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Modeling and simulation of wind turbine with advance blade testing methods

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Abstract
Wind energy utilization for power generation purpose is becoming high interest in electrical power production as a result of easy access to the wind and not be affected by any environment that is clean and sustainable source of energy. In this research a mathematical model and its parameters has been studied that affect the electrical output power generated by the wind turbine. These parameters are wind speed which is affected by temperature that cause air density change and that lead to vary wind speed, and power coefficient as a function of pitch angle and blade tip speed. The modeling and simulation technique will play great role in the design and analysis of these wind turbines. At the end we obtain pitch angle, generator/rotor speed, gear train input torque and response of the yaw with respect to the direction of the wind.

Keywords: HAWT, VAWT, pitch, naccle, heat, energy efficiency

1. Introduction

Wind energy utilization for power generation purpose is becoming high interest in electrical power production as a result of easy access to the wind and not be affected by any environment that is clean and sustainable source of energy. In this research a mathematical model and its parameters has been studied that affect the electrical output power generated by the wind turbine. These parameters are wind speed which is affected by temperature that cause air density change and that lead to vary wind speed, and power coefficient as a function of pitch angle and blade tip speed. The modeling and simulation technique will play great role in the design and analysis of these wind turbines. In the past years, the demand of Matlab-Simulink is one of the most common software, which is important for modeling, and simulation of dynamic systems. It provides a graphical interface, easy to access, design, build and verify mathematical models. These programs can easily make new designs and strategies control as well as tests. The wind turbine generators are the best example of these dynamic systems [1].

Wind turbine is designed to convert the wind energy into electric energy. The wind turbine system consists of three main parts: the rotor, which includes the blades to convert wind energy to low speed rotational energy. The second part is the generator that includes the electrical generator, which include all control circuits with gearbox that convert the rotational low speed into electric power and finally the structure that hold all the previous components and that is the tower and nacelle. Wind turbine is classified into two main groups depending on their axis in which the turbine rotate. It can be classified into horizontal axis and vertical axis. Because the horizontal axis has the ability to collect the maximum amount of wind energy for the time of the day and can adjust their blades pitch angel to avoid high windstorms, they are considered more familiar and more common than vertical axis [2].

Even though there is a reasonable level of use of the renewable energy in the country, a significantly higher level could be attained. Nigeria surely needs the technical assistance from pro-active countries especially from the industrializing developing nations in:

a. The widespread establishment of renewable energy data recording stations.
b. Acquisition of small scale solar cells producing plant
c. Acquisition of a manufacturing plant for components of the small hydro turbines.
d. Acquisition of a manufacturing plant for components of wind turbine and generators and
e. Infrastructure for bottling biogas for cooking and it’s used for generation of electricity.

The wind energy is converted through friction into diffuse heat throughout the earth’s surface and the atmosphere. The earth is non-linearly heated by the sun resulting in the poles receiving less energy from the sun than the equator does. The differential heating powers a global atmospheric convection system reaching from the earth's surface to the stratosphere which acts as a virtual ceiling. Wind energy is the kinetic energy of the air in motion. Total wind energy flowing through an imaginary area A during the time t is:

$$E = A*v*t*\rho*½\ v^2 \qquad (1)$$

Where

V = wind velocity and

ρ = air density.

The formula presented is structured in two parts: (A. v. t) is the volume of air passing through A, which is considered perpendicular to the wind velocity; (ρ. ½v^2) is the kinetic energy of the moving air per unit volume.

Total wind power is:

$$P = E / t = A*\rho*½\ v^3 \qquad (2)$$

Wind power is thus proportional to the third power of the wind velocity.

HAWT (Horizontal Axis Wind Turbine)

A horizontal-axis wind turbine (HAWT) has the main rotor shaft and electrical generator at the top of a tower, and must be pointed into the wind. Small turbines are pointed by a simple wind vane, while large turbines generally use a wind sensor coupled with a servo motor. Most system has a gearbox, which turns the slow rotation of the blades into a quicker rotation that is more suitable for electricity generation process. Since a tower produces turbulence behind it, the turbine is usually pointed upwind of the tower. Turbine blades are made stiff to prevent the blades from being pushed into the tower by high winds. Additionally, the blades are placed in a considerable distance in front of the tower and are sometimes tilted up a small amount. Because turbulence leads to fatigue failures and reliability is so important, most HAWTs are upwind machines.

Downwind machines have been built despite the problem of turbulence. It is because they do not need any additional mechanism for keeping them in line with the wind [3].

