Variable Speed wind Turbine Control System: Design & Model

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Abstract:*At present, the wind turbine is the most common alternative energy source that is being utilized to produce electricity around the globe. The rotor accompanying the blades is thecomponent of wind turbine that transforms the kinetic energy of wind to electrical energy. The control of rotor frequency is the area of problem to be solved. The frequency control can be achieved by controlling the nacelle and rotor blades for the optimum performance of wind turbine, because they have direct impact on wind turbine's performance. The trend of wind speed shows that, it is not constant and it varies throughout the operation of a wind turbine. Therefore, it is required to build a solutionthat will be used to control the rotor's pitch and nacelle's direction to maintain fixed frequency of rotor. The speed of rotor can be controlled by changing pitch angle and nacelle direction to maintain the wind turbine rotor frequency for generator. A sophisticated model is needed to be built to control both parameters. For the testing and validation of the model simulation has been performed.*

Keywords:*Wind Turbine, Controller, Feedback Control System*

1. INTRODUCTION

Use of wind energy is not a new thing. It has been used since at least 3000 years. Initially wind energy was used to crushing grain or driving water. The most common and oldest example of using wind energy as an essential source of power for long-term is sailing ships. The technology that empowers winds energy as a source of power is known as windmills or wind turbines. In 13th century a revolutionary era originated in the field of wind turbines and horizontal-axis wind turbines became an integral part of rural economy [1]. The wind turbine is the most common source of alternative source that is being utilized to produce electricity around the globe. Such wind turbines were used to drive cheap fossil-fuelled engines and then feast rural electrification. In late 19th century, a 12 KW DC wind turbine known as "The Brush Machine" (to generate electricity) was built by Charles F. Brush in the USA and its exploration carried out by LaCour in Denmark [1].

The commercial production of wind turbines started in early 1980s. Since then frequent enhancements are utilized to increase the ability of wind turbines to absorb maximum possible wind energy. Generally these enhancements include use of more impressive rotors, larger blades, better use of composite materials and higher towers. Since 1980, the efficiency of a wind turbine has increased by a factor of more than 200 [2]. Keeping Betz theory in mind which state that the most optimal wind turbine can only capture 59.3% of kinetic energy from wind, the reliability of wind turbines are very high up to 98%, with operating availabilities(the proportion of time in which they are available to operate) [2]. Wind turbines are the only source that can produce electricity at such higher availability.

Generally, todays modern wind turbine's rotor contains three blades. The speed and power of rotor is managed by either yaw or pitch ruling, where stall ruling control the mechanical rotation of blades while pitch ruling manage the blade angle. Blades are manufactured from composite materials like fiberglass and polyester or fiberglass and epoxy.

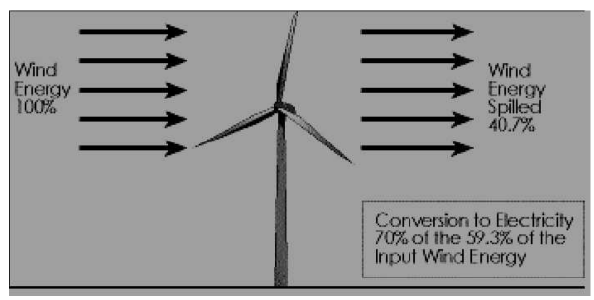

Figure 1: Illustrating the Principal of Betz Law

The fuel for wind power station is wind energy. The commercial value of wind farms are badly affected by just slight changes of wind energy.

It is observed that when the average wind speed doubles, the power of wind turbines increases by factor of eight. Therefore, the small changes in wind speed could affect wind turbines performance very badly. For example, the change of average wind speed from 6 m/s to 10 m/s will affect the energy production performance of a wind turbine over 130% [3]. Therefore, it is necessary to have thorough and consistent information about the power and direction of wind with its blow regularity at suggested site, to build an efficient wind turbine [2].

