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MODELING AND CONTROL OF A VARIABLE SPEED VARIABLE PITCH ANGLE PROTOTYPE WIND TURBINE

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Abstract- This paper focuses on modeling, control and simulation of a $500\,KW$ horizontal axis prototype wind turbine that is being developed in the context of the MILRES (National Wind Energy Systems) Project in Turkey. The prototype turbine is designed as variable speed variable pitch angle wind turbine due to its advantages in efficiency and the structure. Aerodynamic, mechanical and electrical subsystems along with pitch and torque controllers are designed in both Matlab/Simulink and S4WT simulation environments. The main control purpose is to generate a power curve that is close to the ideal power curve where the energy efficiency is maximized below the nominal wind speed of $11\,m/s$ and the power is limited to the nominal value above the nominal wind speed. Turbsim is integrated with both environments to generate a realistic wind profile of Kaimal turbulence model. The performance analysis of the prototype turbine is done under the power production scenario in both environments. Start up, emergency stop, shut down and parked scenarios are also implemented in S4WT.

Key Words- Wind turbine, S4WT, pitch control, torque control

1. INTRODUCTION

Wind energy is the fastest growing source of electricity production among all types of renewable energies. The use of wind energy and more precisely wind turbines have been increased drastically due to its economical, social and environmental advantages. Wind energy can diversify economies of rural communities by adding a new source of property value in rural areas. Moreover, all energy systems including wind are subsidized by the governments. Wind turbines reduce the dependency on the foreign fossil fuels. The wind energy is renewable and sustainable. These advantages have motivated Turkey to concentrate on the wind energy and its economical, social and environmental benefits. Today, the total installed wind capacity has reached $1405.95\,MW$, but the total potential of Turkey is $47{,}849\,MW$ by assuming the wind speeds above 7 m/s. This installed wind capacity has the rank 11 in Europe and 17 in the worldwide.

Wind turbines are electromechanical systems which convert kinetic energy of the wind to the mechanical energy and then to the electrical energy by generators. The main components of a wind turbine are blades, hub, low speed shaft, drive train, high speed shaft, generator and tower. Hub and blades that are the parts of the rotor form the aerodynamic subsystem. Mechanical subsystem consists of low speed shaft, drive train and high speed shaft. Electrical subsystem is composed of the generator. Wind turbines can be designed based on different operating principles. They can be designed as constant/variable speed and constant/variable pitch angle [1,4,9]. Wind turbines are divided into two classes depending on the rotor axis; horizontal and vertical axis wind turbines. While horizontal axis wind turbines have rotor axis parallel to wind streamlines, vertical axis wind turbines have rotor axis perpendicular to wind streamlines. Savonius rotor is the most common example of the vertical axis turbines. Their maintenances are easy because the mechanical components (gearbox, generator) are at the ground level. There is no yaw system. This is countered by disadvantages of the low tip speed ratio and not having a control system for the generated power. Today, modern wind turbines are mostly horizontal axis wind turbines because of their advantages. The rotor blade shape can be aerodynamically optimized to reach the highest efficiency. Furthermore, the rotor speed and the generated power can be controlled by changing the pitch angles [2].

The main problem of the horizontal axis wind turbines is to maximize the power efficiency below the nominal wind speed (low wind speeds) and limit the nominal power above the nominal wind speed (high wind speeds). To solve this problem, variable speed variable pitch angle wind turbines are used due to their advantages in efficiency and structure. These turbines can have different torque controllers to maximize the power efficiency [3] and pitch controllers to limit the nominal power [4]. As shown in the next section, solving this problem is equivalent to achieving the ideal power curve.

The aim of this paper is to develop dynamic models of mechanical, electrical and aerodynamic subsystems and design the control system of the prototype turbine in order to reach the nominal power at the low wind speeds and limit it at the high wind speeds. Design and analysis are done in both Matlab and S4WT environments. In S4WT, wind turbines can be constructed with FEM models and analysis can be performed under various scenarios such as power production, start up, emergency stop, shut down and parked [5].

The organization of the paper is as follows: In section 2, aerodynamic, mechanical and electrical models and the control system of the prototype wind turbine are designed in both Matlab and S4WT. Section 3 presents simulation results of the prototype wind turbine under different scenarios. Finally, Section 4 concludes the paper with some remarks and indicates possible future directions.

2. WIND TURBINE MODELING AND CONTROL

Wind turbines have aerodynamic subsystem, mechanical subsystem, electrical subsystem and necessary controllers such as torque and pitch controllers (see Fig.1).

