:

$$P_a = \frac{1}{2}\varphi\pi R^2 C_p(\lambda, \beta)V^3 \tag{1}$$

In Equation (1), C_p denotes the power coefficient, R rotor radius, V the wind speed, φ air density, β pitch angle and λ tip speed ratio. The prototype turbine has rotor radius of 22.5 m. The power coefficient, C_p is a function of λ and β. Equations (2)-(3) present the model of power coefficient [35]-[36].

$$C_p(\lambda, \beta) = c_1(\frac{c_2}{\lambda_i} - c_3\beta - c_4)e^{-\frac{c_5}{\lambda_i}} + c_6\lambda \tag{2}$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \tag{3}$$

The coefficients c_1, c_2, c_3, c_4, c_5, c_6 are assumed as 0.5176, 116, 0.4, 5, 21, 0.0068. The power coefficient curve that is calculated using Equations (2)-(3), is presented in Figure 5.1.

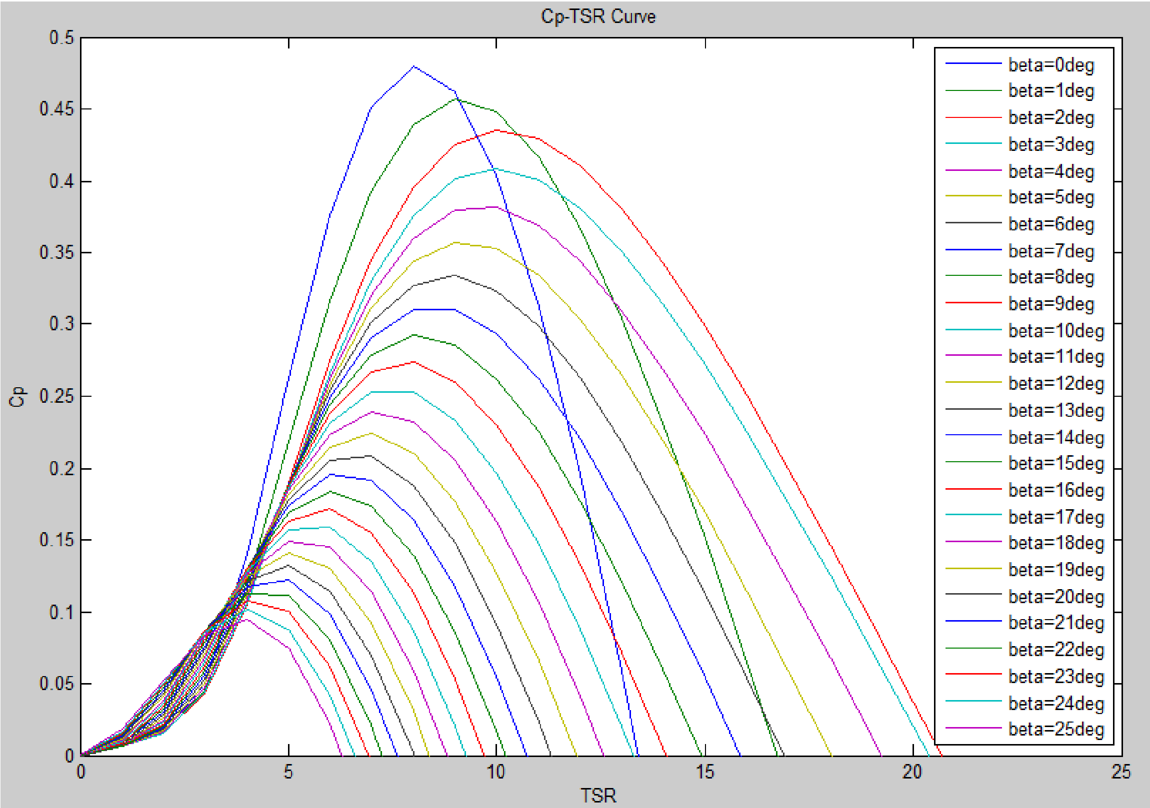

Figure 5.1: The power coefficient curve

The density of dry air can be calculated using the ideal gas law, expressed as a function of temperature and pressure:

$$\varphi = \frac{\rho}{P_{specific}T} \tag{4}$$

In Equation (4), ρ is absolute pressure and $P_{specific}$ is the specific gas constant of dry air and T is absolute temperature. The specific gas constant for dry air is 287.058 $\frac{J}{kgK}$. At 20 deg and 101.325 kPa, dry air has a density of 1.2041 $\frac{kg}{m^3}$. In this thesis, dry air density is calculated as 1.225 $\frac{kg}{m^3}$ at 15 deg and 101.325 kPa [37].

Aerodynamic equations of the wind turbine are computed as shown in [38]-[40]. Tip speed ratio, λ describes ratio of the relative speed at the blade tip to the wind speed:

$$\lambda = \frac{R\omega_r}{V} \tag{5}$$

where ω_r is the angular speed of turbine rotor. The aerodynamic torque of the rotor is calculated by dividing aerodynamic power to rotor speed:

$$T_a = \frac{P_a}{\omega_r} \tag{6}$$

Using Equations (1) and (6), aerodynamic torque is derived as

$$T_a = \frac{1}{2}\varphi\pi R^3 C_q(\lambda, \beta)V^2 \tag{7}$$

In Equation (5), wind speed is computed as:

$$V = \frac{R\omega_r}{\lambda} \tag{8}$$

If Equation (8) is submitted into Equation (7), then aerodynamic torque is calculated as shown in Equation (9).

$$T_a = \frac{1}{2\lambda^2}\varphi\pi R^5 C_q(\lambda, \beta){\omega_r}^2 \tag{9}$$

In Equation (7), C_q is the torque coefficient which is the division of power coefficient to tip speed ratio:

$$C_q = \frac{C_p}{\lambda} \tag{10}$$

Then, the aerodynamic torque has the relationship of:

$$T_a = \frac{1}{2}\varphi\pi R^3 \frac{C_p}{\lambda} V^2 \tag{11}$$

5.2 Mechanical Subsystem

In literature, there are two mechanical models for wind turbines [41]-[42]. Figure 5.2 gives two mass model of wind turbine. The aerodynamic or mechanical torque extracted from the wind is transmitted into the generator side through a coupling mechanism. The coupling mechanism consists of a low speed shaft on the rotor side, a gearbox and a high speed shaft on the generator side. The speed at the rotor shaft is generally low due to large inertia. Thus, this shaft is called low speed shaft. However, huge mechanical torque is applied on it. This torque is reduced and speed at the generator shaft is increased by using the gearbox so generator shaft is called as high speed shaft.

Driving by the aerodynamic torque T_a, the wind turbine rotor runs at the speed w_r. The low speed shaft torque T_{ls} acts as a braking torque on the rotor. The generator is driven by the high speed shaft torque T_{hs} and braked by the generator electromagnetic torque T_{em}. The rotor speed is increased by the gearbox ratio n_g to obtain the generator speed w_g. Rotor and generator dynamics are defined as:

$$J_r\dot{w}_r = T_a - B_r w_r - K_r\theta_r - T_{ls} \tag{12}$$

$$J_g\dot{w}_g = T_{hs} - B_g w_g - K_g \theta_g - T_{em} \tag{13}$$

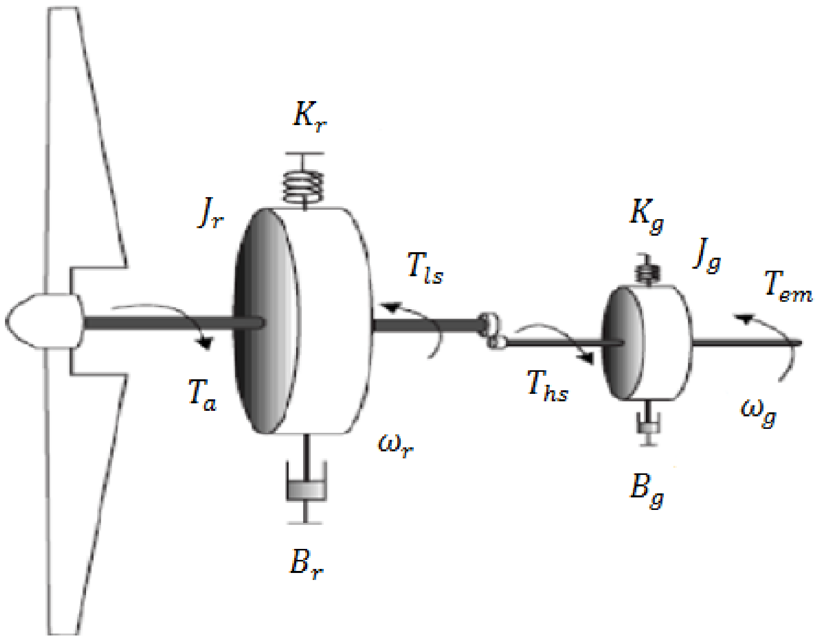

Figure 5.2: Two Mass Dynamic Model of Wind Turbine [42]

In Equation (12), B_r and K_r are external damping and stiffness of the turbine rotor. In Equation (13), B_g and K_g are external damping and stiffness of the generator. The gearbox ratio is defined as:

$$n_g = \frac{w_g}{w_r} = \frac{T_{ls}}{T_{hs}} \tag{14}$$

Using Equation (12)-(14);

$$J_t\dot{w}_r = T_a - K_t w_r - B_t \theta_r - T_g \tag{15}$$

where

$$J_t = J_r + J_g {n_g}^2 \tag{16}$$

$$K_t = K_r + K_g {n_g}^2 \tag{17}$$

$$B_t = B_r + B_g {n_g}^2 \tag{18}$$

$$T_g = T_{em} n_g \tag{19}$$

T_g is the generator torque at the rotor side through the gearbox. The external stiffness and damping values, B_t and K_t are very low so they may be neglected. Therefore, the wind turbine dynamic model become one mass model in Figure 5.3 and the turbine dynamics brought back to the low speed side is simplified as:

$$J_t \dot{w}_r = T_a - T_g \tag{20}$$

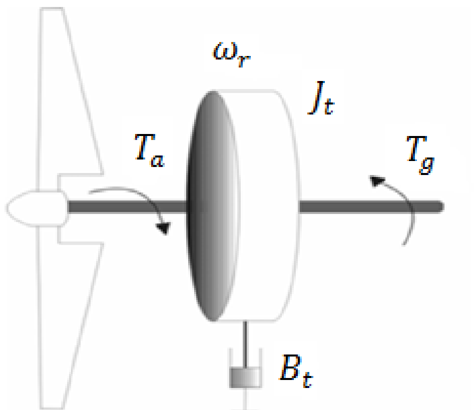

Figure 5.3: One Mass Dynamic Model of Wind Turbine [42]

The mechanical model of the prototype turbine is designed as one mass model and the parameters are presented in Table 5.1.

Table 5.1: The mechanical parameters of the prototype turbine

J_r	4915797.5 $[kg.m^2]$
J_g	81.2 $[kg.m^2]$
n_g	33.5

5.3 Electrical Subsystem

In Figure 5.4, the rotor controlled doubly fed induction generator is shown. In this topology, stator of the generator is directly coupled to the electrical grid. Rotor current components control the active and reactive power. When the generator speed is above the synchronous speed, the wind turbine feeds power to the grid through the generator rotor. When generator speed is below the synchronous speed, the wind turbine is fed by the grid through the generator rotor. The stator of the generator always feeds the grid through the stator windings. Therefore, doubly fed induction machines always work in generator mode both at the above and below synchronous speed.

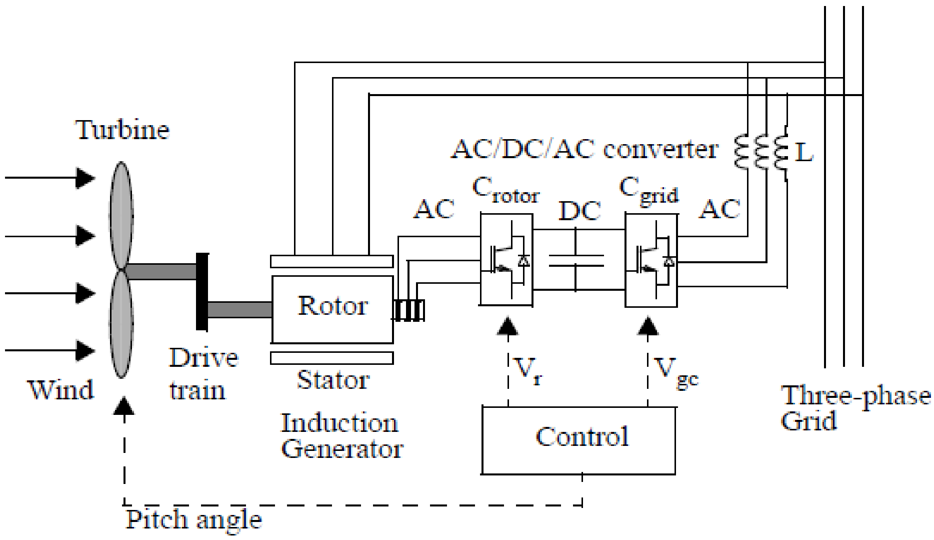

Figure 5.4: Rotor controlled DFIG

Dynamic equations of the DFIG model are derived in [43]-[55] using a stationary frame. Doubly fed induction generator in d-q frame is shown in Figure 5.5.