VAWT (Vertical Axis Wind Turbine)

Vertical-axis wind turbines (VAWT) have main rotor shaft running vertically. Main advantages of this arrangement are the generator and/or gearbox can be placed at the bottom which near the ground. So the tower does not need to support it, and that the turbine does not need to be pointed into the wind. Drawbacks are usually pulsating torque that can be produced during each revolution and drag created when the blade rotates into the wind. It is also difficult to mount vertical-axis turbines on towers, meaning they must operate in the often slower, more turbulent air flow near the ground, resulting in lower energy extraction efficiency [3].

2. SY\stem configuration

Model based designs are more efficient and in our project to design the wind mill we require various steps as per traditional methods which are:

a) Control Algorithm
b) Embedded Software
c) Mechanical Design
d) Electrical output

All these separate systems have to be integrated to make a functioning machine and to get output from the machine. The problem arising with this system is that the requirements given to design the machine may be incomplete, un feasible and could make the combined system very hard to integrate to each other. Another problem is that when we design these parts separately in separate environment it becomes difficult to test these part in integrated design. Errors found this process are very late and any error may lead to lot of time and effort loss.

So it is important to make these designs in a similar environment. Second we want to make sure that the design is directly linked to the requirements document. The while making the design we can compare and improve the design as per the requirement. In our project we have designed a pitch angle controller which can rotate the blades at a certain angle. The control system of the complete machine determines that what should the angle of the blades. Now the control system decides how much the blades have contracted or extended. In our method we have designed a control system model. We have designed a pitch control system to design a wind turbine model. Optimal system designs lead to optimal design choices.

As we knew the requirements as per our model so we have designed the model as per requirements. So for this purpose we have designed a compensator to design a pitch control system. First we are using linear control theory and then we have applied optimization algorithms to non- linear model to design the compensator.

Blade Loads: When an air-flow strikes the blades of wind turbine, it starts to rotate thanks to the aerodynamic forces generated along the blades.

The revolution speed highly depends on the aerodynamic profile of the rotor blades. From the basics of the aerodynamic a wind turbine blade can be imagined as an airfoil which passes through an airflow with a constant speed. The contact between the air and the airfoil creates a pressure distribution on blade surface that consequently generate the lift and the drag forces. Considering a frame system where the plane of rotation of the rotor is perpendicular to the axial wind direction, the system of forces and the system of speeds of a wind turbine blade can be represented with the following scheme

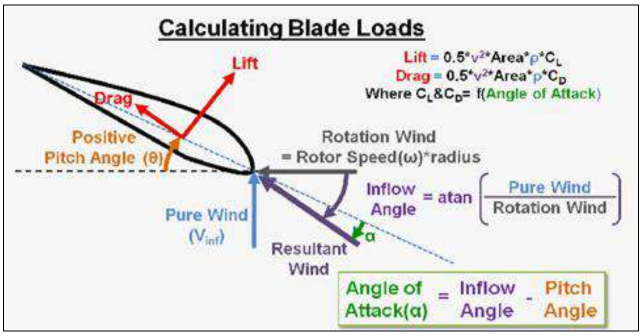

Fig 1: Forces and velocities acting on a blades, axial wind direction frame system

As can be observed from the scheme above, the relative wind speed Urel is defined as a vectorial combination of two orthogonal velocities. The axial component is the free stream velocity U∞ and orthogonal component is the angular contribution of the peripheral speed of the rotor rΩ. The relative speed vector forms an angle with rotation plane that is called inflow angle (ϕ). As it can be seen from the figure this angle can be also expressed as the sum of the two angles, respectively: pitch angle (θP) and the angle of attack (α). The pitch angle is, on active control wind turbines, a variable angle controlled by a hydraulic or electric system that varies the inflow angle in order to arrange the highest lift force available and reducing the drag force component, instead on stall control wind turbines this angle is fixed and the blades are designed to reach the stall conditions at a specific wind speed. The angle of attack is the angle between the airfoil chord and the relative wind speed direction. Looking at the system of forces, it can be stated that the airflow generated on a blade the lift (FL) and the drag (FD) forces, as already mentioned, but since the blades are constrained to rotate on the plane of rotation these forces are projected respectively along this plane and along the plane where the axial wind direction lies. Hence according to this new frame system the F_T force, which is responsible of torque production, and FN force, which determines the thrust force, can be defined using simple trigonometric calculation with the following equations

$$FT = FL\sin(\phi) - FD\cos(\phi) \tag{3}$$
$$FN = FL\cos(\phi) + FD\sin(\phi) \tag{4}$$

As known from theory [5], the drag force generates the thrust force but, as stated in equation, it also contribute to reduce the FT force, responsible of energy production. Therefore in order to improve the efficiency of a wind turbine and increase the power production a pitch control system should be installed, so that the drag component is limited as much as possible. A deeper analysis of definition of lift and drag forces will be presented further. In order to describe all the rotor loads it is necessary modifying again the frame system, setting the X-axes along the main shaft and the Y-axes and Z-axes on fixed to the plane of rotation of the rotor.