Generally wind turbines start working at the wind speed of 3m/s to 4m/s, but the full power operation normally requires 10 m/s to 15 m/s of wind speed [3]. This range of wind speed is known as cut-in speed. At the speed 25 m/s wind turbine goes in shutdown state. The wind speed at which shut down state occurs is known as cut-out speed.

The three main components of wind turbine are tower, rotor and nacelle. Rotor is mounted on tip of tower. Normally rotor contains three blades that helps rotor to transform energy absorbed from wind into mechanical energy and then with the help of generator that mechanical energy transform into electrical energy. Generally, rotor's blades helps rotor to rotate at the constant speed of about 15 to 30 revolutions per minute (rpm) [3], it could be vary as per requirement. The ratio of wind speed to the rotation of blades is known as Tip Speed Ratio. As higher the ratio is, the faster the rotation of blades are at the given wind speed.

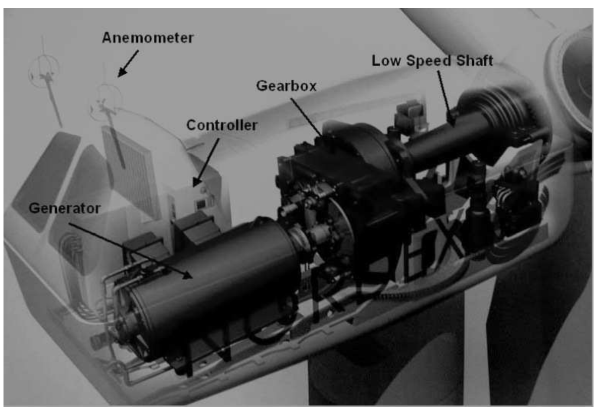

Figure 2: Sample Structure of a Nacelle of a Horizontal Axis Wind Turbine

The rotation of blades is caused by wind energy and controlled by the nacelle which can face the blades to the wind (yaw control) and by changing blades angle (pitch control) to optimal absorption of available wind. The nacelle is the generative part of the wind turbine that contains generator, controller, gearbox, wind vane and an anemometer to monitor the wind speed and wind direction.

It has already seen earlier that slight change of wind speed cause large changes in frequency of wind turbine will badly affects its performance.For this purpose, it is necessary to build such a sophisticated control model that can control wind turbines rotor and blades. Therefore in this study the focus will on this issue and try to come up with an optimal feedback control system in MATLAB environment.

2. LITERATURE SURVEY

2.1 Control Theory

Control systems basically deal with the influencing actions of energetic systems that are needed to run on specific conditions. To meet these required conditions, it is necessary to come up with a small and sophisticated program that could handle the input parameters for desired output features and could built in a microchip. These desired outputs are known as reference. The program that control input parameters is called controller. It could be in the form of software or hardware. Such programs are when found in the form of hardware or chip, known as microcontroller.

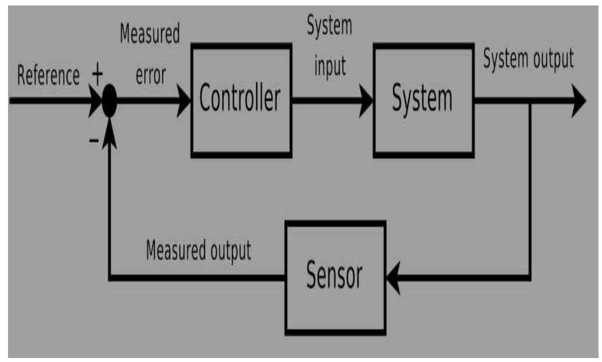

Figure 3: Feedback Control System

2.2 CONTROL STRATEGIES

Control systems have different strategies for the stability of systems. The most common strategies of control systems are:

- Adaptive control
- Hierarchical control
- Intelligent control
- Optimal control
- Robust control
- Stochastic control, etc.

2.2.1 Adaptive Control System:

Adaptive control applied by perceiving operational identification of process factors, in that way attaining robust properties [4]. The adaptive control systems are used in complex systems by automatically finding its way to control the mechanism.