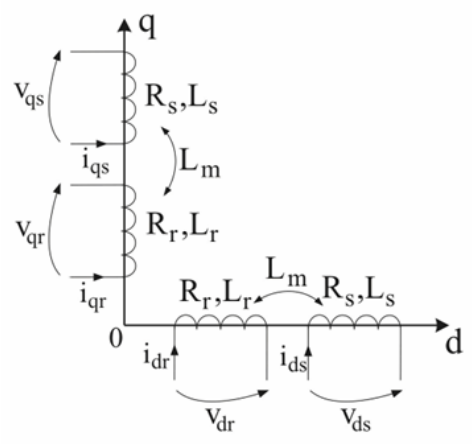

Figure 5.5: The d-q Axis of DFIG

The derivatives of stator magnetic flux equations:

$$\frac{d\psi_{qs}}{dt} = v_{qs} - R_s i_{qs} - \omega_s \psi_{ds} \tag{21}$$

$$\frac{d\psi_{ds}}{dt} = v_{ds} - R_s i_{ds} + \omega_s \psi_{qs} \tag{22}$$

The derivatives of rotor magnetic flux equations:

$$\frac{d\psi_{qr}}{dt} = v_{qr} - R_r i_{qr} - s\omega_s \psi_{dr} \tag{23}$$

$$\frac{d\psi_{dr}}{dt} = v_{dr} - R_r i_{dr} + s\omega_s \psi_{qr} \tag{24}$$

Stator flux equations:

$$\psi_{qs} = (L_s + L_m) i_{qs} + L_m i_{qr} \tag{25}$$

$$\psi_{ds} = (L_s + L_m)i_{ds} + L_m i_{dr} \tag{26}$$

Rotor flux equations:

$$\psi_{qr} = (L_r + L_m)i_{qr} + L_m i_{qs} \tag{27}$$

$$\psi_{dr} = (L_r + L_m)i_{dr} + L_m i_{ds} \tag{28}$$

Stator current equations:

$$k_1 = \frac{1}{(L_s L_r - {L_m}^2)} \tag{29}$$

$$i_{qs} = k_1(\dot{\psi}_{qs} L_r - \dot{\psi}_{qr} L_m) \tag{30}$$

$$i_{ds} = k_1(\dot{\psi}_{ds} L_r - \dot{\psi}_{dr} L_m) \tag{31}$$

Rotor current equations:

$$i_{dr} = k_1(\dot{\psi}_{dr} L_s - \dot{\psi}_{ds} L_m) \tag{32}$$

$$i_{qr} = k_1(\dot{\psi}_{qr} L_s - \dot{\psi}_{qs} L_m) \tag{33}$$

Power and Torque Equations:

$$T_{em} = pL_m(i_{qs} i_{dr} - i_{ds} i_{qr}) \tag{34}$$

$$P_s = \frac{3}{2}(v_{ds} i_{ds} + v_{qs} i_{qs}) \tag{35}$$

$$Q_s = \frac{3}{2}(v_{qs} i_{ds} + v_{ds} i_{qs}) \tag{36}$$

The voltage controller of DFIG model is presented in Figure 5.6. Inputs of the voltage controller are measured active-reactive powers and reference active-reactive powers. The reference active power is the output of torque controller. The reference reactive power is desired to be zero. Errors in active and reactive powers are regulated by PI controllers. Outputs of PI controllers are reference currents in d-q frames, i_{dr}, i_{qr}. These reference values are compared with measured values and resulting errors are regulated by PI controllers. Outputs of these controllers are voltages in d-q frames, v_{dr}, v_{qr} that are given as inputs to DFIG.

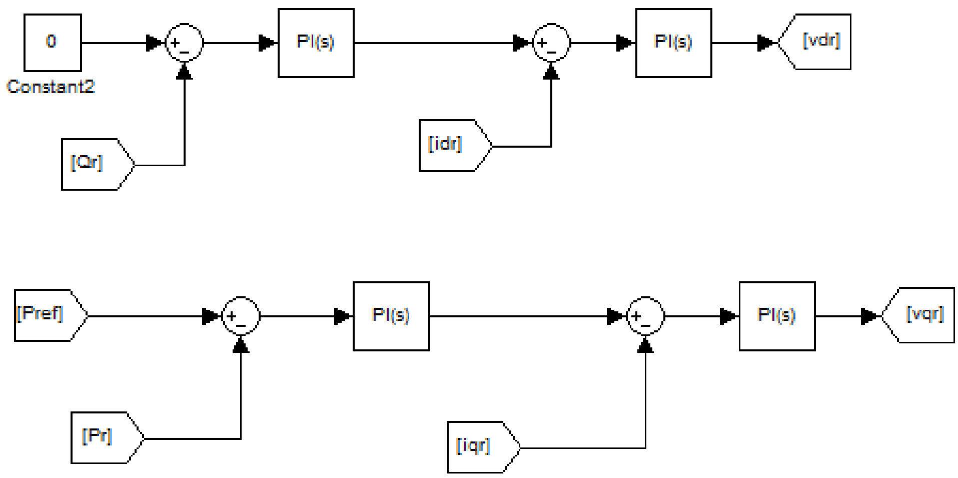

Figure 5.6: DFIG controller in Matlab/Simulink

The prototype turbine has electrical parameters in Table 5.2.

5.4 Torque Control

Simple linear controllers cannot provide good performance due to nonlinearities and uncertainties in the system. Robust controllers are needed. Torque controller is used at the partial load operating region. The goal of the torque controller is to increase energy efficiency and reach nominal power at the

Table 5.2: The electrical parameters of the prototype turbine

R_s	1.06
R_r	0.80
L_s	0.2065
L_r	0.0810
L_m	0.0664
p	4
f_s	60

nominal wind speed. The power coefficient is the function of pitch angle and tip speed ratio in Figure 5.1. Then, the maximum power coefficient depends on the optimal pitch angle and tip speed ratio in Equation (37).

$$C_{pmax} = C_p(\lambda_{opt}, \beta_{opt}) \tag{37}$$

The maximum moment coefficient is calculated using Equation (38).

$$C_{qmax} = \frac{C_p(\lambda_{opt}, \beta_{opt})}{\lambda_{opt}} \tag{38}$$

The aerodynamic torque is derived in Equation (9). Thus, an optimum aerodynamic torque which is the multiplication of optimal gain parameter and square of rotor angular speed, is calculated in Equations (39)-(40).

$$T_{opt} = K_{opt}{\omega_r}^2 \tag{39}$$

$$K_{opt} = \frac{1}{2{\lambda_{opt}}^2}\varphi\pi R^5 C_{qmax} \tag{40}$$

At the partial load region, K_{opt} value is hold constant to achieve the maximum power from the wind. It is difficult to keep K_{opt} in the desired value due to the variable blade aerodynamic profile of the turbine. A sliding mode controller is used to handle nonlinearities and compensate for uncertainties. Sliding mode control uses the Maximum Power Point Tracking (MPPT) algorithm. This control technique is implemented using [19]. The reference power is computed by multiplying optimum aerodynamic moment with angular speed of the turbine rotor as shown in Equation (41).

$$P_{ref} = T_{opt}\omega_r \tag{41}$$

Sliding mode controller destroys the error between the generated power at the low speed side, P_g and the reference power. The maximum power tracking error and its derivative are presented in Equations (42)-(43).

$$\varepsilon_p = P_{ref} - P_g \tag{42}$$

$$\dot{\varepsilon_p} = \dot{P}_{ref} - T_g\dot{\omega}_r - \dot{T}_g\omega_r \tag{43}$$

The derivative of the generator torque is designed as in Equation (44) in order to decrease the maximum power tracking error to zero.

$$\dot{T}_g = \frac{(B+\varsigma)sgn(\varepsilon_p)}{\omega_r}, \dot{B} = |\varepsilon_p|, \varsigma > 0 \tag{44}$$

The generator torque at the low speed side is computed by taking integral of Equation (44). When this torque is divided by gearbox ratio, reference electromagnetic torque is derived. Then, this value is multiplied by generator angular speed and reference active power for voltage controller is calculated. The proof of the designed moment controller is done. If Equation (44) is submitted into Equation (43):

$$\dot{\varepsilon_p} = \dot{P}_{ref} - T_g\dot{\omega}_r - (B + \varsigma)sgn(\varepsilon_p) \tag{45}$$

$$d = \dot{P}_{ref} - T_g\dot{\omega}_r, |d| < B_1 \tag{46}$$

where d is the medium variable and always smaller than B_1 that is a positive value.

$$\dot{\varepsilon_p} = -(B + \varsigma)sgn(\varepsilon_p + d) \tag{47}$$

In order to test whether the error is decreased to zero or not, the Lyapunov candidate function in Equation (48) is used.

$$V = \frac{1}{2}({\varepsilon_p}^2 + (B - B_1)^2) \tag{48}$$

According to the Lyapunov stability rule; if the derivative of the Lyapunov candidate function is zero or negative, then the system is stable. The derivative of Lyapunov candidate function is calculated in Equation (49).

$$\dot{V} = \varepsilon_p\dot{\varepsilon}_p + (B - B_1)|\varepsilon_p| \tag{49}$$

$$\dot{V} = \varepsilon_p(-(B + \varsigma)sgn(\varepsilon_p) + d) + (B - B_1)|\varepsilon_p| \tag{50}$$

$$\dot{V} \leq -\varsigma|\varepsilon_p| \tag{51}$$

It is understood that the derivative of Lyapunov candidate function is zero or negative. According to La Salle theory, maximum power tracking error is decreased to zero. The sgn function is chosen as in Equation (52) to reduce oscillations at the output of the controller.

$$sgn(\varepsilon_p) = \frac{\varepsilon_p}{|\varepsilon_p| + a_1} \tag{52}$$

where a_1 is a positive value and chosen depending on the error size. The prototype turbine has torque controller parameters in Table 5.3.

Table 5.3: The torque control parameters of the prototype turbine

K_{opt}	2.2448e+004
a_1	0.1
ς	0.5

5.5 Pitch Control

Pitch controller is used at the full load operating region in order to protect the turbine from excessive loads at high wind speeds. The goal of the pitch controller is to limit generated power at the nominal value. If the pitch angle changes, then power coefficient changes as shown in Figure 5.1. The power is maximized or limited depending on the increment and decrement of power coefficient. The pitch controller uses the rotor angular speed as an input and the error is given in Equation (53).

$$\varepsilon_\omega = \omega_{nom} - \omega_r \tag{53}$$

Pitch controller is designed using proportional (P) controller in Equation (54). The desired pitch angle is the summation of measured pitch angle and the pitch angle change in Equation (55).

$$\Delta\beta = K_p \varepsilon_\omega \tag{54}$$

$$\beta_d = \beta + \Delta\beta \tag{55}$$

The pitch angle of the wind turbine is changed using the pitch actuator mechanism. The dynamic model of the pitch actuator is given in Equation (56).

$$\dot{\beta} = -\frac{\beta}{\tau} + \frac{\beta_d}{\tau} \tag{56}$$

where τ is the time constant and β_d is the desired pitch angle. The pitch angle is increased by pitch controller using pitch to feather method for prototype turbine. The prototype turbine has pitch controller parameters in Table 5.4.

Table 5.4: The pitch control parameters of the prototype turbine

w_{nom}	2.80 [rad/s]
K_p	0.01

Chapter VI

6 Simulation Results

First simulations are done using simple wind turbine components under power production scenario for a 2 MW turbine:

- Partial load operating region results using constant speed wind in X direction under power production scenario
- Full load operating region results using constant speed wind in X direction under power production scenario

Power production scenarios provide performing transient analysis at both partial and full load operating regions. This is the simplest scenario for the wind turbines. Much more complicated simulations can be done using standard components under different scenarios (start-up, emergency stop, shut down, parked) in S4WT.

Power generation is not possible at the start up scenarios because the efficiency at the start up wind speed is very low. The wind turbine begins to transmit voltage to the generator when wind speed reaches the cut-in wind speed, not the start up wind speed. Therefore, these speeds should not be confused each other.

Shut down scenarios have manual control and generator operation is fully stopped. Turbine blades will not turn anymore.

Shut down scenarios are performed when the wind speeds exceeds the cut-off wind speed so that turbine will be protected from excessive loads. Turbine can be shut down electrically or mechanically. In this scenario, turbine is shut down by a mechanical brake disk.

In emergency stop scenarios, the grid connection is lost. Grid loss occurs due to the technical faults at the transmission cable and the environmental facts such as stroke of lightning. Whenever the grid loss occurs, the wind turbine operation will be stopped.

In parked scenarios, blades are locked in a special parked angle whenever the generated power starts to exceed the demanded power. Thus, the generated power to the grid will not be higher than the desired value.

Simple components are replaced by standard models and prototype turbine parameters are assigned to S4WT standard components. Then, prototype turbine simulations are done using different wind models under power production, start-up, emergency stop, shut down and parked scenarios. The faults which are related to grid and pitch mechanism can also be analyzed in S4WT. The summary of 500 KW prototype wind turbine simulations are:

- Power production scenario
  - Partial load operating region results using constant speed wind in X, Y and Z directions
  - Full load operating region results using constant speed wind in X, Y and Z directions
  - Simulation using the wind speed of Terkos lake (prototype turbine constructed area)
  - Simulation of a grid loss using Kaimal wind speed model

- Simulation of a pitch stuck using Kaimal wind speed model

- Power production scenario results using Kaimal wind speed model
- Start up scenario results using Kaimal wind speed model
- Shut down scenario results using Kaimal wind speed model
- Emergency scenario results using Kaimal wind speed model
- Parked scenario results using Kaimal wind speed model

The performance analysis of the prototype wind turbine is also done in Matlab/Simulink environment. The prototype turbine is tested at both partial load operating region and full load operating region.

6.1 The results of 2 MW wind turbine transient analysis in S4WT environment

S4WT has default parameters of 2 MW wind turbine. These parameters are assigned to simple components. Then, simulations are done at both full load and partial load operating regions under power production scenario. The goal of these simulations is to figure out steps of designing and analyzing a 2 MW wind turbine by implementing S4WT theory. The input wind speed is 5 m/s at the partial load simulation and 11 m/s at the full load simulation in Figure 6.1. At the partial load operating region, mechanical power is around 2 GW in Figure 6.2 since each blade length is 41 m and this provides huge mechanical power extraction from the wind.

However, the generated electrical power is around 1.8 MW. At the full load operating region, mechanical power is also huge with 2.2 GW, but, the generated electrical power reaches the nominal power of 2 MW.