Fig 2: The new frame system from simscape library of matlab

According to this system it is possible to define a vector of generalized forces as follow

$$\mathbf{Q} = \begin{bmatrix} F_x \\ F_y \\ F_z \\ M_x \\ M_y \\ M_z \end{bmatrix} \tag{5}$$

This vector expresses respectively the force and the moments along the three directions of the frame system. The Fx force is the thrust force, defined with equation (5). The Fy force represents the total weight force of the rotor system which consists of the weight of the three blades plus the rotor hub weight. The force on Z direction, Fz, can be set equal to zero since this force arises only if an eccentricity between the center of mass of the rotor and the shaft axis occurs; for instance this issues arises when there are misalignment errors during assembly phase. This force causes a periodical load which depends on the rotor speed as well as on the value of the eccentricity. Fz can be expressed with the following equation

$$FZ = m^{\epsilon}\omega^2\sin\omega t \tag{6}$$

Where is the eccentricity, and ω is the rotor speed. In general for the modern wind turbines the Fz force can be considered negligible since they are assembled with advanced techniques and the rotor is designed in order to guarantee the correct balance both in static and dynamic conditions. Concerning the three moment components, the moment along X-axes simply represents the torque transmitted to the drivetrain system, calculated as the product between the spinning force and the distance of the its point of application to the center of rotation. The moments My and Mz should be considered only for the wind turbines equipped with a yaw system. When such a device is present, according to the frame system My is defined as yaw moment. This moment comes from the energy necessary to overcome the frictions between the surface of motion of the yaw mechanism and under dynamic condition depends on the inertia of the entire nacelle. The yaw moment can be expressed with the following expression

$$M_y = c\,\theta^{\cdot} + I\theta \tag{7}$$

Where c represents the friction coefficient that must be estimated either theoretically or empirically while the I is the nacelle inertia. The formula (7) does not include the aerodynamic resistance of blades because it is a second order effect as the yaw motion is small. The moment along the Z-axes Mz represents the gyroscopic moment arising from the presence of a yaw motion. The gyroscopic effect occurs when external torque is perpendicularly applied to the axis of rotation of a spinning system with a torque applied, giving rise to a moment orthogonal to both torque directions, the gyroscopic moment.
According to [5] the gyroscopic moment for a three blades wind turbine can be analytically described with the following equation

$$Mz = 3\omega_k\,\omega \sum_{i=1}^{n} m_i\, r_i^2 \; (3.5) \tag{8}$$

Where ωk is the angular yaw speed, ω the rotor speed, m_i the i^{th} discrete mass of the rotor blade discretization and r_i is the distance from the rotor center to middle point.