2.2.2Hierarchical Control System:

Large system's controls are always planned in a distributed hierarchy. Hierarchical controls is the branch of control systems that replicating a divided and conquer strategy. In hierarchical control systems, set of actuators and principal software are arrange in a hierarchical tree [4].

2.2.3 Intelligent Control System:

To attain sophisticated goal by a system, an Intelligent Control System is prefer to use because it could work independently, while due to unexpected changes in system, its components are not well-defined. Intelligent control systems use one of different AI techniques as per requirement, like; neural network, fuzzy logics, etc. to control the system [4].

2.2.4Optimal Control System:

Optimal control system is the technique in which control signal are optimized at given point [4]. Optimal control system considers a more comprehensive condition in which decision variable and the level of state machine affect the change in the state variable. The future growth of state variable depends on current decision and current decision is based on state variables.

2.2.5Robust Control System:

Robust control systems are those control mechanisms that controls the system by taking all parameters in account. It could handle all the minor differences that occur between the real systems and the model that design to use [4].

2.2.6 Stochastic Control System:

Stochastic control deals in modeling and control of dynamic systems inclined by stochastic turbulences and indecisions. Stochastic control systems are the systems that could account all noises and disturbances, which could occur in a system [4]. In stochastic control, the abnormal conditions and system's efficiency is monitored and accommodated.

2.3WIND TURBINE FEEDBACK CONTROL SYSTEM

In implementation of a wind turbine controller, various types of controllers are required that are assigned to control different functions of wind turbines. Controller objectives are to be assigned very carefully, keeping all parameters in consideration. Because controllers might have major effects on structural loads, therefore it is necessary to consider these during designing optimal control algorithm. The objective of controller may include regulate aerodynamic torque, gearbox operation, pitch activity, controlling tower vibration, yaw controlling, etc.

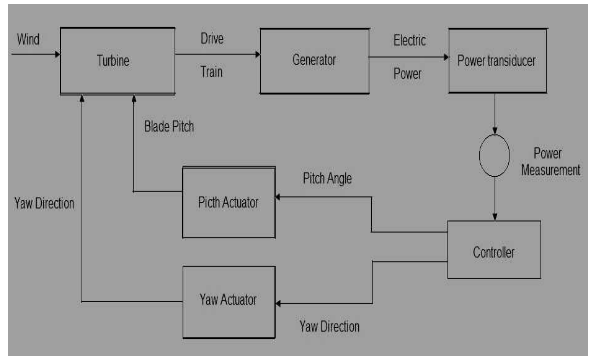

Figure 4: Block Diagram of a Wind Turbine Feedback Control System

In this study, a hierarchical control strategy is use to attain the wind turbine requirements. The hierarchical control model could be observed by figure 5. Figure 5 show that main controller transfers the control initially to pitch controller on the basis of mathematical calculations. Pitch controller is assigned to control the pitch angle of rotor's blades according to wind speed conditions.

If pitch controller is unable to meet the requirements of wind turbine, the control will transfer to yaw controller. Then yaw controller will try to adjust the rotor to face the blades to the wind. If still the required conditions doesn't meet then the control will transfer to state controller that decide to switch wind turbine's state to start-up or shut-down states. The moment when wind speed crosses either upper or lower speed limit, the state controller switches the wind turbine to shut-down state.

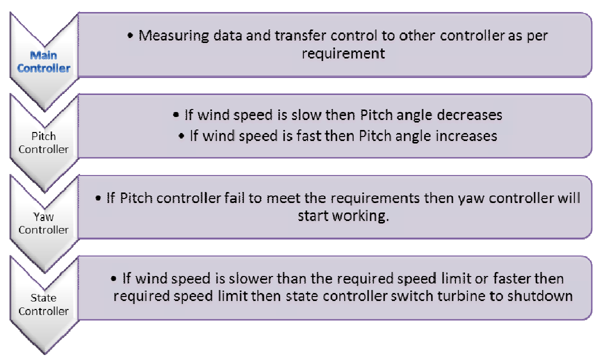

Figure 5: The Hierarchical Control Model for Wind Turbine

2.4 RESEARCH SURVEY

Many researchers have done extensive work on controlling wind turbine in different regions of the world. Engelen *et al* [5] defines the design tools for wind turbine control algorithms by focusing on frequency domain analysis and synthesis of (linearized) turbine models.