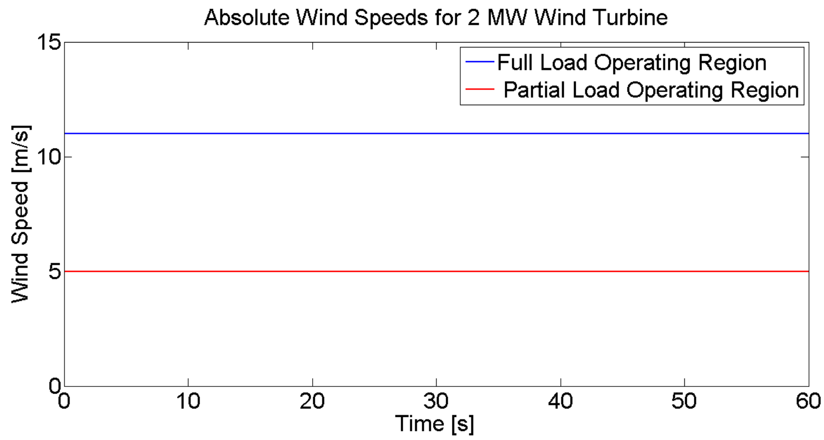

Figure 6.1: Absolute values of constant wind speeds

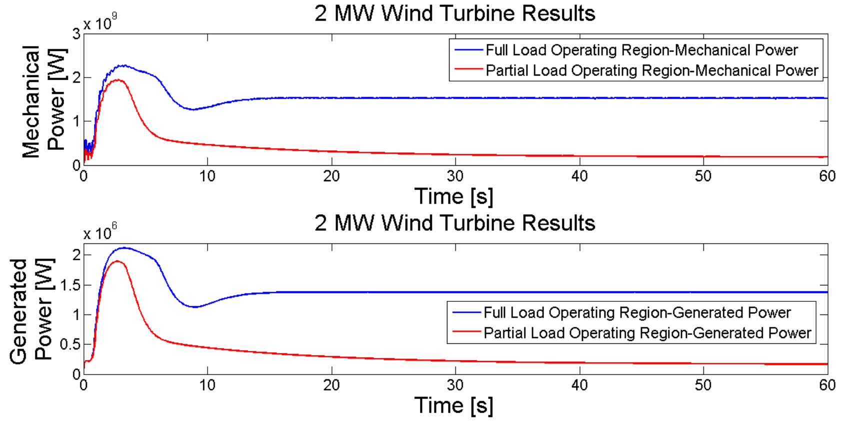

Figure 6.2: Resulting mechanical and electrical powers under power production scenario

The generated torque reaches the maximum of 14,000 N.m, but it drops down to 10,000 N.m when the mechanical and generated powers reach their steady state values at the full load operating region in Figure 6.3.

Similarly, generated torque at the partial load operating region increases to maximum torque, but it drops smaller values compared with generated torque at the full load operating region.

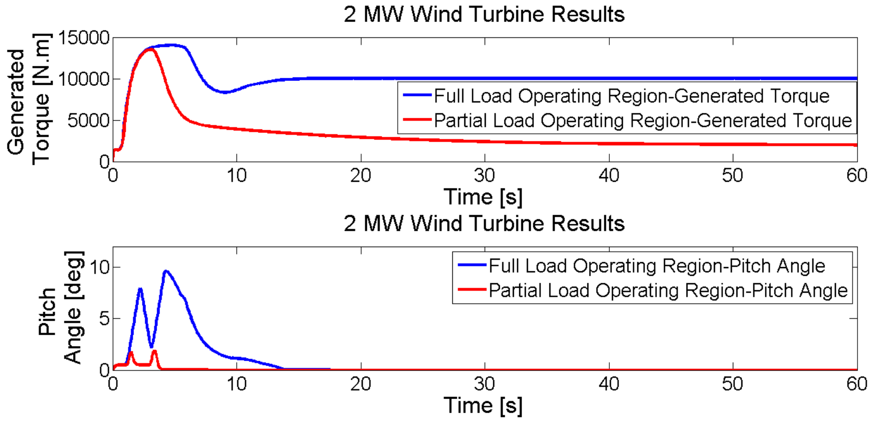

Figure 6.3: Resulting torque and pitch angle under power production scenario

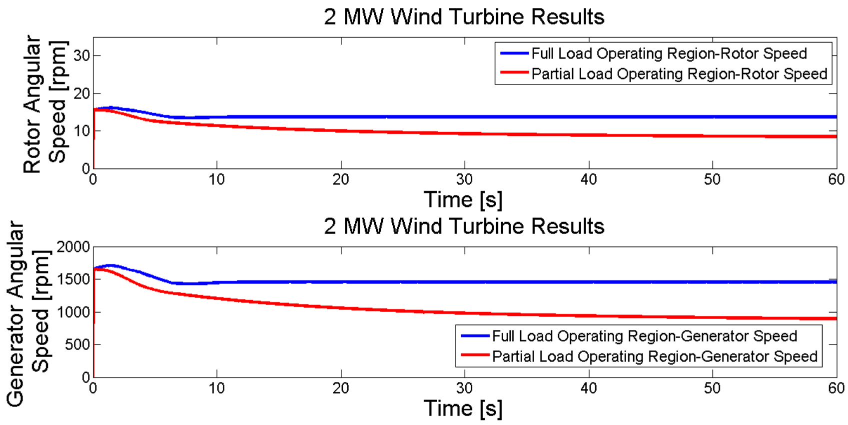

Figure 6.4: Resulting rotor and generator angular speeds under power production scenario

Pitch angles are increased twice by the pitch controller in the first 10 seconds of the simulations at both operating regions. The first increment is because of the pitch function.

The speed of rotor shaft depends on the mechanical power extraction. Angular speeds of rotor shaft are close to nominal values in Figure 6.4 at both operating regions. Then, pitch angles are increased again by PI controller with gain scheduling in order to prevent the huge mechanical power extraction from the wind. Otherwise, excessive loads damage the turbine and its shaft.

6.2 The results of the prototype turbine transient analysis in S4WT environment

Power production scenario is implemented at both full load and partial load operating regions. The wind input is generated as constant wind speeds in three directions of X, Y and Z. The wind speed is taken as 7 m/s in X direction, 3 m/s in Y direction, 2 m/s in Z direction at the partial load operating region.

The wind speed is taken as 11 m/s in X direction, 3 m/s in Y direction, 2 m/s in Z direction at the full load operating region. These wind speeds are presented in Figure 6.5.

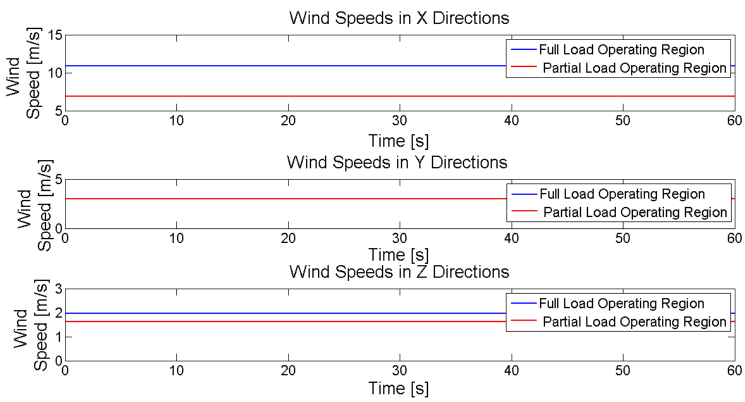

Figure 6.5: Constant wind speeds in X, Y and Z directions

The calculated absolute wind speeds are around 7 m/s at the partial load operating region and 11 m/s at the full load operating region in Figure 6.6.

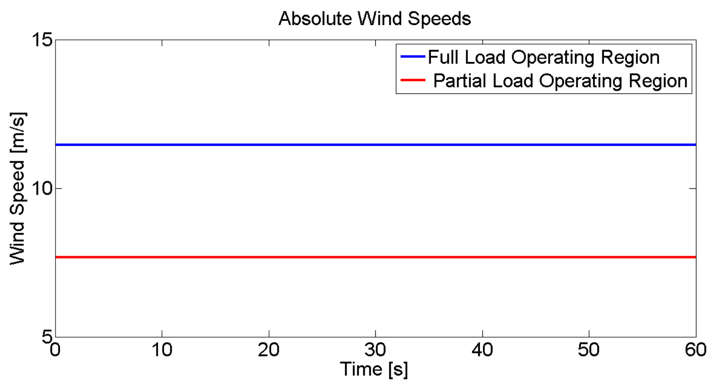

Figure 6.6: Absolute values of constant wind speeds

The mechanical power is around 600 KW and the generated electrical power is 500 KW at the full load operating region. The mechanical and generated electrical powers at the partial load operating region are small compared to the powers at the full load operating regions since the input wind speed does not reach to the nominal value. These powers are presented in Figure 6.7.

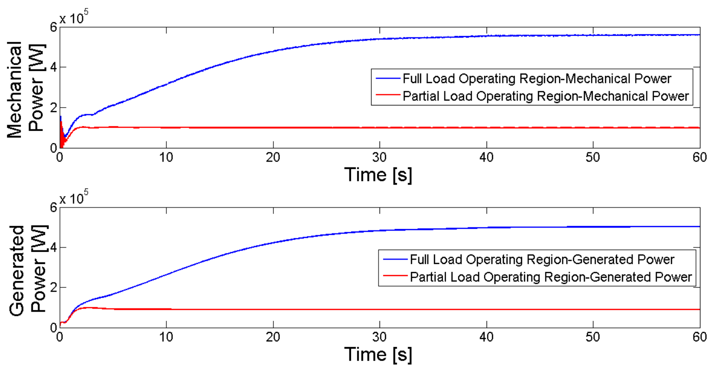

Figure 6.7: Resulting mechanical and electrical powers using constant wind speed

The maximum torque of the generator is produced at the full load operating region in Figure 6.8. The generated torque is below the maximum value at the partial load operating region. The pitch angles increase due to the pitch function at both operating regions. As it is expected, rotor and generator angular speeds reach their nominal values at full load operating regions and they do not at the partial load operating region in Figure 6.9.

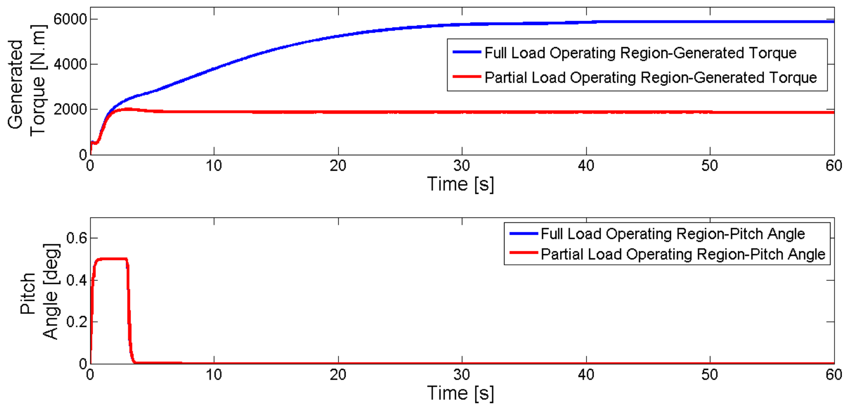

Figure 6.8: Resulting torque and pitch angle using constant wind speed

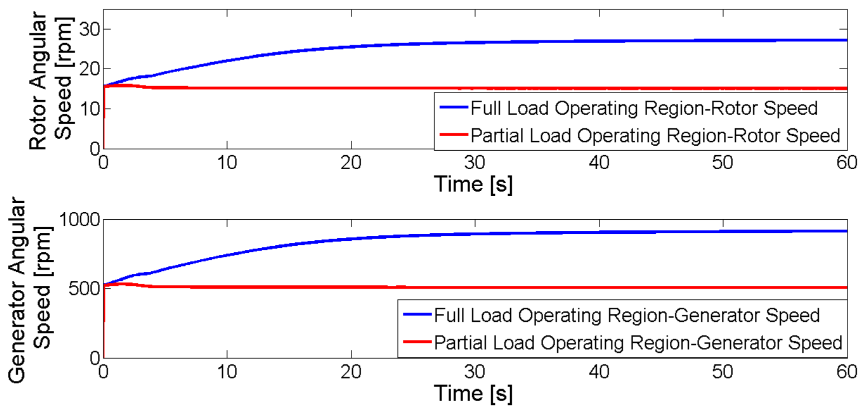

Figure 6.9: Resulting rotor and generator angular speeds using constant wind speed

The measured wind profile is also required for prototype wind turbine analysis. The wind speed of Terkos lake is used as an input to the model. The wind speed data of Terkos lake in Figure 6.10 is externally imported to S4WT.

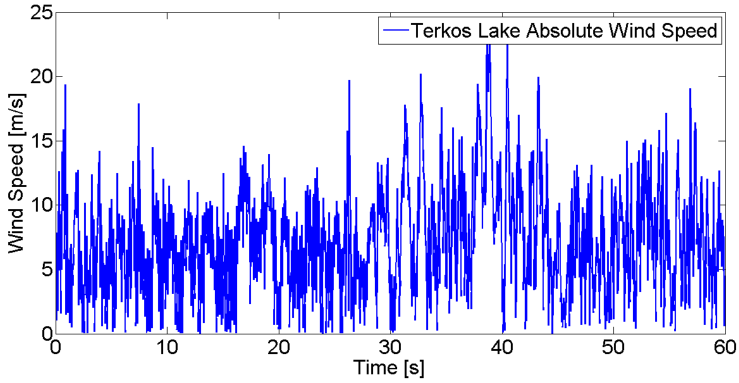

Figure 6.10: Terkos Lake absolute wind speed

The mechanical power which is gained from the wind in Figure 6.11, is around 60 KW because average of the wind speed is below the nominal wind speed, 11 m/s. Then, generated electrical power in Figure 6.12 is around 50 KW.