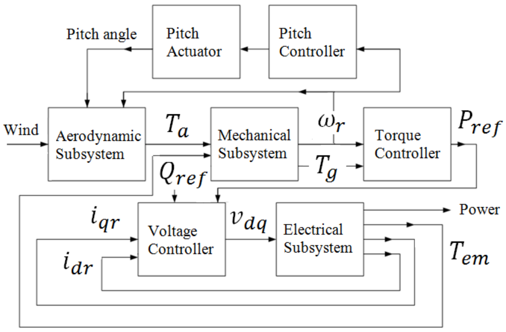

Figure 1. Wind turbine block diagram

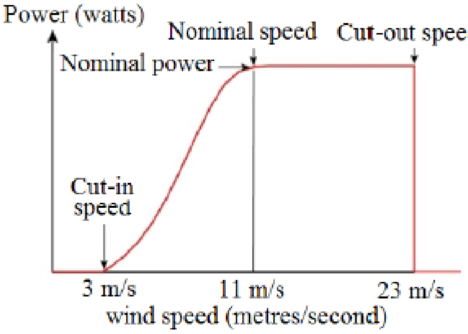

Figure 2. Ideal power curve

The capacity of wind turbines is related to the maximum power captured from the wind. Ideal power curve shows the optimum energy gathering from the wind depending on the wind speed. A typical power curve for a wind turbine is given in Fig. 2. The ideal power curve has two operating regions depending on the wind speeds; the partial load and the full load operating region. The partial load operating region has the wind speeds below the nominal value (low wind speeds) and the full load operating region has the wind speeds above the nominal value (high wind speeds).

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 power at the nominal wind speed. To achieve this, torque control is needed. The aim of the torque controller is to determine an optimal pitch angle and tip speed ratio that are the functions of the power coefficient. When the power coefficient is maximized, the nominal power can be reached. This torque controller is mentioned in Sections 2.1.5 and 2.2.2 for both environments. 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. Pitch controller decreases the power coefficient by increasing the pitch angle. This principle is given in Sections 2.1.6 and 2.2.2 for both environments. When the wind speed reaches cut-out wind speed, the wind turbine must be shut down since loads become excessive. The torque control is also used at the full load operating region because the pitch actuator changes the pitch angle slowly.

2.1. Wind turbine modeling and control in Matlab/Simulink environment

Aerodynamic, mechanical and electrical subsystems of the prototype turbine are designed in Matlab/Simulink environment in Sections 2.1.1-2.1.3. The pitch and torque controllers are used to achieve an actual power curve that is very close to the ideal one. A sliding mode controller (SMC) is utilized for controlling the torque to increase power efficiency at the partial load operating region in Section 2.1.5. A simple Proportional (P) controller is used for the pitch controller at the full load operating region in Section 2.1.6. Torque controller is also an auxiliary controller at that region due to the slow pitch mechanism.

2.1.1. Aerodynamic Subsystem

The aerodynamic torque and power that are extracted from the horizontal axis wind turbines are :

$$T_a = \frac{1}{2\lambda^2}\varphi\pi R^5 C_q(\lambda,\beta)\omega_r^2 \text{ and } P_a = \frac{1}{2}\varphi\pi R^2 C_p(\lambda,\beta)V^3 \tag{1}$$

where C_p, R, V, φ, β, λ and ω_r denote the power coefficient, rotor radius, wind speed, air density, pitch angle, tip speed ratio and angular speed of the turbine rotor, respectively. The power coefficient C_p is a function of the tip speed ratio and the pitch angle. Eqns. (2) and (3) present the model of power coefficient.

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

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

The power and torque coefficient curves are presented in [6]. Tip speed ratio, λ, describes ratio of the relative speed at the blade tip to the wind speed and the torque coefficient, C_q, is the division of power coefficient to tip speed ratio :

$$\lambda = \frac{R\omega_r}{V} \quad \text{and} \quad C_q = \frac{C_p}{\lambda} \tag{4}$$

2.1.2. Mechanical Subsystem

In literature, there are two mechanical models for wind turbines. Fig. 3 gives two mass model of wind turbine. Driving by the aerodynamic torque, the wind turbine rotor runs at the speed ω_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 ω_g. Rotor and generator dynamics of two mass system are presented in [7]. The gearbox ratio is defined as :

$$n_g = \frac{\omega_g}{\omega_r} = \frac{T_{ls}}{T_{hs}} \tag{5}$$

The wind turbine dynamic model become one mass model in Fig. 4 when turbine dynamics brought back to the low speed side :

$$J_t \dot{\omega}_r = T_a - T_g \tag{6}$$

where T_g is the generator torque at the rotor side through the gearbox, J_t is the total inertia of the rotor and the generator.