3. Modeling and Simulation Pitch angle control

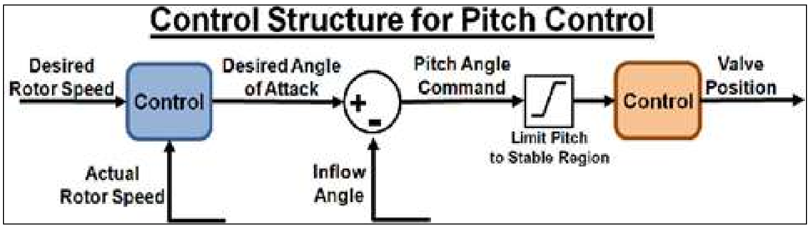

Fig 3: Control structure of pitch control

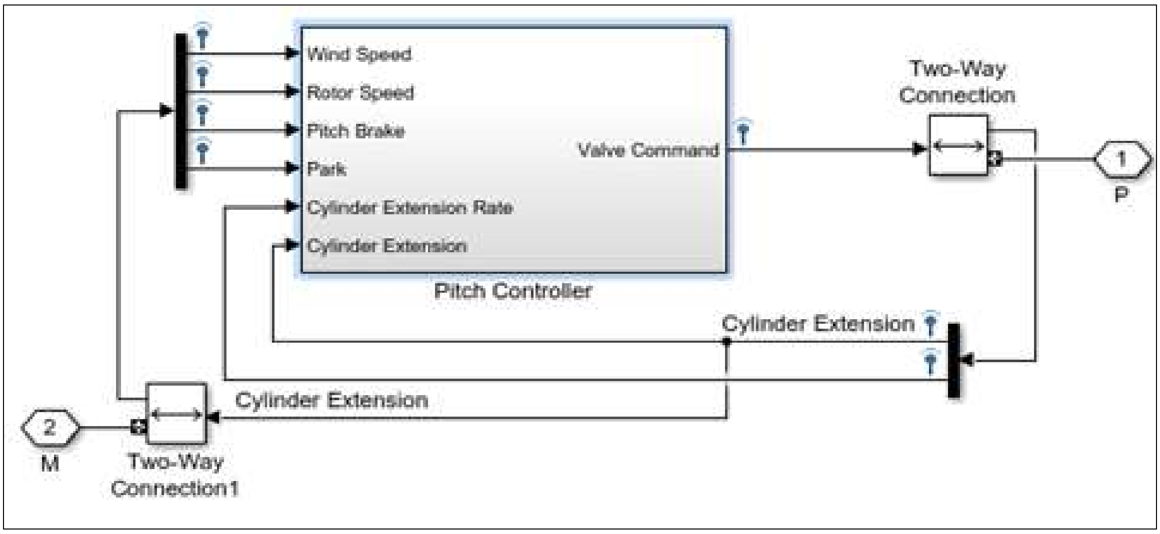

Fig 4: Simulink model of pitch angle controller

As shown in the figure the pitch angle controller controls the valves of the hydraulic system and a two way valve is shown in the diagram which actuates as per the instructions given the controller.

Supervisory control: The figure below shows the Simulink model of the supervisory control model of the wind turbine. This block acts as a control system which decides when to turn on or off various parts of the wind turbine.

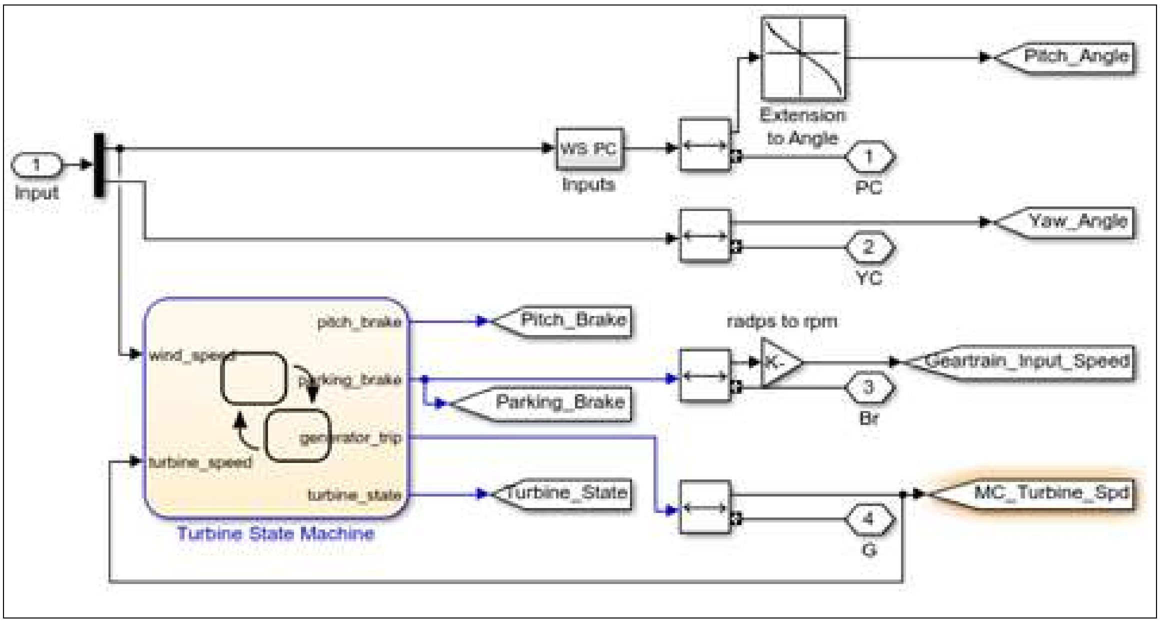

Fig 5: Simulink model of supervisory control

Nacelle Design: Similarly we have nacelle which holds the every part of the wind turbine and controls it by using various tool designed by us.