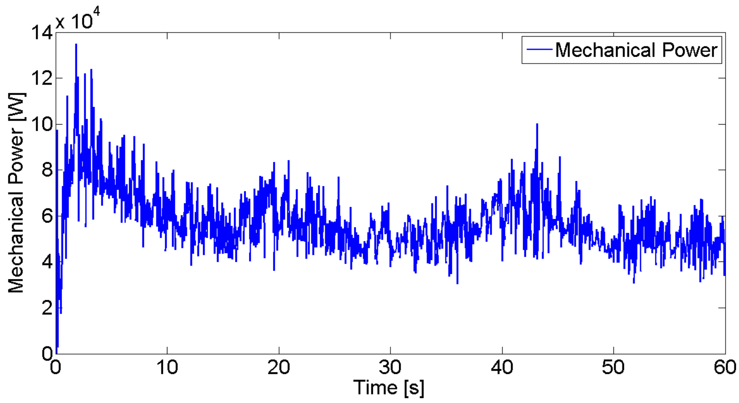

Figure 6.11: Resulting mechanical power using Terkos lake wind speed

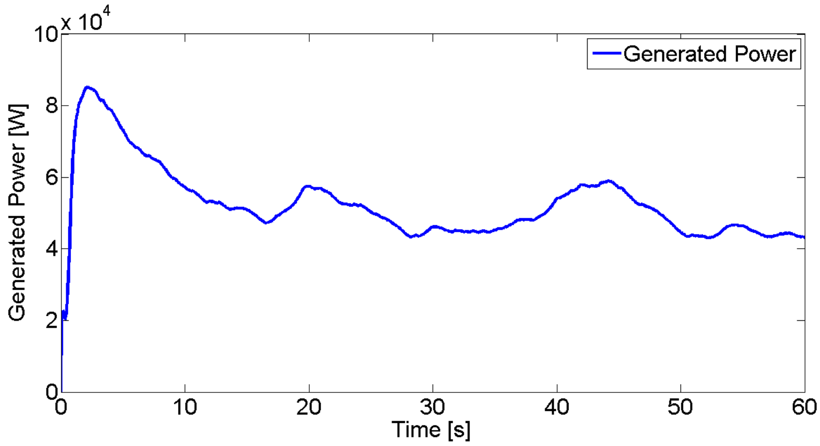

Figure 6.12: Resulting electrical power using Terkos lake wind speed

The generated torque is so small compared to the maximum torque of 5851 N.m in Figure 6.13. The pitch angle increases to 0.5^o due to the pitch function. Then, the pitch angle decreases to zero because the goal is to reach the nominal power and the blades are positioned at zero degree for the maximum efficiency. Rotor and generator angular speeds reach 15 rpm and 500 rpm in Figure 6.15 which are smaller than the nominal values. Nominal values of rotor and generator angular speeds are 26.8 rpm and 900 rpm.

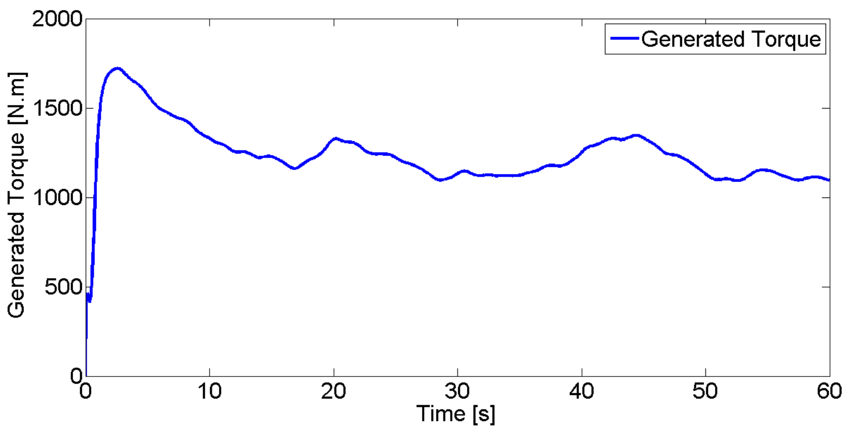

Figure 6.13: Resulting torque using Terkos lake wind speed

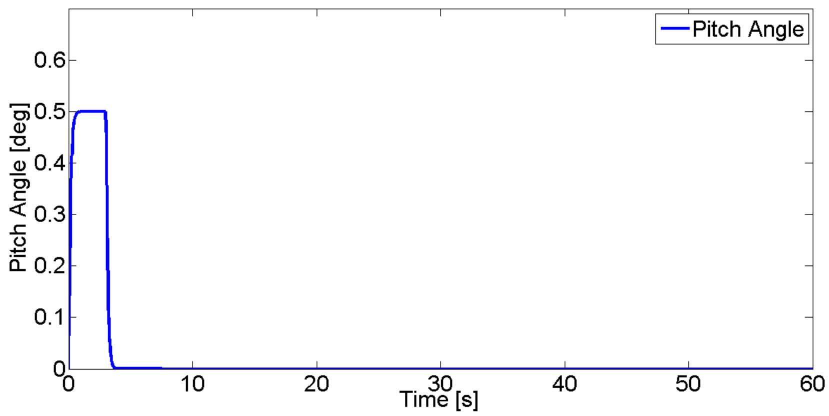

Figure 6.14: Resulting pitch angle using Terkos lake wind speed

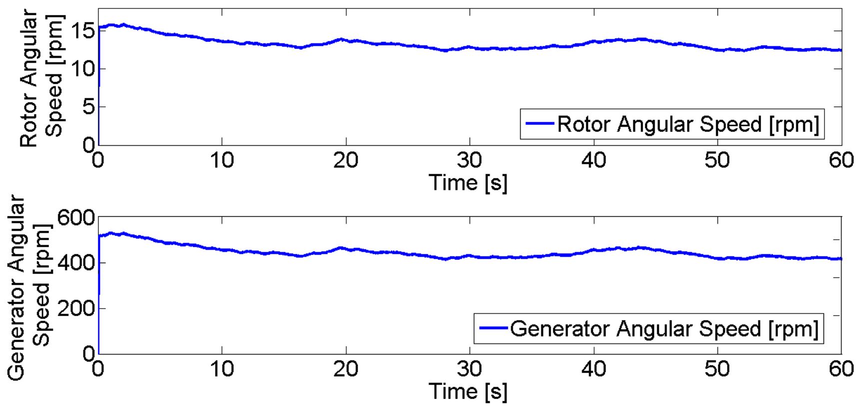

Figure 6.15: Resulting rotor and generator angular speeds using Terkos lake wind speed

Kaimal wind speed model is generated using the data in Table 3.2. The absolute wind speed of 11 m/s, is presented in Figure 6.16. In this simulation, grid connection is lost at the 30.seconds. Then, mechanical and generated electrical power drop to zero immediately in Figures 6.17- 6.18. When grid connection is improved at the 33.seconds, peak occurs in the mechanical power since the rotor shaft turns during the grid loss in Figure 6.21.

However, this peak effect is not seen in the generated electrical power because the torque controller is active.

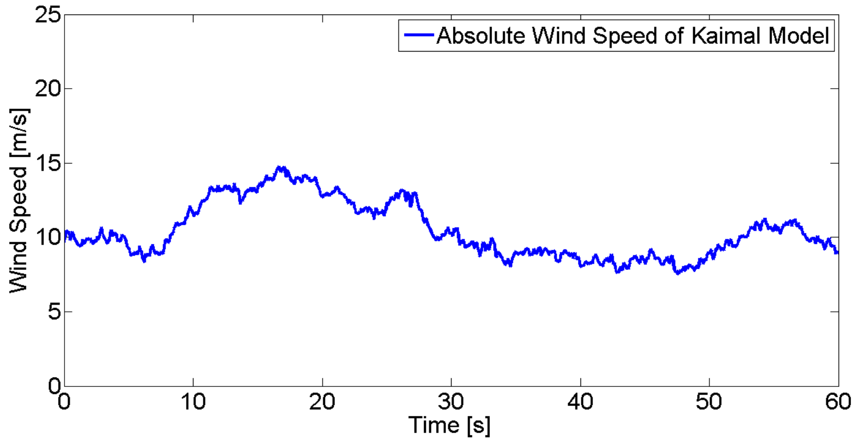

Figure 6.16: Absolute wind speed generated for grid loss connection fault

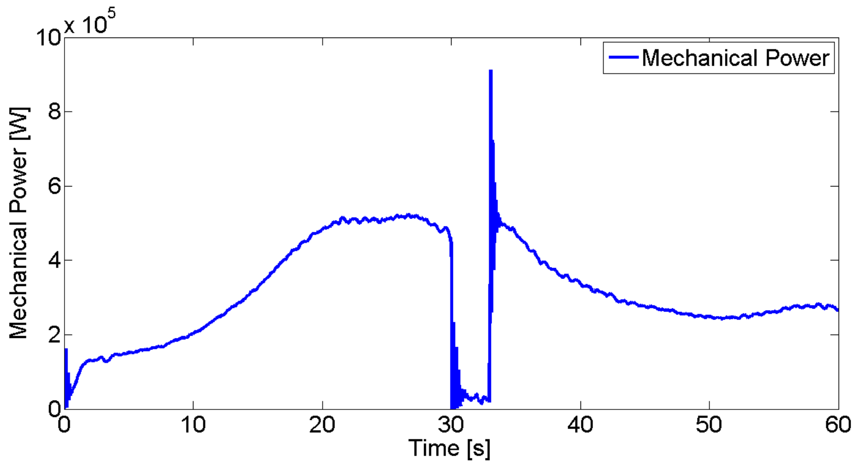

Figure 6.17: Resulting mechanical power at the grid loss connection fault

Torque controller does not let that generated torque in Figure 6.19 exceeds the maximum torque of 5851 N.m. When the wind speed decreases to smaller values at the 40-50.seconds, mechanical power and so generated electrical power drop down from nominal values.

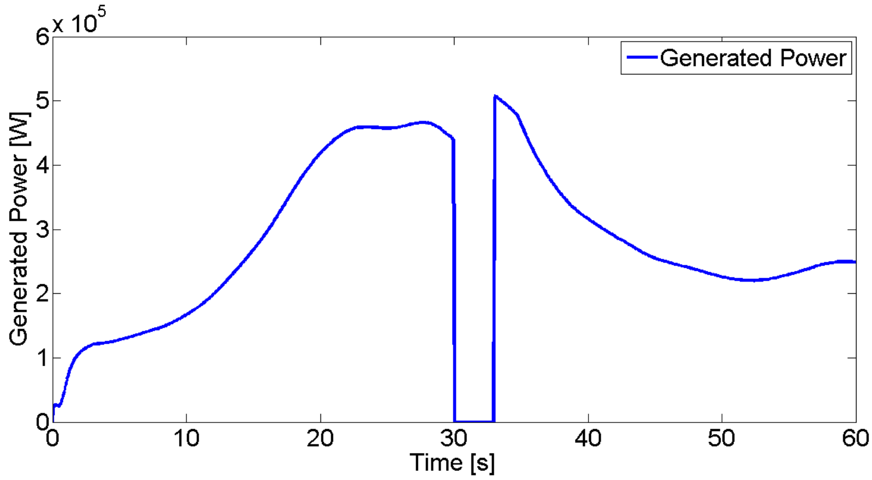

Figure 6.18: Resulting electrical power at the grid loss connection fault

Pitch controller keeps pitch angle at the zero degree to increase the maximum efficiency. However, mechanical power and generated electrical power do not reach the nominal values. Resulting torque reduces to 4000 N.m due to low wind speeds. The rotor and generator angular speeds also decrease from their nominal values.

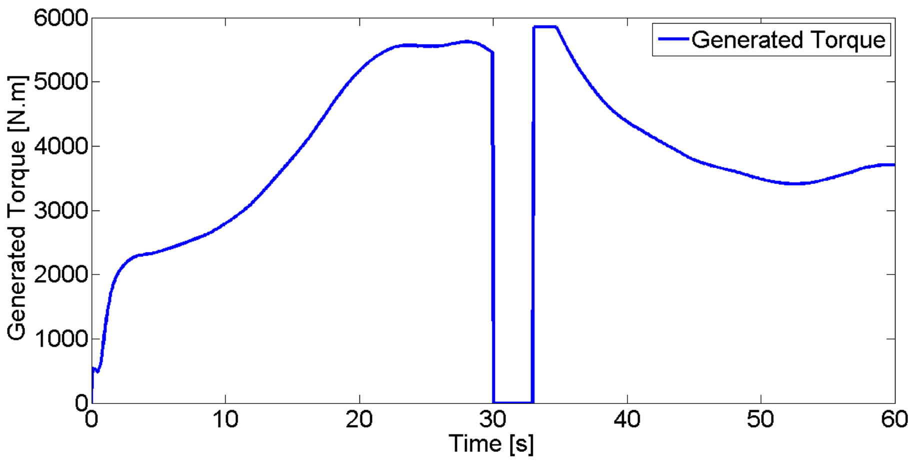

Figure 6.19: Resulting torque at the grid loss connection fault

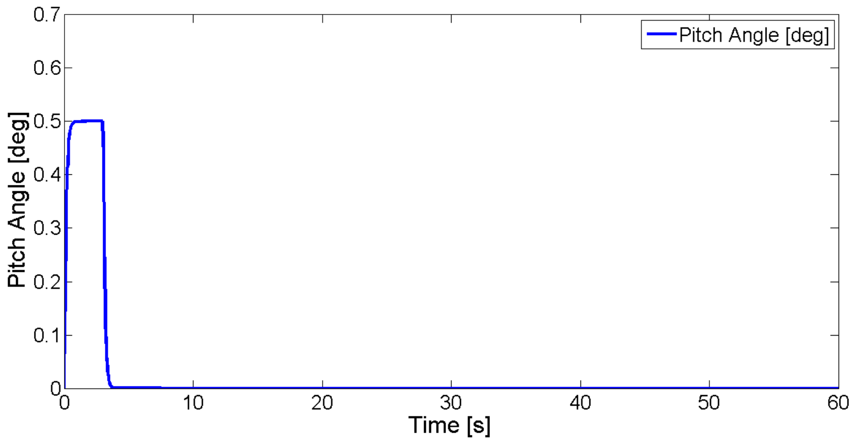

Figure 6.20: Resulting pitch angle at the grid loss connection fault

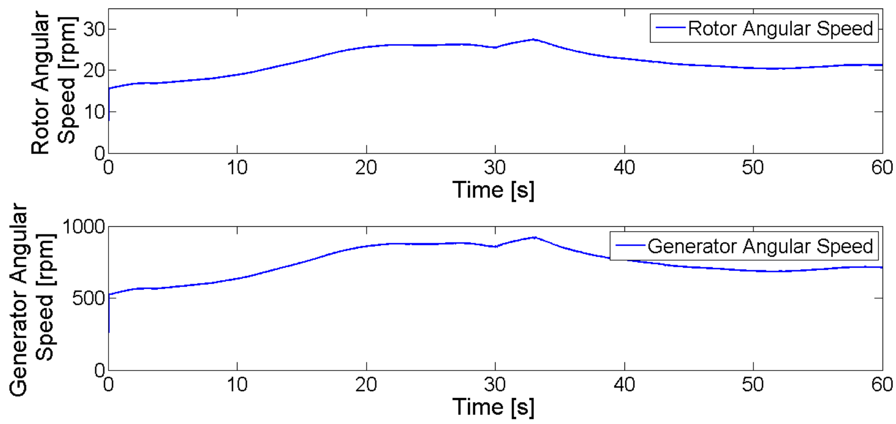

Figure 6.21: Resulting rotor and generator angular speeds at the grid loss connection fault

The fault of a pitch stuck can also be simulated in S4WT. This fault can be implemented to each of the blades. The wind speed model of grid loss simulation is also used for pitch stuck simulation. The absolute wind speed is presented in Figure 6.22. In Figures 6.23-6.24, the mechanical power is around 500 KW and the generated electrical power is 450 KW. The generated torque is around 5500 N.m in Figure 6.25.