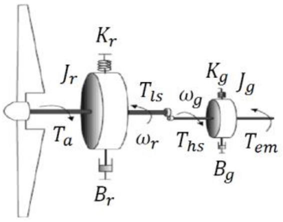

Figure 3. Two mass model

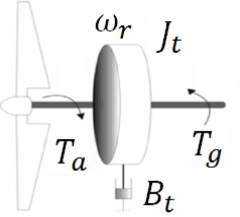

Figure 4. One mass model

2.1.3. Electrical Subsystem

In electrical subsystem, the rotor controlled doubly fed induction generator (DFIG) is used. 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. This is the advantage of DFIG. Flux and current dynamics of rotor and stator which are related to Fig. 5 are given in [8]. Power and torque equations are :

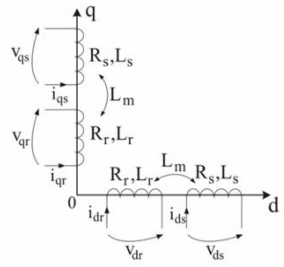

Figure 5. d-q axis of DFIG

$$T_{em} = pL_m\left(i_{qs}i_{dr} - i_{ds}i_{qr}\right) \tag{7}$$

$$P_s = \frac{3}{2}\left(v_{ds}i_{ds} + v_{qs}i_{qs}\right) \tag{8}$$

$$Q_s = \frac{3}{2}\left(v_{qs}i_{ds} + v_{ds}i_{qs}\right) \tag{9}$$

2.1.4. Voltage Controller

The voltage controller of DFIG model is designed using PI controllers in Fig. 1. 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 which is given in Section 2.1.5. 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_{qr}, i_{dr}. 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_{qr}, v_{dr} that are given as inputs to DFIG in Fig. 1.

2.1.5. Torque Controller

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 nominal wind speed. Then, the maximum power and torque coefficients depend on the optimal pitch angle and tip speed ratio in Eqn. (10).

$$C_{pmax} = C_p\left(\lambda_{opt}, \beta_{opt}\right) \quad \text{and} \quad C_{qmax} = \frac{C_p\left(\lambda_{opt}, \beta_{opt}\right)}{\lambda_{opt}} \tag{10}$$

The aerodynamic torque is derived in Eqn. (1). Thus, an optimum aerodynamic torque which is the multiplication of optimal gain parameter and square of rotor angular speed, is calculated :

$$T_{opt} = K_{opt}\,\omega_r^2 \quad \text{and} \quad K_{opt} = \frac{1}{2\lambda_{opt}^2}\varphi\pi R^5 C_{qmax} \tag{11}$$

At the partial load region, K_{opt} value is hold constant to achieve the maximum power from the wind. From Eqn. (11) it is seen that K_{opt} depends on the maximum torque coefficient. Thus, the goal of the torque controller is to find an optimal pitch angle and tip speed ratio which are the functions of the maximum power and torque coefficients. 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 developed in [9] is used to handle nonlinearities and compensate for uncertainties. It uses the Maximum Power Point Tracking (MPPT) algorithm. In this technique, the reference power is computed by multiplying optimum aerodynamic moment with the angular speed of the turbine rotor. Sliding mode controller eliminates the error between the generated power at the low speed side, P_g and the reference power.

$$P_{ref} = T_{opt}\,\omega_r \,,\ \varepsilon_p = P_{ref} - P_g \quad \text{and} \quad \dot{\varepsilon}_p = \dot{P}_{ref} - T_g\dot{\omega}_r - \dot{T}_g\omega_r \tag{12}$$

The derivative of the generator torque is designed as in Eqn. (13) in order to decrease the maximum power tracking error to zero.

$$\dot{T}_g = \frac{(B+\zeta)sgn(\varepsilon_p)}{\omega_r} \tag{13}$$

The generator torque at the low speed side is computed by taking integral of Eqn. (13). When this torque is divided by the gearbox ratio, reference electromagnetic torque is obtained. This value is then multiplied by the generator angular speed to calculate the reference active power for voltage controller in Section 2.1.4.