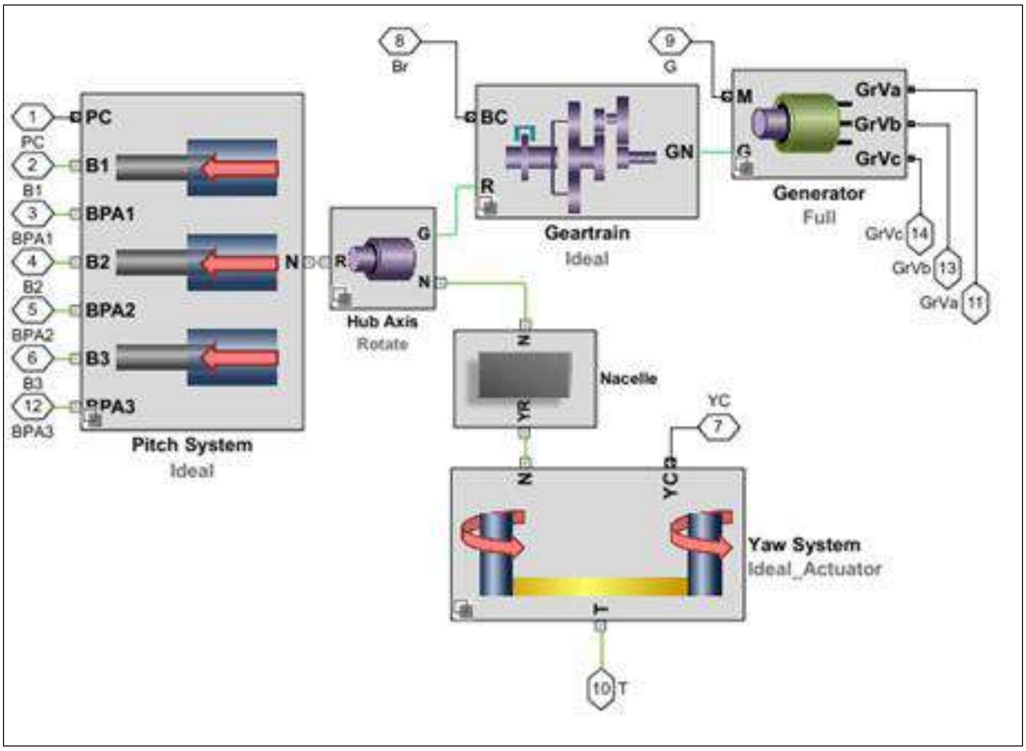

Fig 6: Design of the nacelle

Complete model structure

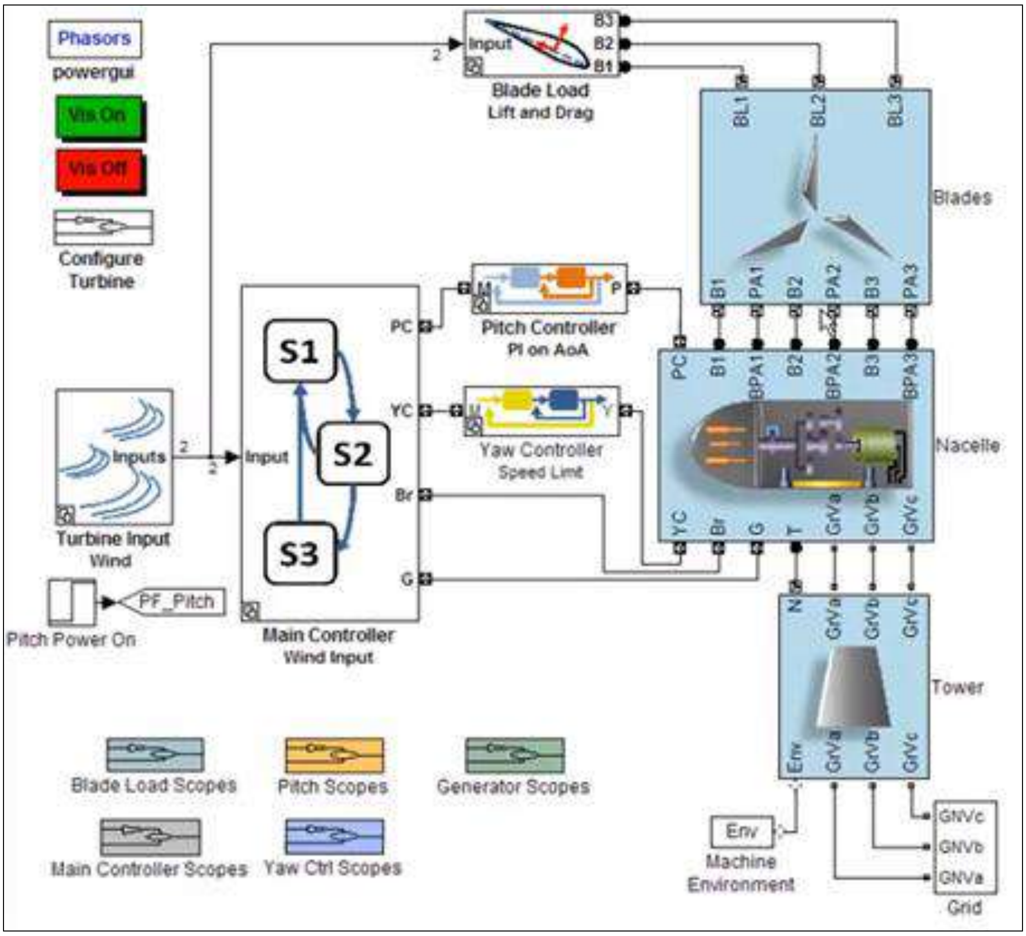

Fig 7: Complete project model

4. Results and Discussions

The results demonstrate the performance of the wind turbine in different wind conditions. At the start of the simulation we can see that when the speed of the wind increases as shown in fig 1 initially there is no effect on the turbine blades. When the speed of the wind turbine becomes high enough the system comes to life as shown in the figure 8. We can see during the simulation that the blades of the turbine have pitched to catch the wind and rotate the rotor.