It is understood that turbine does not have the nominal values although the input wind speed is around 11 m/s because the pitch angle of blade 1 to be stuck in 3^o and similarly, the pitch angle of blade 3 is to 8^o in Figure 6.26. The prototype turbine does not gain enough aerodynamic power from the wind and generated electrical power is not 500 KW.

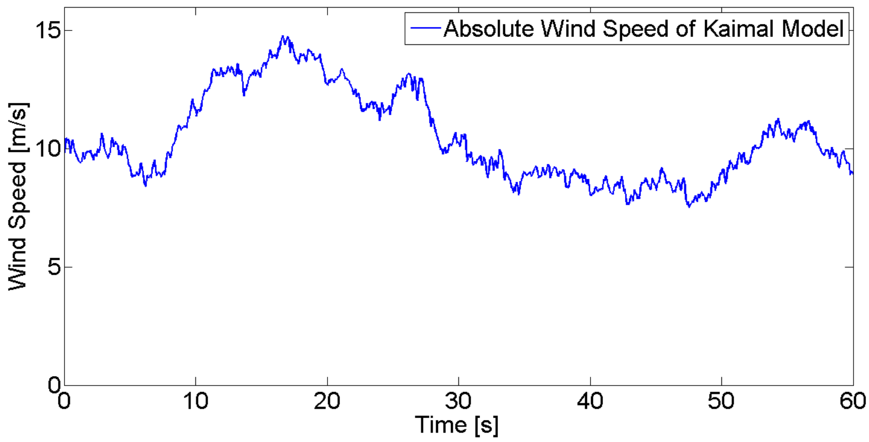

Figure 6.22: Absolute wind speed generated for pitch stuck connection fault

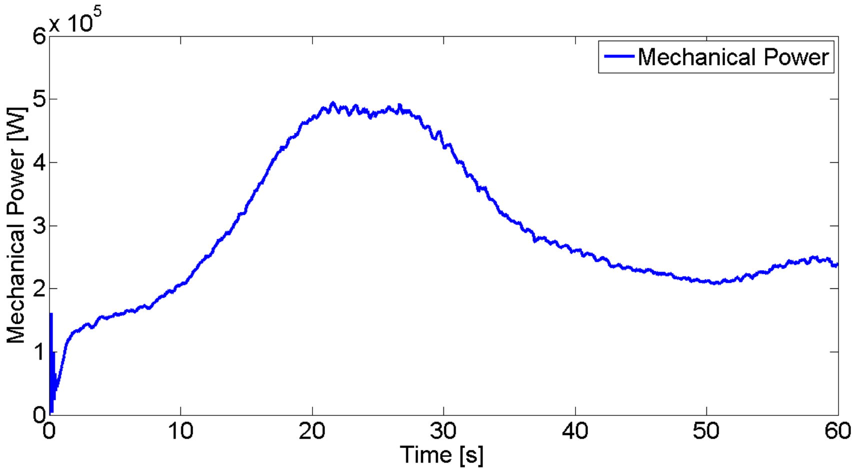

Figure 6.23: Resulting mechanical power at the pitch stuck connection fault

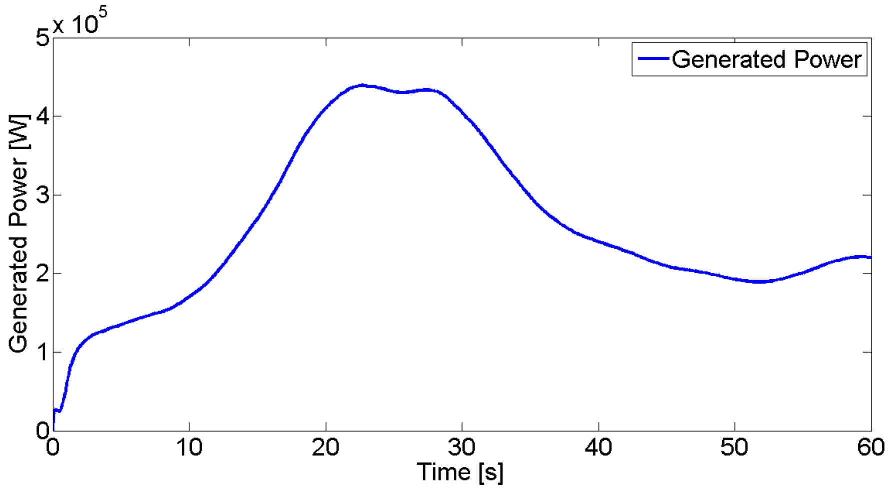

Figure 6.24: Resulting electrical power at the pitch stuck connection fault

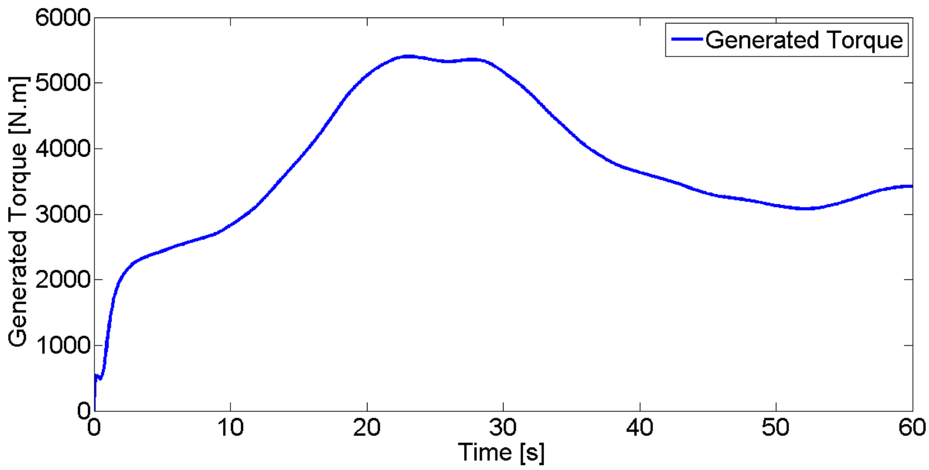

Figure 6.25: Resulting torque at the pitch stuck connection fault

Similarly, rotor and generator angular speeds are not exactly at the nominal values, but they are close; the rotor speed reaches 25 rpm and the generator speed reaches to 860 rpm in Figure 6.27. Input Kaimal wind speed decreases to smaller values at the 40-50 seconds so resulting powers, torque and angular speeds also reduce at that time.

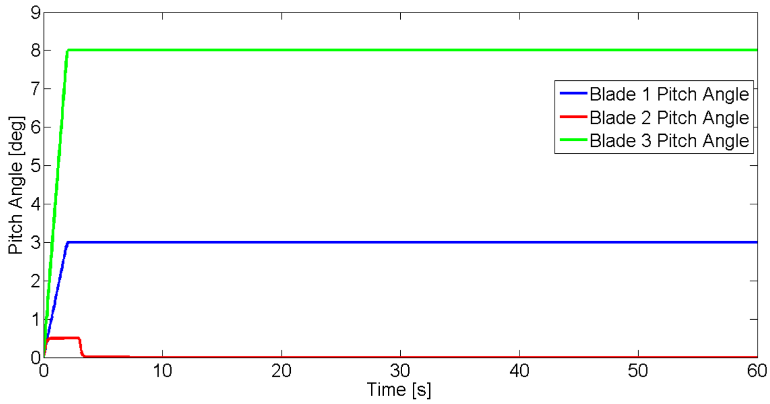

Figure 6.26: Resulting pitch angles at the pitch stuck connection fault

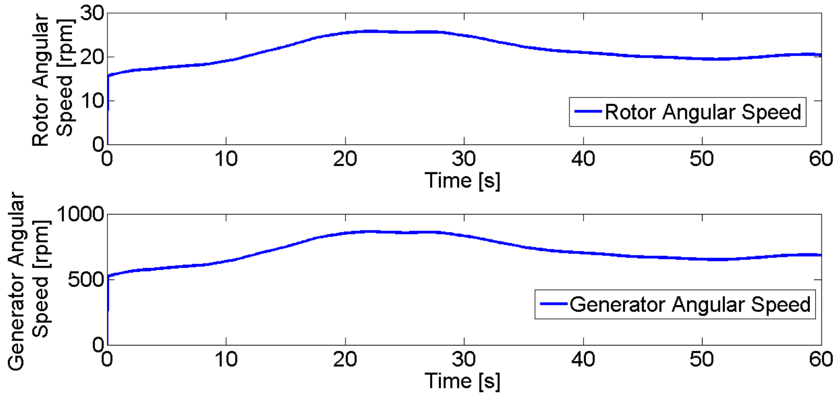

Figure 6.27: Resulting rotor and generator angular speeds at the pitch stuck connection fault

Both partial and full load scenarios are simulated. The wind speed is 7 m/s at the partial load operating region and the wind speed is 11 m/s at full load operating region in Figure 6.28. Then, generated power is around 150 KW as it is expected at the partial load operating region since input wind speed is not close to the nominal wind speed. However, generated power is around the nominal value of 500 KW at full load operating region due to increment in the wind speed to nominal value in Figure 6.29.

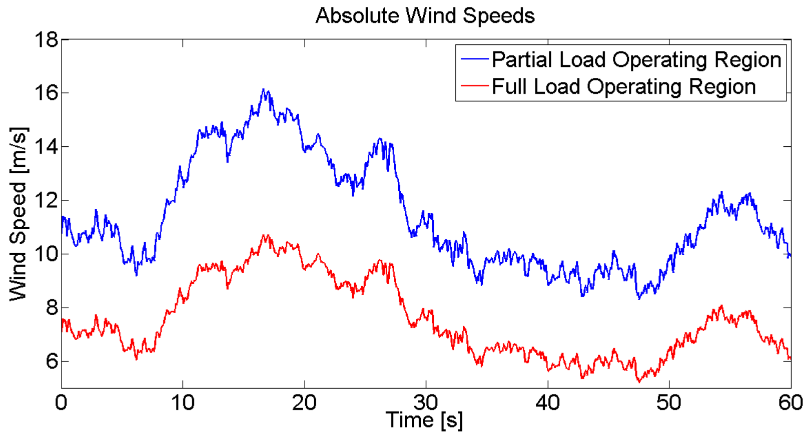

Figure 6.28: Absolute values of Kaimal model wind speeds under power production scenario

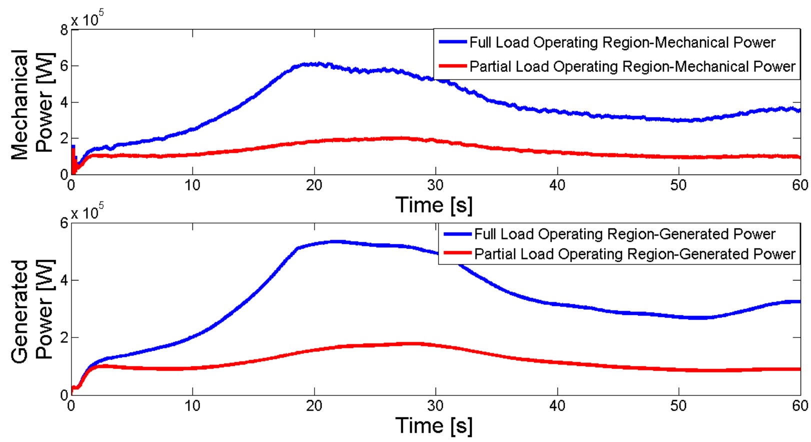

Figure 6.29: Resulting mechanical and electrical powers under power production scenario

As it is understood from Figure 6.30, pitch angle increases when the rotor speed exceeds nominal value so the generated power is limited. After 30 seconds, the wind speed decreases to 9 m/s at the full load operating region and 6 m/s at the partial load operating region. Low wind speeds prevent limitation of generated electrical power at the full load operating region and prototype turbine does not gain 600 KW mechanical power anymore.

At the partial load operating region, increase in the power production with maximum efficiency stops and prototype turbine generates electrical power which is smaller than beginning. As it is expected, resulting torque, rotor and generator angular speeds decrease at both operating regions.

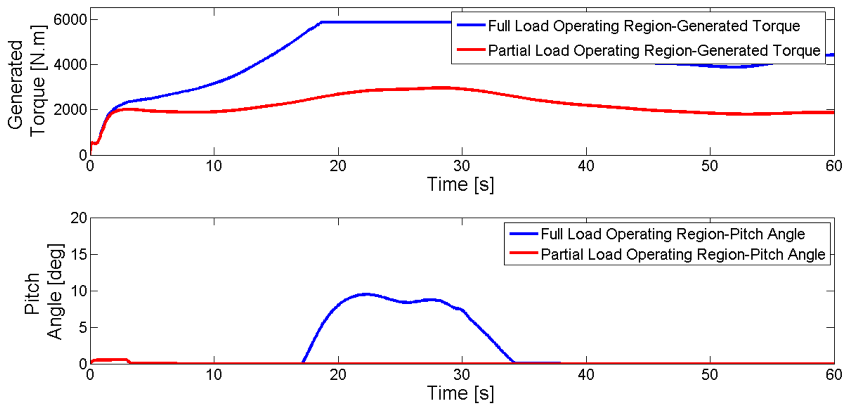

Figure 6.30: Resulting torque and pitch angle under power production scenario

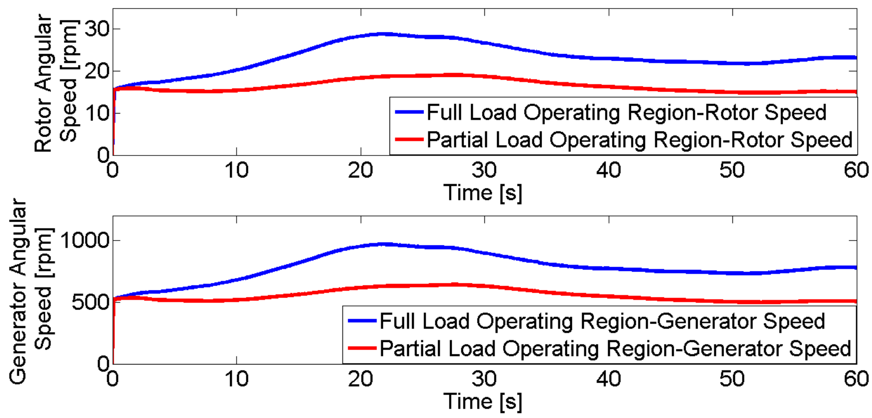

Figure 6.31: Resulting rotor and generator angular speeds under power production scenario

In start-up scenario, the wind speed is given as 1 m/s which is smaller than cut-in wind speed in Figure 6.32. Start-up scenario starts at 15 seconds and its duration is 25 seconds.