2.1.6. Pitch Controller

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 of $500\ KW$ at the full load operating region. We know that if the pitch angle changes, then the power coefficient changes as shown in Eqn. (2). Then, the power is maximized or limited depending on the increment and decrement of power coefficient so the pitch angle must be increased by the pitch controller to decrease the power coefficient. Therefore, the generated power is limited. The pitch controller uses the rotor angular speed as an input and the error is given in Eqn. (14).

$$\varepsilon_\omega = \omega_{nom} - \omega_r \tag{14}$$

Pitch controller is designed using proportional (P) controller in Eqn. (15). The desired pitch angle is the summation of measured pitch angle and the pitch angle change.

$$\Delta\beta = K_p \varepsilon_\omega \quad \text{and} \quad \beta_d = \beta + \Delta\beta \tag{15}$$

The dynamic model of the pitch actuator is given in Eqn. (16) :

$$\dot{\beta} = -\frac{\beta}{\tau} + \frac{\beta_d}{\tau} \tag{16}$$

where τ is the time constant and β_d is the desired pitch angle.

2.2. Modeling and control in S4WT environment

The basic goal of S4WT is to construct a model of a wind turbine from basic components, to import engineering parameters to the model and then to analyze the model with the designed parameters. The modeling of the turbine is given in Section 2.2.1. There are two ways to control the pitch angle in S4WT; pitch function and PI controller with gain scheduling. Torque controller is designed using the optimal mode gain method. These controllers are presented in Section 2.2.2. The detailed parameters of the mechanical components and the whole control system are presented in [10].

2.2.1. S4WT Modeling

The wind turbine model consists of segmented tower, bedplate, gearbox, rotor, rotor shaft, coupling shaft and generator in S4WT. The prototype tower is $63.5\ m$ long. The bedplate supports the hub, the gearbox and the generator. There is one main bearing in the bedplate to support the rotor shaft. The gearbox consists of two planetary stages and one helical stage. The prototype gearbox has the reduction ratio of 33.5. It is assumed that three rotor blades are used and that each of the blades are identical. Each blade length is $21.5\ m$ and rotor diameter is $45\ m$.

2.2.2. S4WT Control

The pitch controller can be designed in two ways; the pitch function and PI controller with gain scheduling. Turbine rotor speed is used as an input by the pitch function. However, the error between the measured and nominal generator speed is used as an input by PI controller with gain scheduling. Gain scheduling is necessary because it makes the controller more robust by changing K_P and K_I values of PI. These are changed when they are multiplied by a weight function which depends on the instantaneous blade pitch. Both methods can be used to control the pitch angle in the same simulation by designing a threshold time parameter. Before reaching this time, the pitch function is used, and after that the PI algorithm is used. The torque controller is designed using optimal mode gain method. The demanded generator torque T_{demand} is given by Eqn. (17).

$$T_{demand} = K_{optimal}\, \omega_g^2 \qquad (17)$$

where $K_{optimal}$ is a constant parameter and if it is chosen appropriately, the wind turbine achieves the condition of optimum tip speed ratio so the optimum power coefficient.

3. SIMULATIONS

The Kaimal wind speed model is created by a turbulent wind simulator Turbsim [11]. It can be integrated with both Matlab and S4WT. This wind model which is given as an input to the system is $7\, m/s$ in Fig. 6. Resulting mechanical power is around $12000\, W$ and torque is around $500\, N.m$ in Fig. 8. Fig. 7 shows that the 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 the 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 as in Fig. 10.