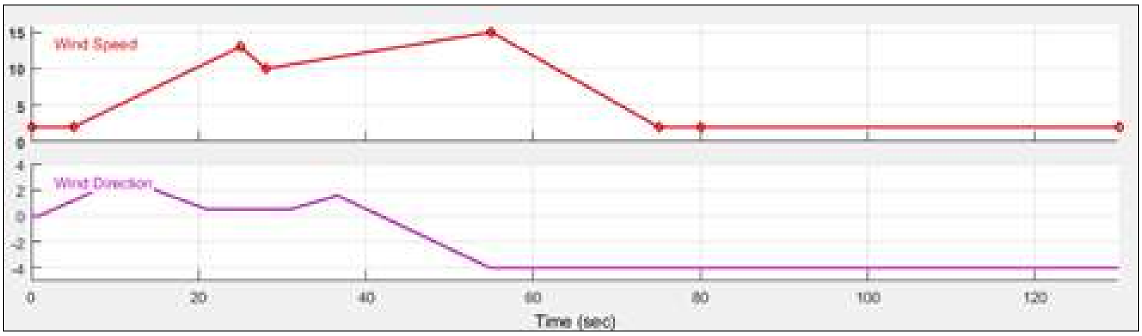

Fig 8: Wind speed and direction (input given in signal builder block)

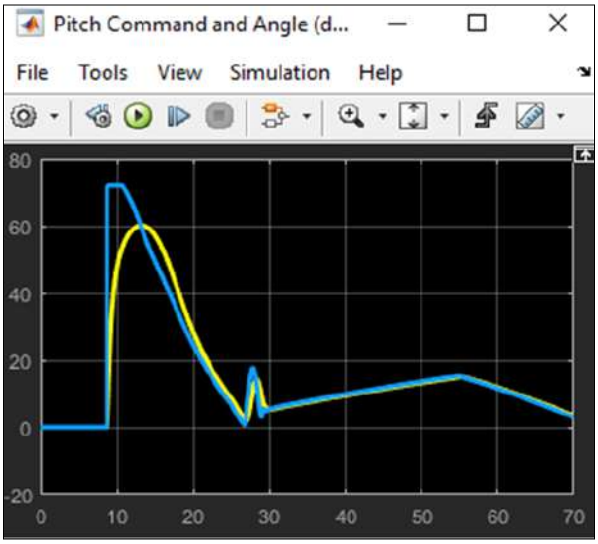

Fig 9: Pitch command and angle

This actuates the rotor of the generator at the same time and the rotor starts to rotate. When the rotor has reached the certain speed the machine stabilizes itself and the pitch angle is decreased as shown in fig 8. The speed of the rotor can be seen in fig 9 below. As the speed of the wind decreases after a certain time the pitch angle is again adjusted by the supervisory control by giving signal to the hydraulic system to keep the speed of the rotor constant.