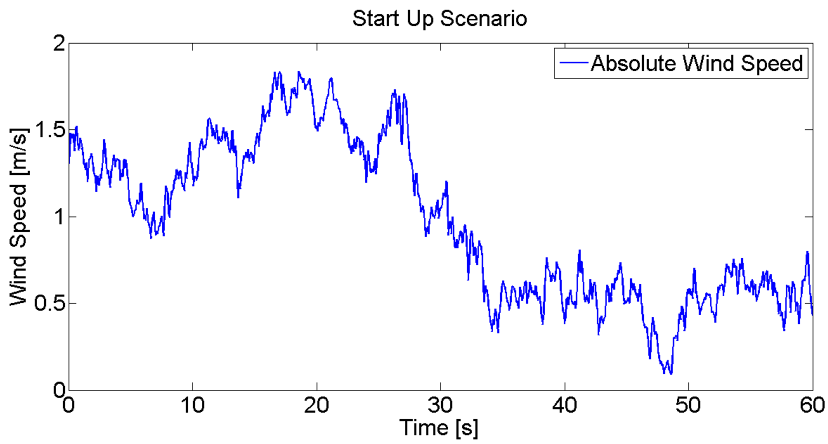

Figure 6.32: Absolute values of Kaimal model wind speeds under start up scenario

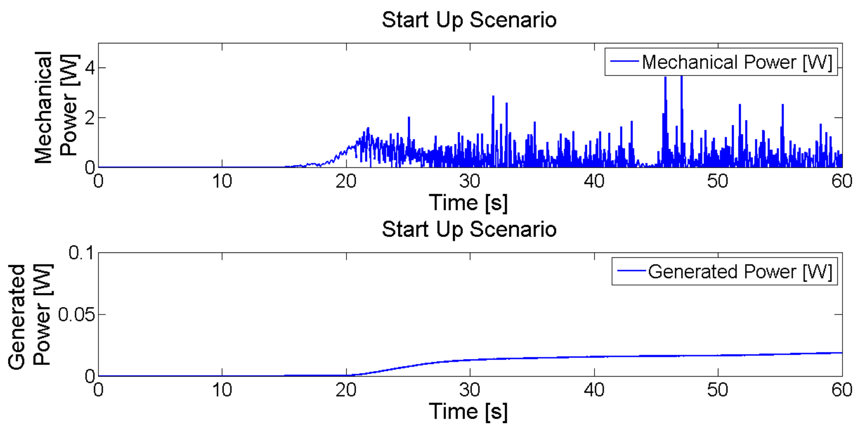

Figure 6.33: Resulting mechanical and electrical powers under start up scenario

The prototype turbine must not generate electrical power at the 15.seconds since the input wind speed is below of cut-in wind speed, 3 m/s.

It must be provided that the pitch angle is limited to 90^o until the beginning time of start-up scenario so the mechanical power extraction from the wind is prevented.

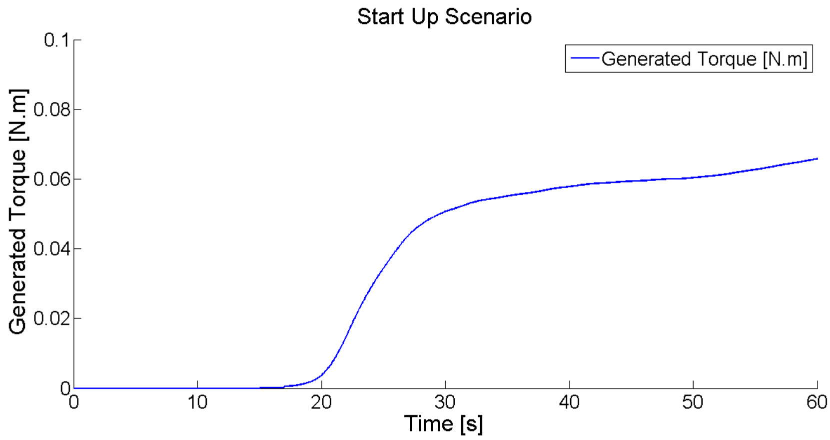

Figure 6.34: Resulting torque under start up scenario

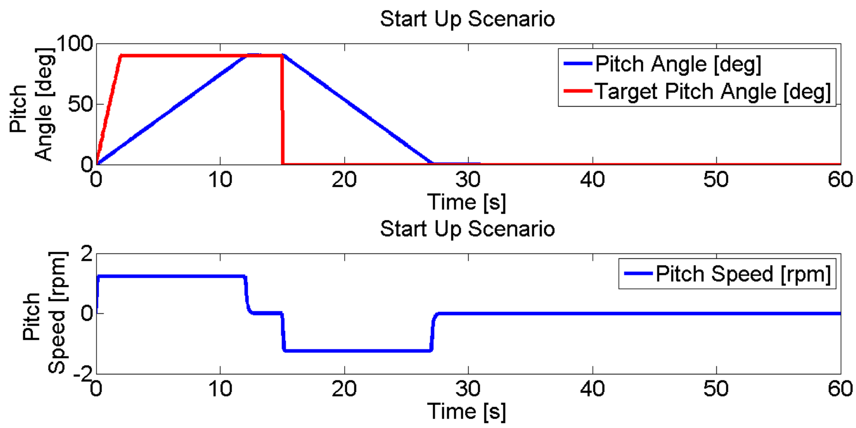

Figure 6.35: Resulting pitch angle and pitch speed under start up scenario

The generated power is zero at the beginning of the scenario by limiting the pitch angle to 90^o in Figure 6.33. The pitch speed limit is around 1 rpm during the increment of the pitch angle to 90^o and it decreases to -1 rpm during the pitch angle decrement to 0^o.

Resulting torque, rotor and generator angular speeds have small values in Figure 6.34 and Figure 6.36.

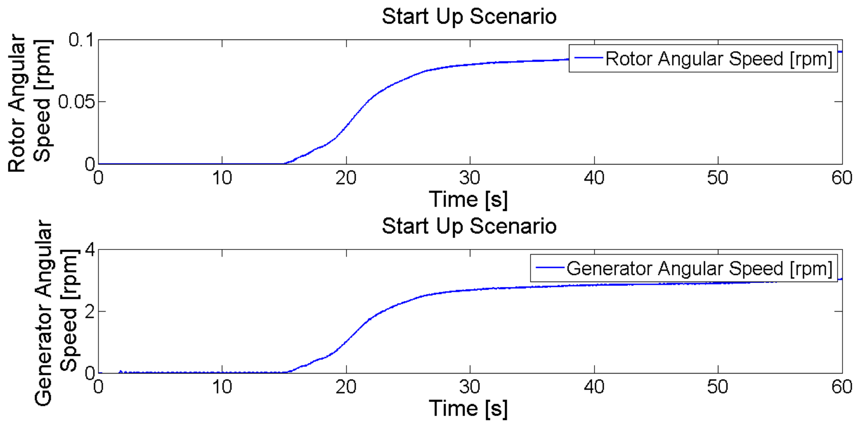

Figure 6.36: Resulting rotor and generator angular speeds under start up scenario

In normal shut down scenario, input wind speed exceeds the cut-off wind speed, 23 m/s in Figure 6.37. Then, turbine operation must be stopped to protect it from excessive loads since mechanical power is around 3 MW in Figure 6.38 due to high wind speeds.

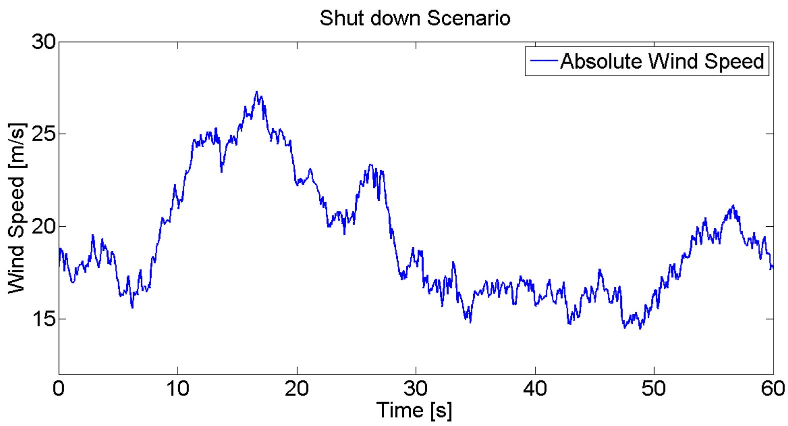

Figure 6.37: Absolute values of Kaimal model wind speeds under shut down scenario

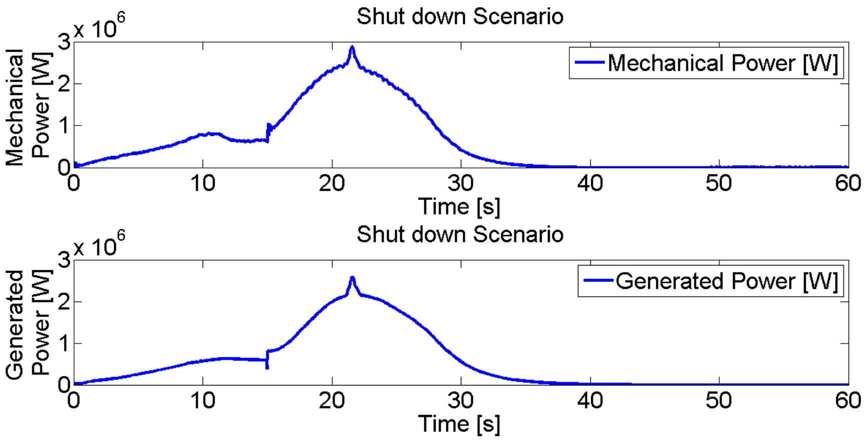

Figure 6.38: Resulting mechanical and electrical powers under shut down scenario

To achieve this, the pitch angle is limited to 90^o and the prototype turbine will not gain mechanical power anymore. In Figure 6.39, torque controller helps pitch controller between the 10-15.seconds of the simulation. However, it becomes ineffective after the 15.seconds and the generated torque exceeds the maximum torque.

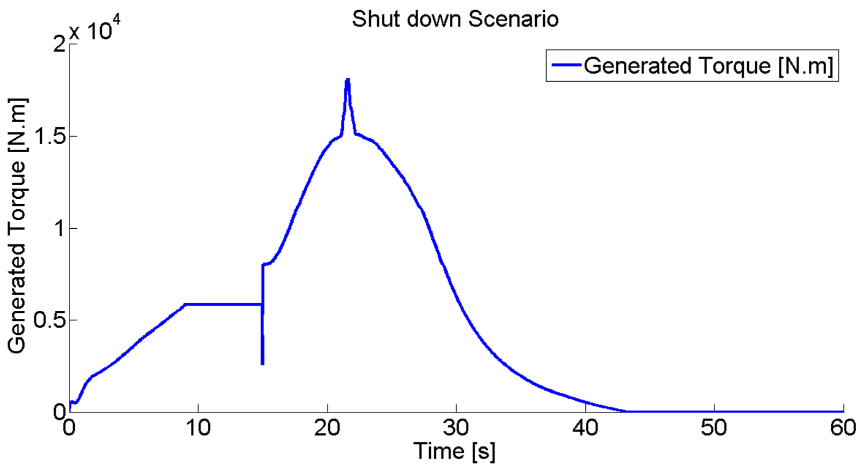

Figure 6.39: Resulting torque under shut down scenario

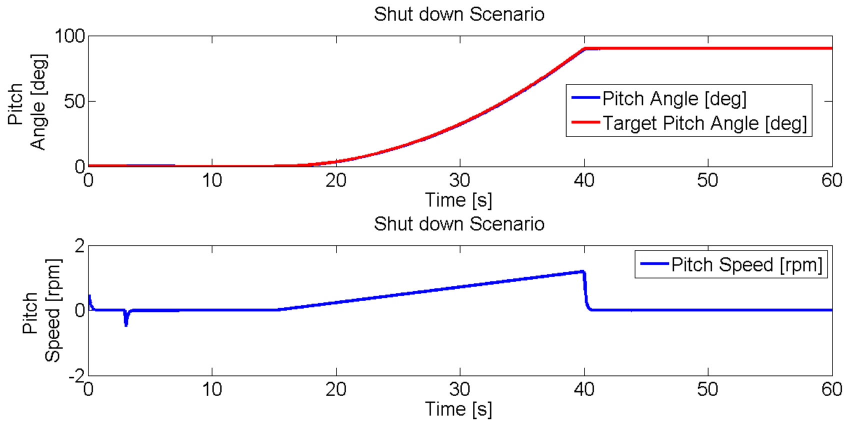

Figure 6.40: Resulting pitch angle and pitch speed under shut down scenario

It is reminded that the main usage area of the torque controller is the partial load operating region and it is only the auxiliary controller for the full load operating region. The pitch controller is the main controller in this simulation. The rotor and generator shafts stop turning when the blades are limited to 90^o in Figure 6.41. The generated electrical power decreases to zero value.