D. J. LEITH *et al* encountered three important generic implementation issues of controllers of pitch regulated constant speed wind turbines [6]. The encountered issues are named as:

- accommodation of the strongly nonlinear rotor aerodynamics [6],
- automatic controller start-up, shut-down and accommodation of velocity [6] and
- acceleration constraints within the actuator [6].

Alan D. Wright defines the control system which applies modern state-space control design methods to a two-bladed upwind machine [7]. He defines Disturbance Accommodating Control (DAC) method and provides accountability for wind-speed fluctuations [7].

Boubekeur Boukhezzar *et al* use nonlinear controllers to improve the efficiency and to evaluate the related efficiency; he used nonlinear static and dynamic state feedback controllers [8].

Kathryn E. Johnson *et al* work on the variable speed wind turbines [9]. He explores the steadiness of an adaptive torque control rule and the gain adaptation rule which are in use at Controls Advanced Research Turbine (CART) [9].

Pradeep Bhatta *et al* focuses on the control law, derived from an energy-like Lyapunov function (**Lyapunov functions** are used to prove the stability of a static point in a dynamical system). He guarantees the system stability for all operating points of the wind energy conversion system (WECS) [10].

3. SIMULATION AND MODELING

The model of wind turbine controller is simulated in MATLAB environment. The effectiveness of the proposed model is evaluated by carrying out the simulation experiments, in which rotor speed is controlled by adjusting pitch angle with respect to variable wind speed. To evaluate this model, it is necessary to have variable wind speed. For this purpose, in this model wind speed is simulated by using "Weibull Distribution". The effectiveness of controller in terms of controlling wind turbine is depending on the effective wind energy at the given region.

It was already mentioned in **Chapter 1** and **Chapter 2** that wind turbine starts operation on 3 m/s to 4m/s and full operation available on 10 m/s to 15 m/s, as per requirement. Therefore, in the simulation process, it is especially kept in consideration that wind speed must vary in such a way that wind turbine will not switch to shut down state. The proposed control model is based on hierarchical control strategy.

3.1 SIMULATION OBJECTIVES

The primary objective of designing a wind turbine control model is to attain the wind turbine requirements. The controlling of wind turbine is a very serious problem because of the complex structure of the wind turbine along with variable wind speed. The control of variable wind speed is essential to meet the wind turbine requirements. Wind speed can be controlled by adjusting the wind turbine's blades. These blades are controlling by adjusting their angle as per requirement. If wind speed is faster than the defined speed limit, the blades angle increases, so that the area of absorbing wind energy decreases. Similarly, if wind speed slower than the defined speed limit, the blades angle decreases, so that the area of absorbing wind energy increase. Because of the hierarchical control strategy, initially controller try to meet the requirements of wind turbine by adjusting pitch angle than the control will transfer to yaw control. Therefore, in the simulation process, the proposed controller model especially targeted to manage the blades pitch angle.

The wind turbine controller is also responsible to control the dynamics of nacelle. The structural load of the wind turbine is mainly because of its nacelle. The nacelle of the wind turbine contains generator, controller, gearbox, drive train, etc. All these components of nacelle make its weight very heavy.

3.2 SIMMULATION MODEL

The proposed simulation model contains blade height (bh), initial pitch angle (pa) and required Tip Speed Ratio (TSR) as input variables. The output variables of this model contain pitch controlling bit (pitch), wind speed (wind) and rotor rpm (rpm). The list of variables use in model can be observed by table 3.1:

Table 3.57: Variable names and their acronyms

VARIABLE NAME	VRIABLE ACRONYM
Rrpm	Rotor RPM
Bh	Blade Height
Grpm	Generator RPM
Ws	Wind Speed
Pa	Initial Pitch Angle
TSR	Tip Speed Ratio
Pbit	Pitch Controller Bit
Ybit	Yaw Controller Bit