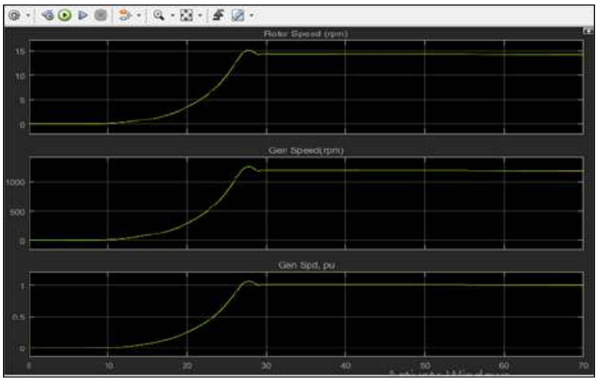

Fig 10: Rotor speed and Generator speed w.r.t time

In a pitch actuato system we can rotate the angle of wind turbine to a certain angle and as discussed earlier our control system determines what that angle should be which further indicates how much force should be applied for spread or contraction of wind turbine. This can be seen more clearly in the fig 11 and 12 here the pink line in fig 11 shows the command and the yellow line shows the pitch and fig 12 shows how much force is required to be given to the hydraulics system as per the wind speed.

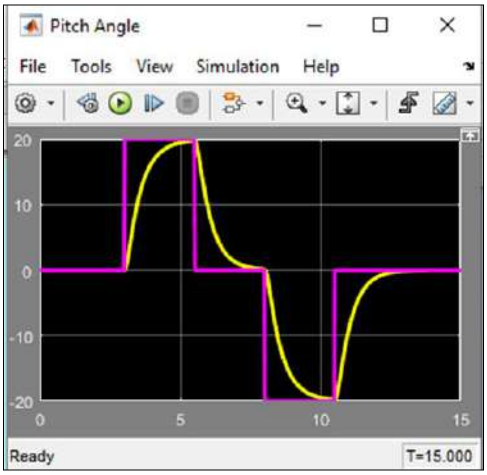

Fig 11: Pitch angle and command for actuation system w.r.t time

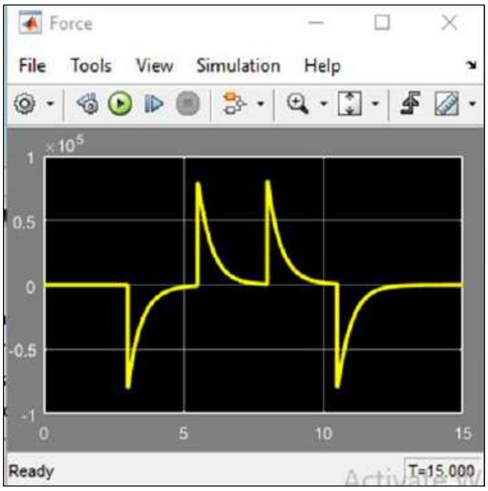

Fig 12: Force applied by the hydraulics system w.r.t time

As the wind turbine blades change the pitch angle with respect to the speed the speed the turbine also changes the direction by starting the yaw actuator when the direction of the wind changes. So it can be seen from the fig 12 that as the direction of the wind changes which can be seen in fig 13 the yaw angle changes as the hydraulics are actuated and the machine changes the direction.

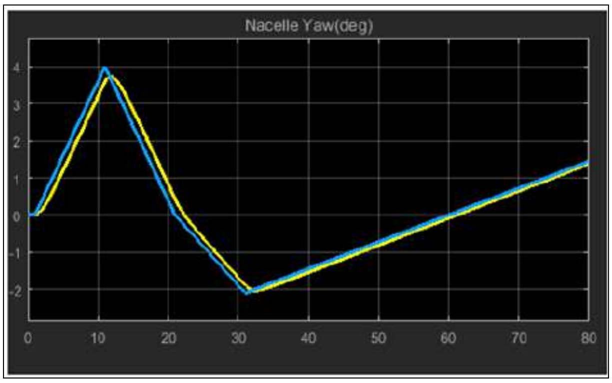

Fig 13: Yaw direction and wind speed w.r.t time

Determining the mechanical loads

Determining the loads, deflections, and oscillation of a wind turbine is not an easy process so the individual parts designed ed in the project have been designed in a similar environment. The mechanical loads are shown by the figures below. As shown above the speed of the wind at the start is low so the supervisory controller is leaving the wind turbine turned off and when the wind speed increases to a desired speed the supervisory controller turns the wind turbine on. This can be seen in figure given below:

As the speed of the wind increases it affects the torque generated in the gear train. And we can also see that the loads in bearings of the blades are sine waves which shows the system is rotating.