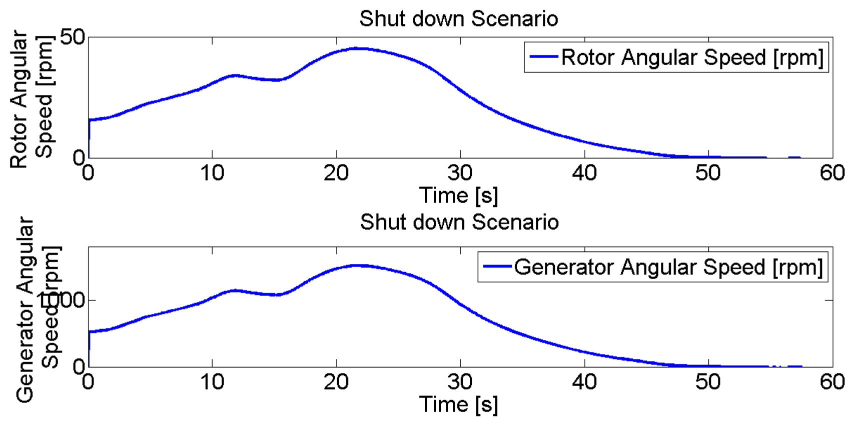

Figure 6.41: Resulting rotor and generator angular speeds under shut down scenario

In emergency scenario, grid loss connection is simulated. However, this is different from the previous grid loss connection simulation. The prototype turbine has three seconds connection loss in the previous simulation. In emergency scenario, problem is huge since grid is disconnected due to the light striking or technical faults at the transmission cable. The connection loss takes much more time of 25 seconds.

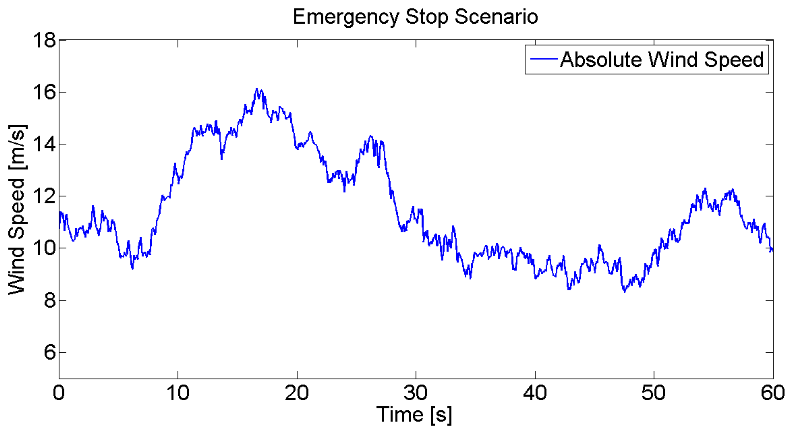

Figure 6.42: Absolute values of Kaimal model wind speeds under emergency scenario

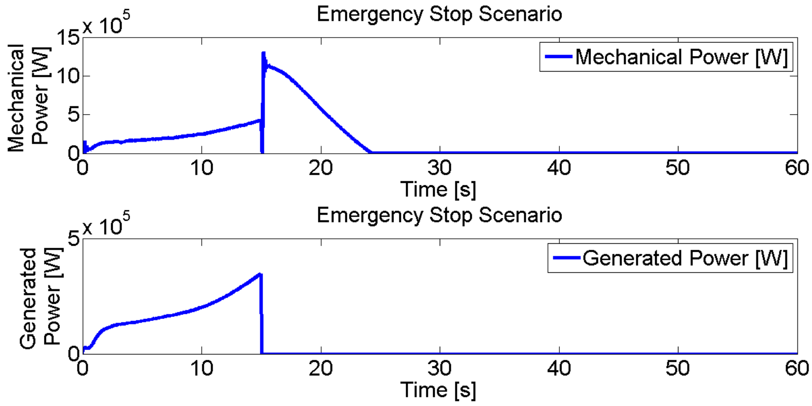

Figure 6.43: Resulting mechanical and electrical powers under emergency scenario

The given wind speed is as in Figure 6.42. This wind speed is above the nominal wind speed, 11 m/s. Grid loss occurs at the 15 seconds. Then, the peak occurs at that time in the mechanical power. However, generated power drops to zero because generator is immediately disconnected with the turbine in Figure 6.43.

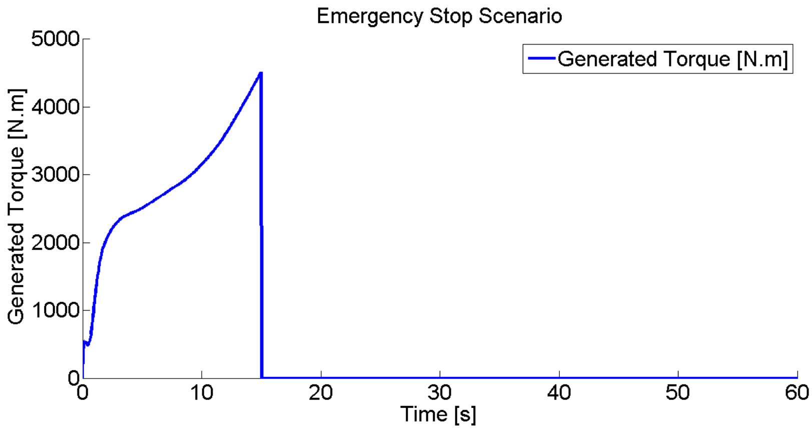

Figure 6.44: Resulting torque under emergency scenario

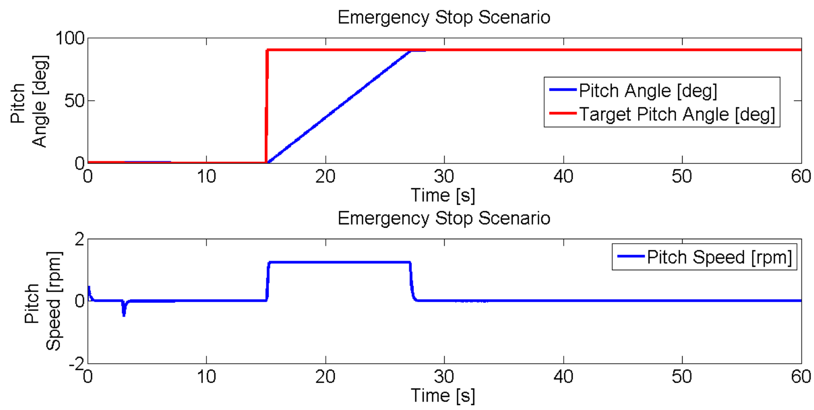

Figure 6.45: Resulting pitch angle and pitch speed under emergency scenario

At that time, the pitch angle is increased to target value of 90^o to decrease rotor shaft speed to zero. Therefore, mechanical power is not gained anymore.

The rotor and generator angular speeds drops to zero in Figure 6.46.

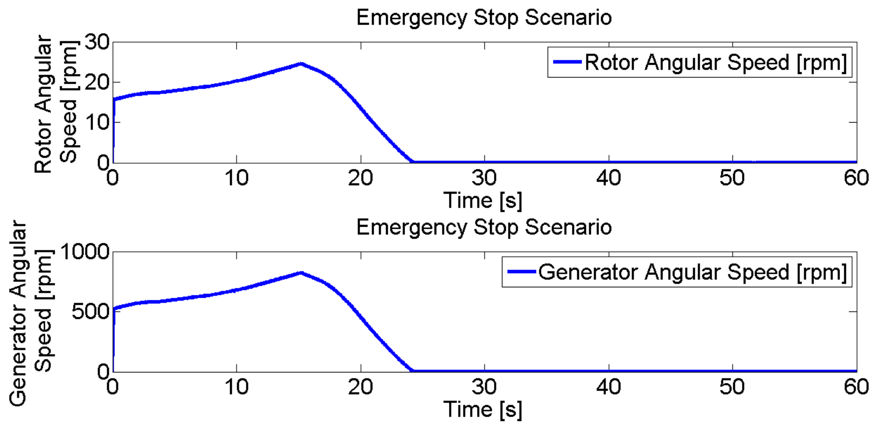

Figure 6.46: Resulting rotor and generator angular speeds under emergency scenario

In parked scenario, the wind speed is given as in Figure 6.47. Blades are parked to 90^o by the pitch controller to decrease the generated power as in Figure 6.48. The mechanical power decreases from 5000 W to zero value and generated electrical power reduces from 1800 W to zero value.

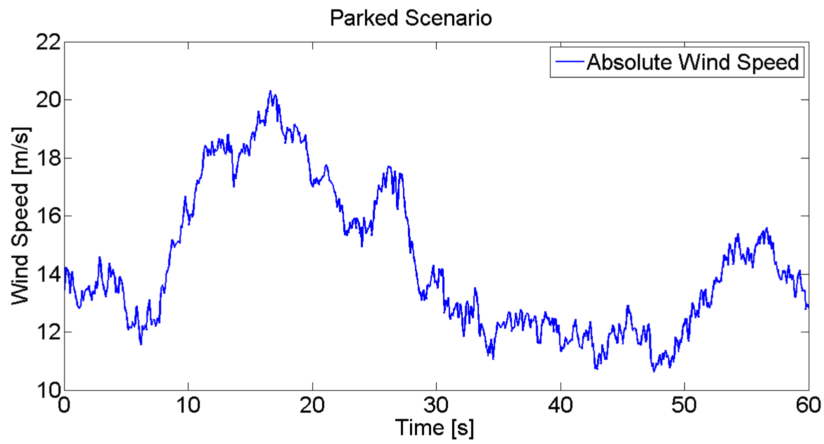

Figure 6.47: Absolute values of Kaimal model wind speeds under parked scenario

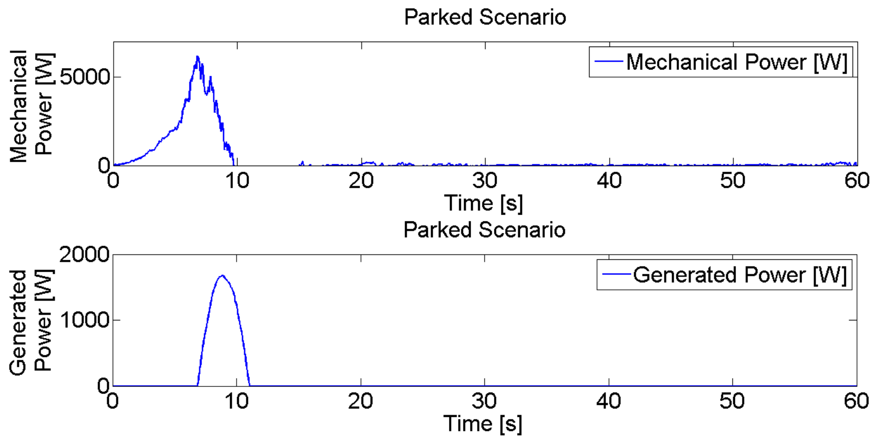

Figure 6.48: Resulting mechanical and electrical powers under parked scenario

The generated torque also decreases from 130 N.m to zero in Figure 6.49. The pitch speed limit is 1 rpm until the blades are parked to 90^o. Then, it becomes zero since the pitch mechanism keeps the blade angle to 90^o.

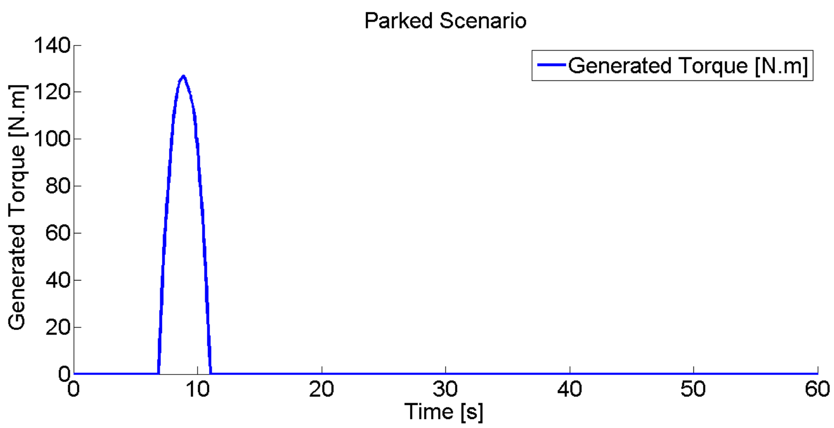

Figure 6.49: Resulting torque under parked scenario

When pitch angles are parked to 90^o, rotor and generator shafts stop to turn. Rotor and generator angular speeds are presented in Figure 6.51.

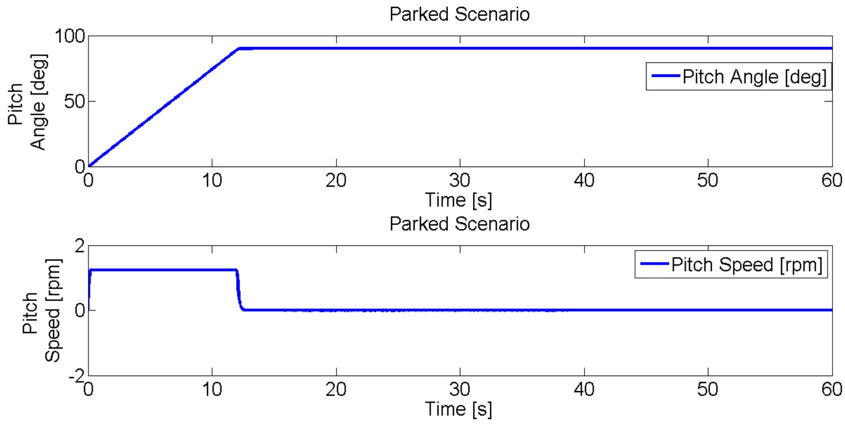

Figure 6.50: Resulting pitch angle and pitch speed under parked scenario

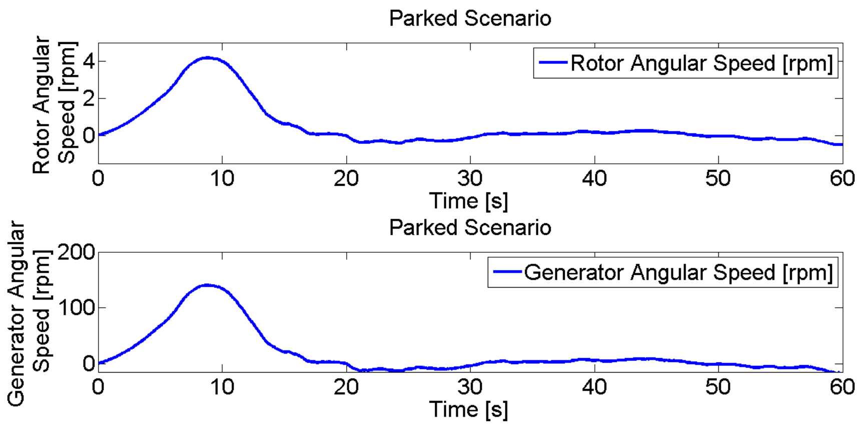

Figure 6.51: Resulting rotor and generator angular speeds under parked scenario

6.3 The results of the prototype turbine transient analysis in Matlab/Simulink environment

Kaimal wind speed model which is generated in S4WT using Turbsim, is imported to Matlab model as an input for both operating regions. At the partial load operating region, the wind speed is 7 m/s in Figure 6.52. Resulting mechanical power is around 12000 W and torque is around 500 N.m in Figure 6.53. Figure 6.54 shows that generated active power tracks the reference active power. Generated active power is about 10 KW at the partial load operating region. This result is expected since input wind speed does not reach the nominal wind speed. The reactive power drops to zero as it is desired. Rotor and generator speeds cannot reach the nominal values in Figure 6.55.