In this proposed model some values are taken as constant values. These values are depending on requirements of desired energy level, wind turbine's coefficient requirements and mainly depend on the site region. The lists of these constant values are observed by table 3.2:

Table 3.58: List of Constant Values

NAME	CONSTANT VALUE
Tip Speed Ratio	4
Rotor RPM	28 – 32
Final Pitch Angle	15

The proposed model diagram can be viewed by figure 6:

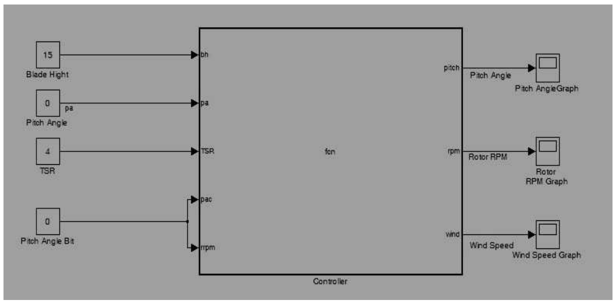

Figure 6: Proposed Model of Wind Turbine Controller

The formula to calculate rotor rpm is derived from the formula of Tip Speed Ratio (TSR), where TSR is kept to be constant and wind speed variation is simulated by using Weibull Distribution.

$$Rotor\ RPM(\gamma) = \frac{30 * \zeta * \lambda}{\pi * \partial}$$

Where, ζ is Tip Speed Ratio,
λ is Wind Speed,
γ is Rotor rpm,
∂ is blade height.

The main "controller" model contains the basic controlling code that governs the wind turbine on the basis of input values. Basically the code works on hierarchical basis. First it try to adjust rotor speed by adjusting pitch angle, but if rotor speed is not meet the required speed then it transfer control to yaw controller. The proposed controller code that governs the wind turbine controller is depicted by Figure 7.

```
while ((rrpm < 28) || (rrpm > 32))
if ((rrpm < 28) && ((pa <= 15) && (pa >= 0)))
    pa = (pa - 1);
    pbit = -1;
    rrpm = (30*(TSR*ws)/(pi*bh));
    pitch = pa;
    yaw = yawc;
    rpm = rrpm;
    wind = ws;
    return;
    if ((rrpm >= 28) && (rrpm <= 32))
    end
    rrpm = (30*(TSR*ws)/(pi*bh));
    pitch = pa;
    yaw = yawc;
    rpm = rrpm;
    wind = ws;
    return;
elseif ((rrpm > 32)  && ((pa <= 15) && (pa >= 0)))
    pa = (pa + 1);
    pbit = 1;
    rrpm = (30*(TSR*ws)/(pi*bh));
    pitch = pa;
    yaw = yawc;
    rpm = rrpm;
    wind = ws;
    return;
    if ((rrpm >= 28) && (rrpm <= 32))
    end
    rrpm = (30*(TSR*ws)/(pi*bh));
    pitch = pa;
    yaw = yawc;
    rpm = rrpm;
    wind = ws;
    return;
```

Figure 7: Part of code that control pitch angle

The first line of the above given chunk of code shows that the controller works only when, rotor rpm decreased or increased from the defined range. The second line of code has made a check to verify the current rotor speed for below the desired speed. If the rotor speed is below the desired condition and pitch angle is in between its initial and final condition then the controller pass the signal to decrease the pitch angle. After decreasing pitch angle, controller makes a check that either rotor speed meets the desired requirement or not.