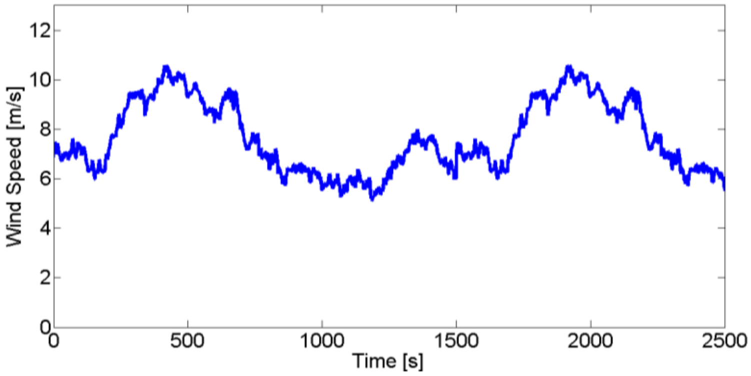

Figure 6. Wind speed profile

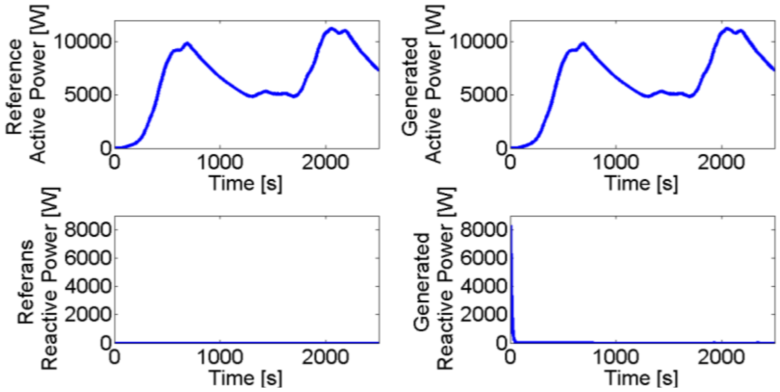

Figure 7. Reference and generated powers

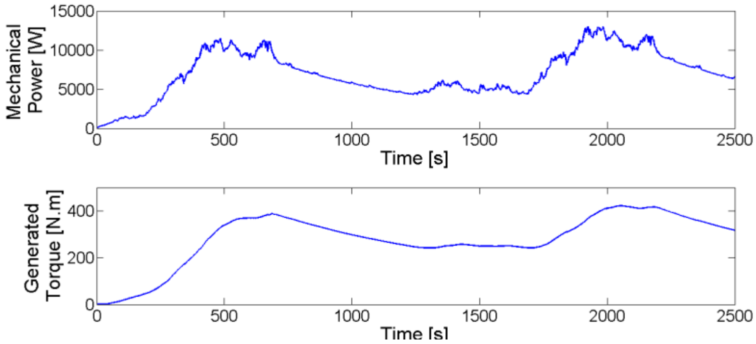

Figure 8. Mechanical power and torque

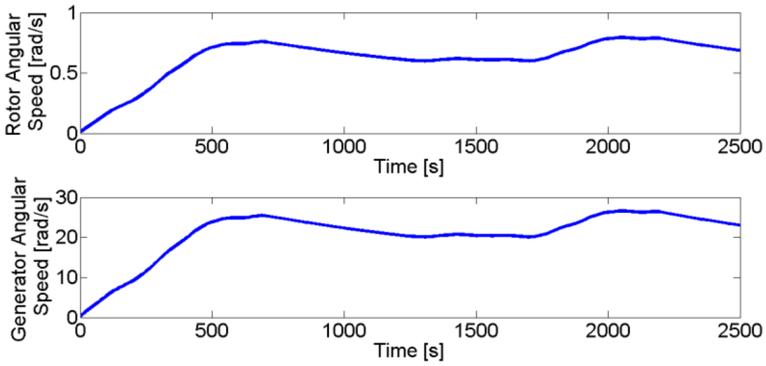

Figure 9. Rotor and generator speeds

At the full load operating region, wind speed is $11\ m/s$ in Fig. 10. Resulting mechanical power is $600\ KW$ and the generated torque reaches the maximum value in Fig. 12. The generated active power reaches the nominal value of $500\ KW$ at the full load operating region in Fig. 11 because the wind speed increases to the nominal value. The rotor and generator speeds are presented in Fig. 13. Both of them reach the nominal values.