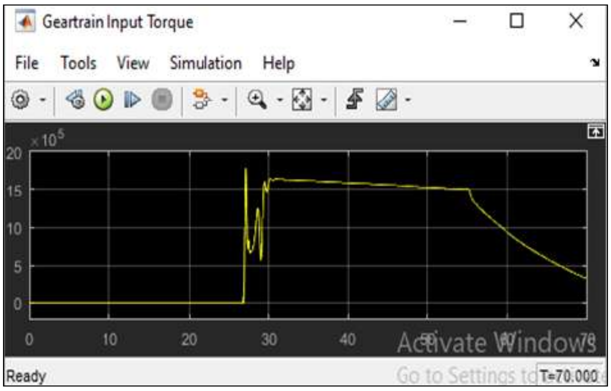

Fig 14: Gear train input torque w.r.t time

Now as we see with time the speed and the direction of the wind is changing, we can see that the torque and the force on the bearings changes as shown in the fig 14.

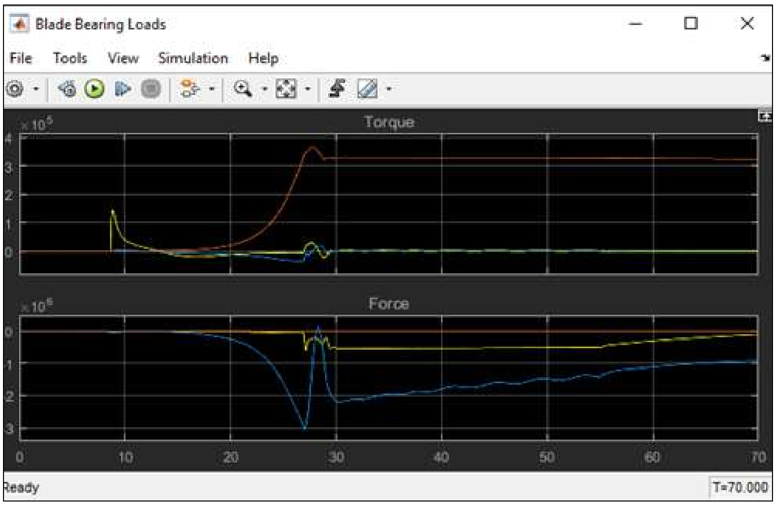

Fig 15: Blade bearing loads

Thus it is clear that when the speed of the wind drops the torque and the force drops as seen in the graph.

5. Conclusion

The main task of this project is to model the loads acting on the drivetrain interfaces of a wind turbine, specifically rotor and generator. The report begins stating that the large part of downtime of wind turbines is caused by drivetrain failures. This fact have encouraged energy companies to start a strong researches in order to limit this issue. A lack of knowledge about the loads which a wind turbine drivetrain system is subjected to is highlighted. Therefore the investigation of the drivetrain loads of each interface is a meaningful work.

After simulating the wind turbine model, the Rotor Load Interface is obtained, which is a multi-body system and is divided into four blocks, respectively: wind conditions, aerodynamic loads, rotor blades and generator. The wind conditions block set defines a set of different wind condition the aerodynamic loads block is responsible of calculating the loads that are generated by the interaction between the air flow and blades. Our method divides the blades into a different segments and for each of them calculates the respective lift and drag force, then the values are summed up and a more realistic load is obtained. The blades block includes the rigid bodies representing the blades, each of them are defined by inertia and mass properties. Lastly the generator block is set as a counter torque for balancing the rotor torque. The Generator Load Interface model defines an induction and a PM generator with a third order differential equations generator, consisting of two electromagnetic differential equations, for calculating the electromagnetic torque, and a mechanical differential equation, which is the torque balance equation of the drive train system. The GLI model presents two drivetrain system models, namely one-mass, which considers the consists of one single mass rotating, and two-masses, which takes under consideration the shaft flexibility. Both Induction and PM generators responses under a constant mechanical torque as well as a step of mechanical torque are analyzed.

As conclusion, with our project, a new tool has been developed that can be used for two different tasks. First, the three interface models can provide the input data for dynamic analysis of advanced drive train models in order to evaluate the internal and testing of the blades of the wind turbine. The strength of this tool is possibility of providing input data with a good accuracy, for different operational conditions, in a faster way compared to other techniques. Second, the data of the models can also be used to design new wind turbines; indeed it possible to estimate the amounts loads under critical operational scenarios, for instance high turbulence condition, that allow to properly design the drivetrain system components (e.g. gears) and possibly guarantee the durability of 20 years.

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