The second check has made to verify the current rotor speed for above the desired speed. If the rotor speed is above the desired condition and pitch angle is in between its initial and final condition then the controller pass the signal to increase the pitch angle. After increasing pitch angle, controller makes a check that either rotor speed meets the desired requirement or not.

```
elseif (((rrpm < 28) && (pa == 15))||((rrpm > 32)  && (pa == 0)))
    yawc = yawc + 1;
    ybit = 1;
    rrpm = (30*(TSR*ws)/(pi*bh));
    pitch = pa;
    yaw = yawc;
    rpm = rrpm;
    wind = ws;
    return;
    if ((rrpm >= 28) && (rrpm <= 32))
    end
    rrpm = (30*(TSR*ws)/(pi*bh));
    pitch = pa;
    yaw = yawc;
    rpm = rrpm;
    wind = ws;
    return;
elseif (((rrpm < 28) && (pa == 15))||((rrpm > 32)  && (pa == 0)))
    yawc = yawc + 1;
    ybit = -1;
    rrpm = (30*(TSR*ws)/(pi*bh));
    pitch = pa;
    yaw = yawc;
    rpm = rrpm;
    wind = ws;
    return;
    if ((rrpm >= 28) && (rrpm <= 32))
    end
    rrpm = (30*(TSR*ws)/(pi*bh));
    pitch = pa;
    yaw = yawc;
    rpm = rrpm;
    wind = ws;
    return;
```

Figure 8: Part of code that control nacelle direction

The second part of code is depicted by Figure 8, which deals with the control of nacelle direction or simply says that deals with yaw controller. The first check in this part of code verifies the current rotor speed for below the desired speed and as well as the condition of pitch angle. If the rotor speed is below the desired condition and if there is no chance to decrease pitch angle further then the controller transfer the control to the yaw controller and pass signal to yaw controller to change the nacelle direction. After changing nacelle direction, controller makes a check that either rotor speed meets the desired requirement or not.

The second check in this part of code verifies the current rotor speed for above the desired speed and as well as the condition of pitch angle. If the rotor speed is above the desired condition and if there is no chance to increase pitch angle further then the controller transfer the control to the yaw controller and pass signal to yaw controller to change the nacelle direction. After changing nacelle direction, controller makes a check that either rotor speed meets the desired requirement or not.

In next section results obtained by running the proposed controller simulation will discuss and analyze.

4. RESULT ANALYSIS

It has been discussed in **Chapter 3** that in this model wind speed is simulated by using “Weibull Distribution” and it is especially kept in consideration that variation of wind speed must occurs in such a way that wind turbine will not switch to shut down state. Therefore, in the simulation process, the proposed controller model will project only the effectiveness of pitch angle controlling part,and it is sure that yaw controlling part will show its effectiveness in real-time environment. The surety of this statement is based on the fact that in real-time environment, many different sensors and equipment could be arranged that can sense the output values and feedback to controller.

For example, a counter can be set that sense the current pitch angle value and increase or decrease as per controlling signal response. This counter can be used to feedback the status of current pitch angle value. Likewise a sensor can be used, which feedback wind speed or wind direction status from anemometer which is very useful to adjust pitch angle or nacelle direction. On the basis of counter which feedback the pitch angle value, it is easily decidable that whether control transfer to yaw controller is needed or not. While in the simulation process of wind turbine controller, such accommodations are not available, therefore complete simulation of proposed controller is not possible.

The effectiveness of the proposed controller model is evaluated by carrying out the simulation experiments. For this purpose, values of required parameters that are needed to run simulation are already defined in table 3.2. After running simulation process, three different graphs will obtained, where first graph depicted by Figure 9 shows wind speed variation, second graph depicted by Figure 9 shows the rotor speed in revolution per minutes (rpm) and the last graph depicted by Figure 9 shows the action of pitch controller. Figure 9 shows the variation of wind speed which is simulated using “Weibull Distribution”. By analyzing wind simulation graph it can be observed that with the reference of discussion in **Chapter 3**, the variation of wind speed is occurs in such a way that wind turbine will not switch to shut down state.

The simulation process is running with following assumptions:

- After every single pitch increment or decrement, there is a delay of two seconds to observe the current rotor speed. Basically it depends on wind speed variation.
- On each single increment or decrement, the limit of pitch actuator to increase or decrease pitch angle is predefined.
- The wind speed variation does not allow wind turbine to go in shut down state.