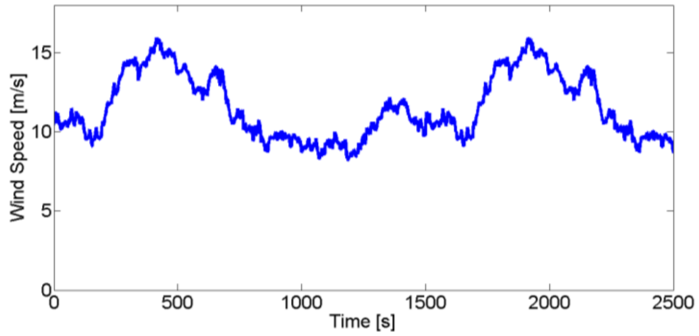

Figure 10. Wind speed profile

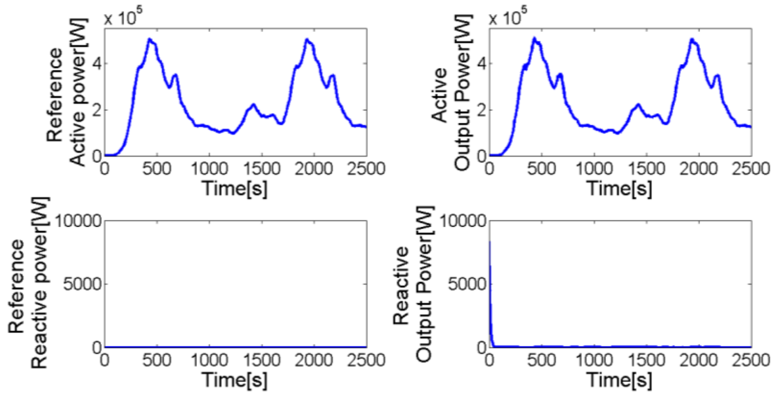

Figure 11. Reference and generated powers

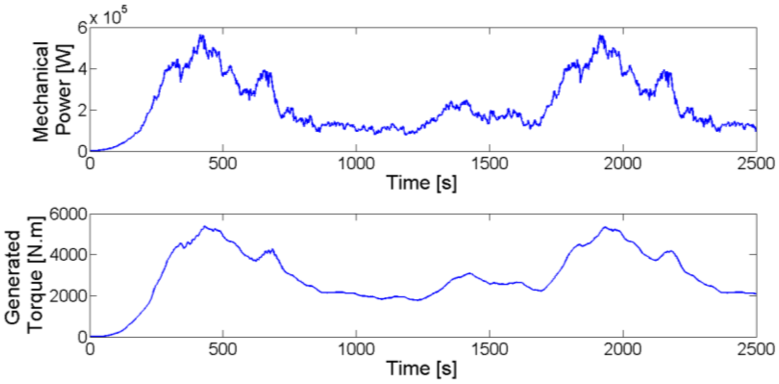

Figure 12. Mechanical power and torque

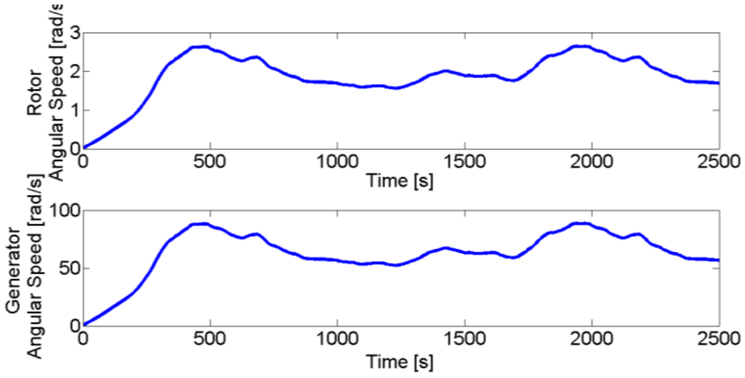

Figure 13. Rotor and generator speeds

Power production, start up, emergency stop, shut down and parked scenarios can be implemented in S4WT. First simulations are done under the power production scenario. Power production scenarios provide performing transient analysis for both partial and full load operating regions similar to Matlab/Simulink analysis. The input wind speed is $7\,m/s$ at the partial load operating region and $11\,m/s$ at the full load operating region as shown in Fig. 14. At the partial load operating region, the generated power is less than the mechanical power since the generator has 90% efficiency. At full load operating region, the nominal power of $500\,KW$ is reached as it is desired. The pitch angle is increased by the PI controller with gain scheduling when the rotor speed exceeds its nominal value as depicted in Fig. 15. Thus, the generated power is limited.

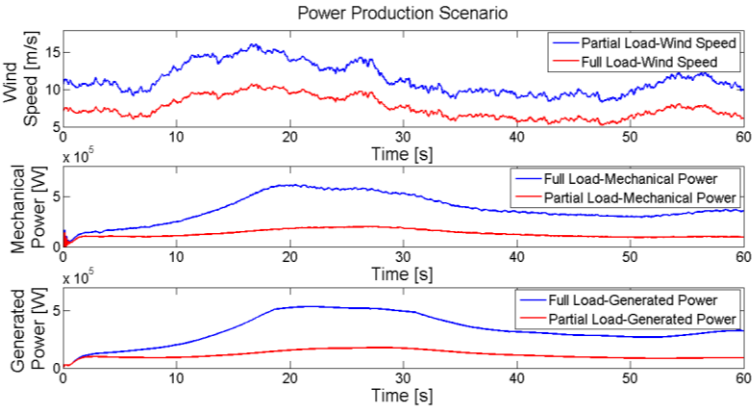

Figure 14. Wind speeds and results

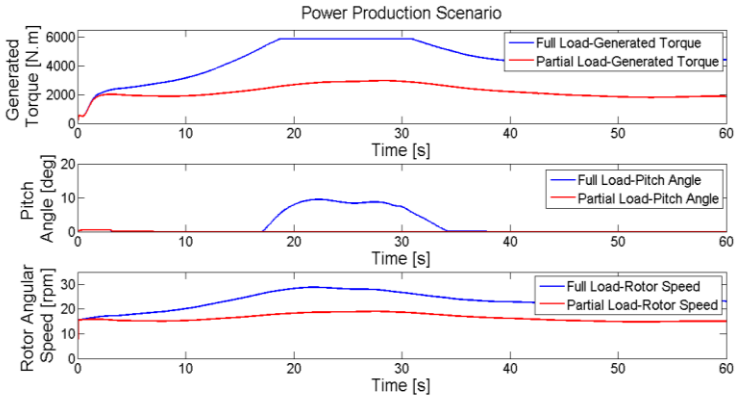

Figure 15. Results of power production scenario

The power is not generated at the start up scenarios, due to low efficiency of the start up wind speed. The input wind speed of the start up scenario is $1\,m/s$ as shown in Fig. 16. This speed is even smaller than the cut-in wind speed, $3\,m/s$. To prevent the mechanical power extraction from the wind, the pitch angle is increased to the target value of 90^o.