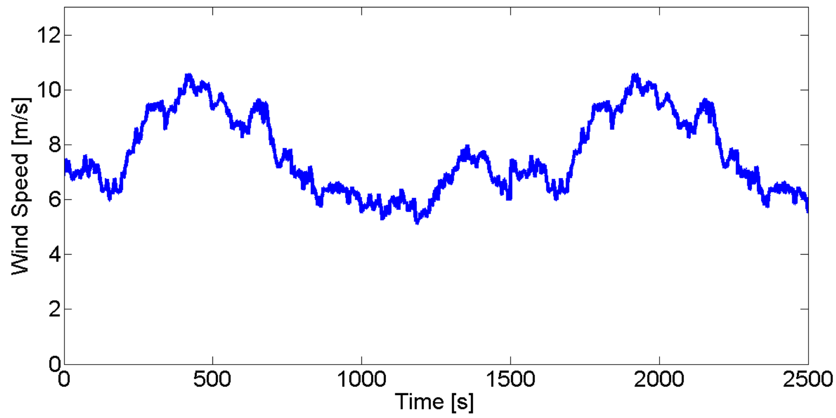

Figure 6.52: Wind speed profile for partial load operating region

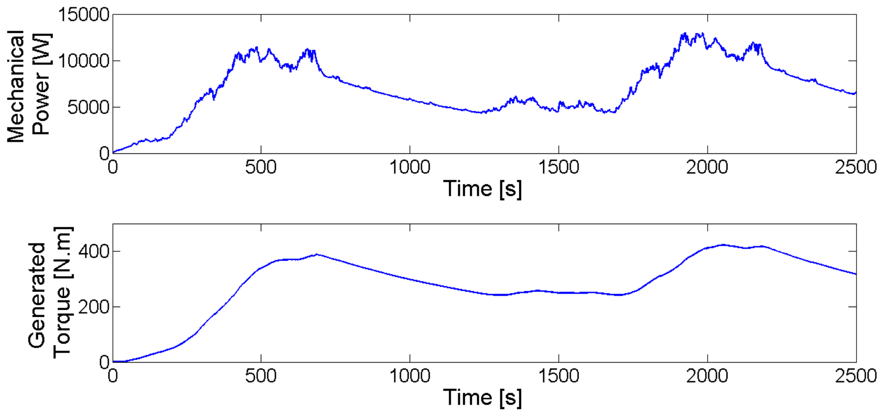

Figure 6.53: Resulting mechanical power and torque at the partial load operating region

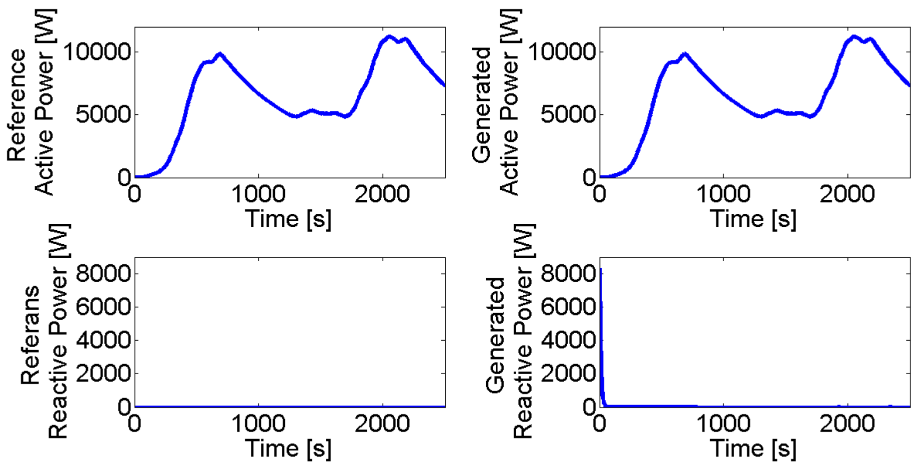

Figure 6.54: The reference and generated active and reactive powers at the partial load operating region

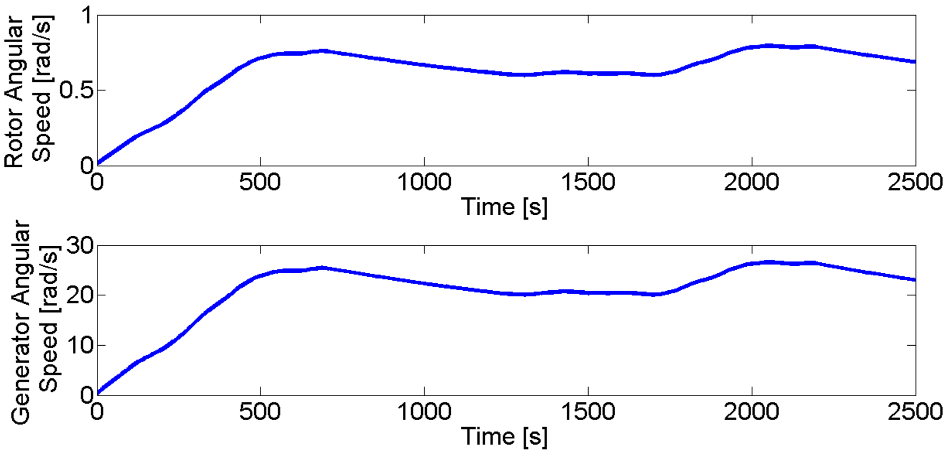

Figure 6.55: Rotor and generator angular speed at the partial load operating region

At the full load operating region, wind speed is 11 m/s in Figure 6.56. Resulting mechanical power is 600 KW and the generated torque reaches the maximum value in Figure 6.53.

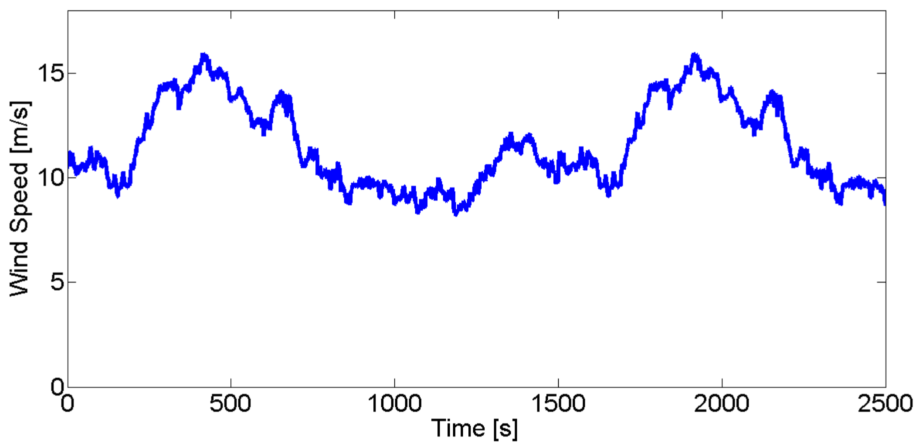

Figure 6.56: Wind speed profile for full load operating region

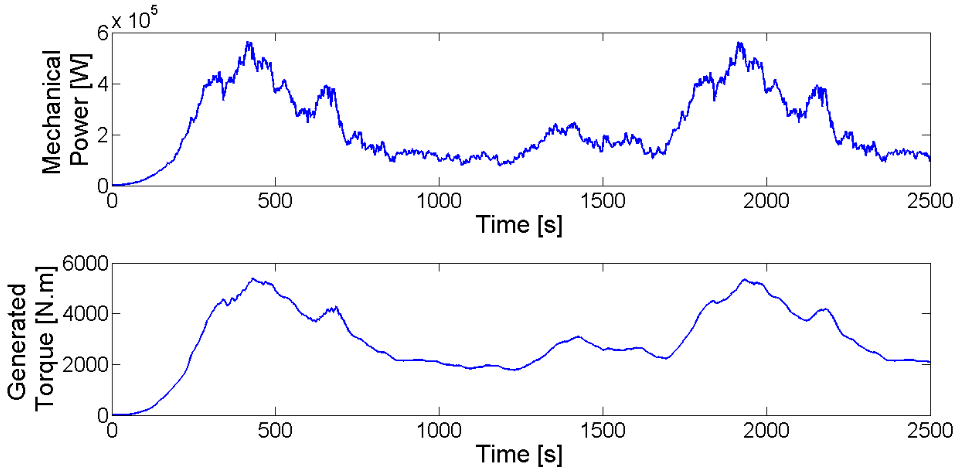

Figure 6.57: Resulting mechanical power and torque at the full load operating region

The generated active power reaches the nominal value of 500 KW at the full load operating region in Figure 6.58 because the wind speed increases to nominal value. The generated reactive power drops to zero as it is desired. The rotor and generator speeds are presented in Figure 6.59. Both of them reach the nominal values.

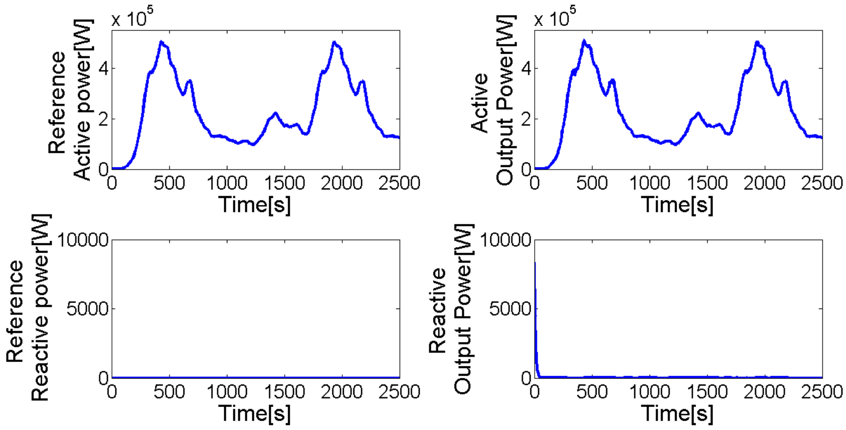

Figure 6.58: The reference and generated active and reactive powers at the full load operating region

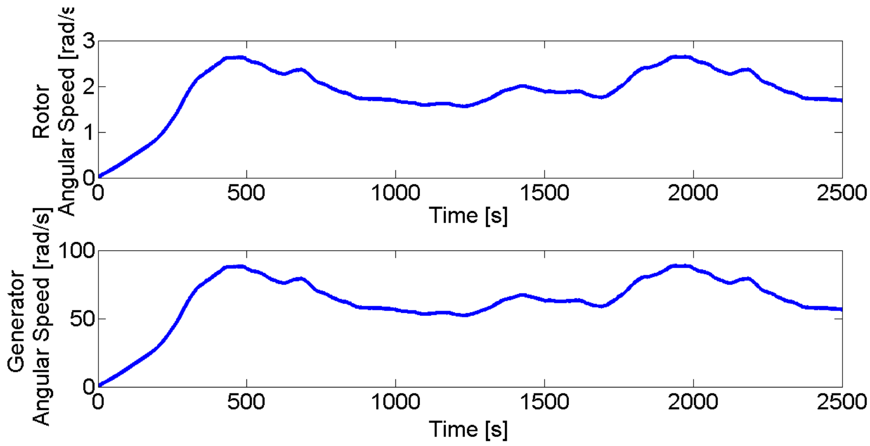

Figure 6.59: Rotor and generator angular speed at the full load operating region

Chapter VII

7 Conclusion & Future Works

We have now presented modeling, control and simulation of a prototype wind turbine in S4WT and Matlab/Simulink environments. The parameters of the prototype wind turbine components (tower, bedplate, gearbox, blades, rotor shaft, coupling shaft and generator) are used in simulations. Realistic wind profiles are created by using Kaimal spectrum in Turbsim. In S4WT environment, the pitch controller is designed such that it consists of pitch function and the PI controller with gain scheduling. PI starting time parameter is used for distinguishing how to control the pitch angle. S4WT torque controller ensures that the wind turbine achieves the condition of optimum tip speed ratio (TSR) by using the optimal mode gain parameter, $K_{optimal}$. In Matlab/Simulink environment, proportional (P) controller is designed to control pitch angles and the sliding mode controller is utilized to keep the tip speed ratio. The pitch actuator mechanism changes slowly, so the torque controller is also used at the full load operating regions under the power production scenario in both environments.

First, S4WT simulations are done for a 2 MW wind turbine under power production scenario in order to figure out S4WT environment. Power production is the simplest scenario for wind turbine performance analysis and it is implemented at both partial load and full load operating regions. A constant wind speed in X direction is given as an input to 2 MW wind turbine model which consists of simple components. After simple components are replaced by standard components, parameters of the 500 KW prototype wind turbine are assigned to this model. Different wind models are generated for 500 KW prototype wind turbine. Constant wind speeds in three directions of X, Y and Z are used under power production scenario. Also, simulations of the prototype turbine are done during the grid loss connection and pitch stuck faults using Kaimal wind speed model. Start-up, shut down, emergency and parked scenarios are also simulated with different wind speeds of Kaimal spectrum in S4WT. The performance analysis of the 500 KW prototype turbine is also done in Matlab/Simulink environment using generated Kaimal wind speed model in S4WT environment. Results are quite successful.

As a future work, modal and fatique analyzes can be performed under different turbine scenarios. Wind models including Extreme Coherent Gust, Extreme Direction Change, Extreme Coherent Gust with Direction Change, Extreme Operating Gust and Extreme Wind Shear can be used as inputs for these scenarios.

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