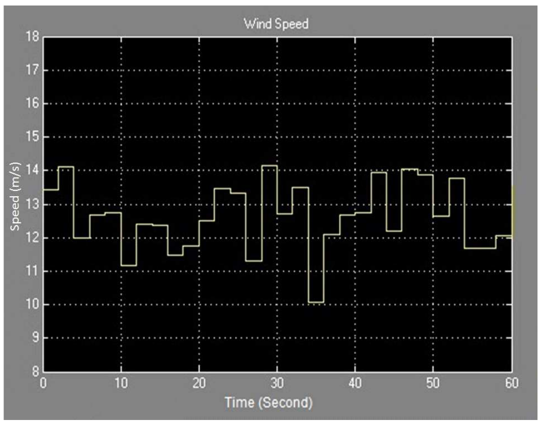

Figure 9: Wind Speed (m/s)

The second graphcan be viewed by observing figure 10, which shows the rotor speed. By observing figure 9 and 10 simultaneously, it can be conclude that the ideal wind speed at which rotor speed is in ideal condition i.e. 30 rpm is 12 m/s.

By observing figure 9 and 10 simultaneously, it is also conclude that when wind speed goes above 13 m/s, the rotor speed also increases and cross the predefined upper limit. When wind speed goes below 11 m/s, the rotor speed also decreases and falls down the defined lower limit.

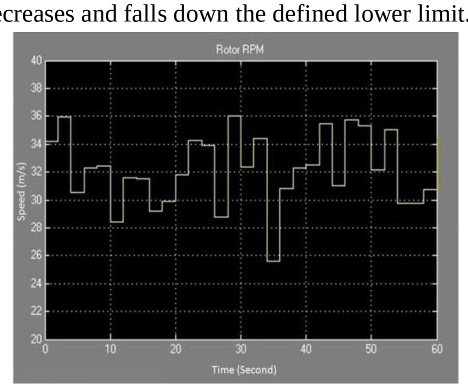

Figure 10: Rotor Speed (rpm)

By viewing figure 9, 10 and 11 concurrently, it could be observe that when rotor speed cross the upper limit, pitch controller pass the signal to pitch actuator to increase the pitch angle. Increasing pitch angle allows rotor to slower down its speed. While, when rotor speed cross lower limit, pitch controller pass the signal to pitch actuator to decrease the pitch angle. Decreasing pitch angle allows rotor to increase its speed.

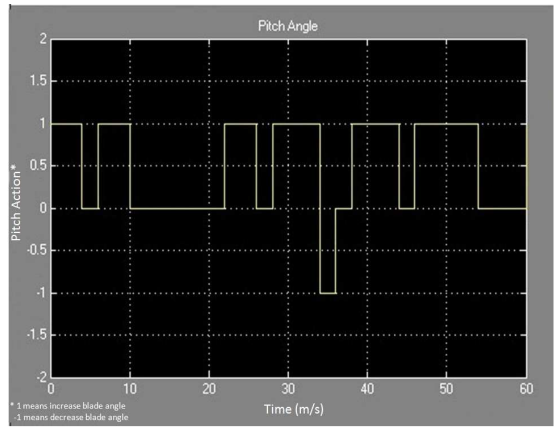

Figure 8: Pitch Angle Signaling

5. CONCLUSION

The design task of such a control system that can efficiently control wind turbine, must address several issues, such as variable wind speed which causes a variation in the wind turbine's rotor frequency i.e. rpm, thereby resulting in mismatch between rotor and generator rpm, which can damage the generator. In this study, a hierarchical control model namely, "Rotor Speed Feedback Control" is proposed to resolve the problems of controlling wind turbine and to maintaining its consistency i.e. rotor's rpm; this control model is tested, and analyzed via simulation process.

The control strategy is validated using simulation only, due to the unavailability of sensors and counters; it was not possible to validate it for real world environment. As wind turbines are sensitive to wind speed, the proposed control model is used to control pitch and nacelle direction to maintain the required rotor speed i.e. between 28 and 32 rpm. The results discussed in previous chapter shows that proposed control model does achieve desired stability results, hence fulfill the requirements of this study.

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