Shut down scenarios are required whenever the wind speeds exceed the cut-off wind speed because the turbine must be protected from excessive loads at high wind speeds. In Fig. 17, it is observed that the input wind speed exceeds the cut-off wind speed, 23 m/s. By limiting the pitch angle to 90^o, the generated power and the rotor speed decrease to zero as in Fig. 18.

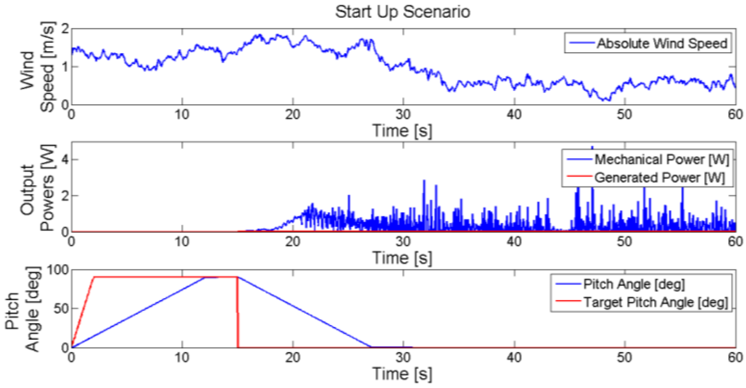

Figure 16. Wind speed profile and the results of start up scenario

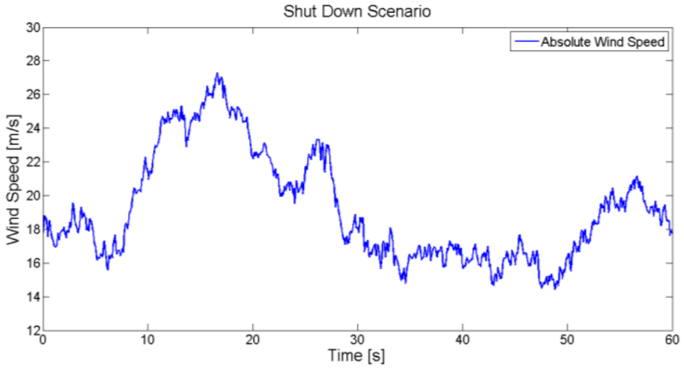

Figure 17. Wind speed profile

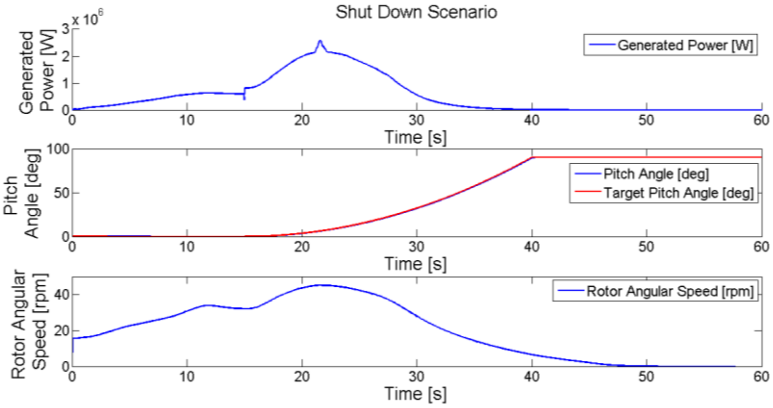

Figure 18. The results of shut down scenario

In the emergency stop scenarios, the operation of the turbine is fully stopped because of the grid loss. Grid loss occurs due to the technical faults at the transmission cable and the environmental facts such as stroke of lightning. Grid connection is lost at the $15th\ sec$. The generated power drops to zero because generator is immediately disconnected from the turbine as shown in Fig. 20. However, there is a peak in the mechanical power because the rotor shaft still turns. In order to decrease the rotor shaft speed to zero, the pitch angle is increased to the target value of 90^o.

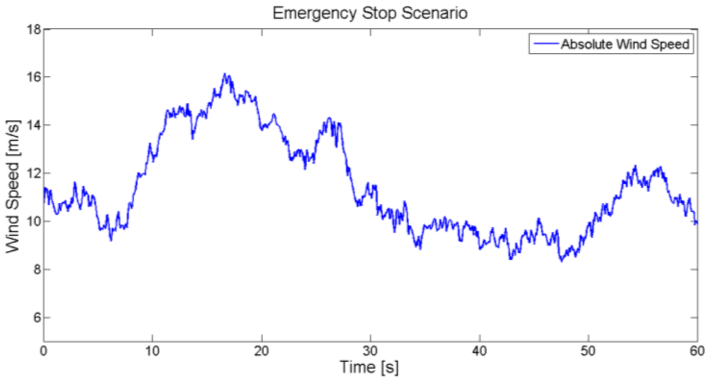

Figure 19. Wind speed profile

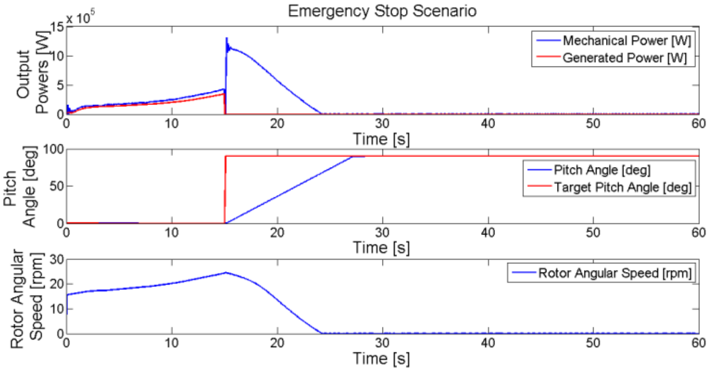

Figure 20. The results of emergency stop scenario

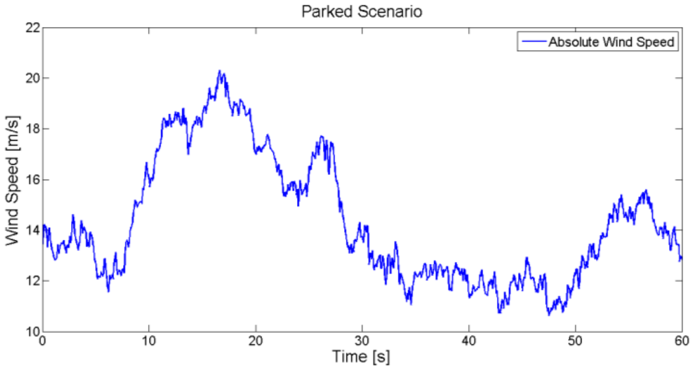

Figure 21. Wind speed profile

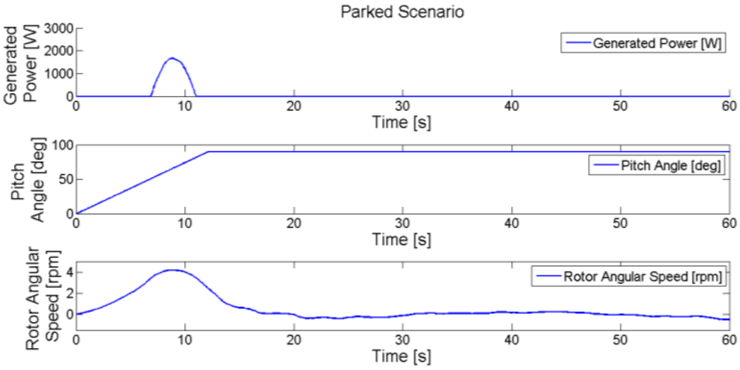

Figure 22. The results of parked scenario

In parked scenarios, the 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. The generated electrical power reduces from 1800 W to zero value as shown in Fig. 22.

4. CONCLUSION AND FUTURE WORKS

We have now presented modeling, control and simulation of a prototype wind turbine in S4WT and Matlab/Simulink environments. By the integration of Turbsim, Kaimal turbulence model is generated and used as a realistic wind profile. The prototype turbine analysis is done at both operating regions under the power production scenario in Matlab/Simulink. Power production, start up, emergency stop, shut down and parked scenarios are also implemented in S4WT. The results are quite successful.

As a future work, modal and fatique analyzes will be done under different turbine scenarios. The other IEC wind models including Extreme Coherent Gust, Extreme Direction Change and Extreme Wind Shear will be used as inputs for these scenarios.

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