

A Basic Approach for Designing Pitch, Yaw and Supervisory Control System of Wind Turbines

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Abstract— This paper proposes a strategy for designing pitch, yaw and supervisory control of wind turbine including a 3D modeling of the whole system. The system is considered here to avoid mechanical losses as well as maintain a constant rotor speed in wind turbine. The wind speed will be varying from time to time, so to protect the turbine from any kind of damage due to wind speed variation, the pitch control system is designed. The direction of nacelle is also varying with time to capture the maximum energy from the air, a yaw control system is premeditated. To analyze operating conditions for determining the state of turbine to enable or disable operation such as bringing the turbine to stop by applying parking brake or releasing the brake enabling the turbine to spin, supervisory control system is introduced as an intermediary link in between pitch and yaw control system to avoid undesirable events. The 3D model, pitch, yaw and supervisory control system of wind turbine has been simulated in MATLAB Simulink™ and simulation results also show the coherence with the proposed analogy.

Index Terms— *Blade forces; Pitch, Yaw and Supervisory Control; 3D Modeling of Wind Turbine; Renewable Energy.*

INTRODUCTION

Since 1979, the Chinese economy has increased at an average annual rate of 10%, doubling every 7 years. To maintain this high rate of economic growth, China needs to continue expanding its electricity supply. China is rich in coal reserves, but limited in gas and oil supply. Electricity generation based

on coal is highly polluting and carbon-intensive, thus creating significant political and international pressure [1]. As an alternative, China has so far achieved remarkable progress in wind energy development. Wind power now represents 4% of the overall power generation [2] which is largely due to the country's vast wind resource, relative technical maturity and relatively low cost compared to other renewable resources. In 2018, China has produced 366,000 GWh [3] electricity from wind energy having the capacity of 184,260 MW [4]. To capture the maximum power from wind, after the capital costs of commissioning wind turbine generators, the biggest costs are operations, maintenance and insurance. Reducing maintenance and operating costs can considerably reduce the payback period and provide the impetus for investment and extensive acceptance of this clean energy source.

A wind turbine has a tower, in top of the tower there sits the nacelle. Inside the nacelle, we will find the generator which is connected to the electrical grid. The wind turbine attempts to spin the generator at a constant speed or at its rated speed. For the generator to spin, we have a hub which can rotate and blades are connected to the hub. The wind strikes the blades which enables the hub to rotate and the hub is connected to the generator with a gear train. In order to control the lift and drag which the blades generate, a yaw control system that points the wind turbine into the incoming wind and there is a pitch control system that controls the angle of the blades in order to control how much lift and drag the blades produce. The gearbox interconnects the rotor shaft and generator shaft. The power generated from the generator is sent to the grid by a transformer. A basic structure of wind turbine is given below in Fig. 1.

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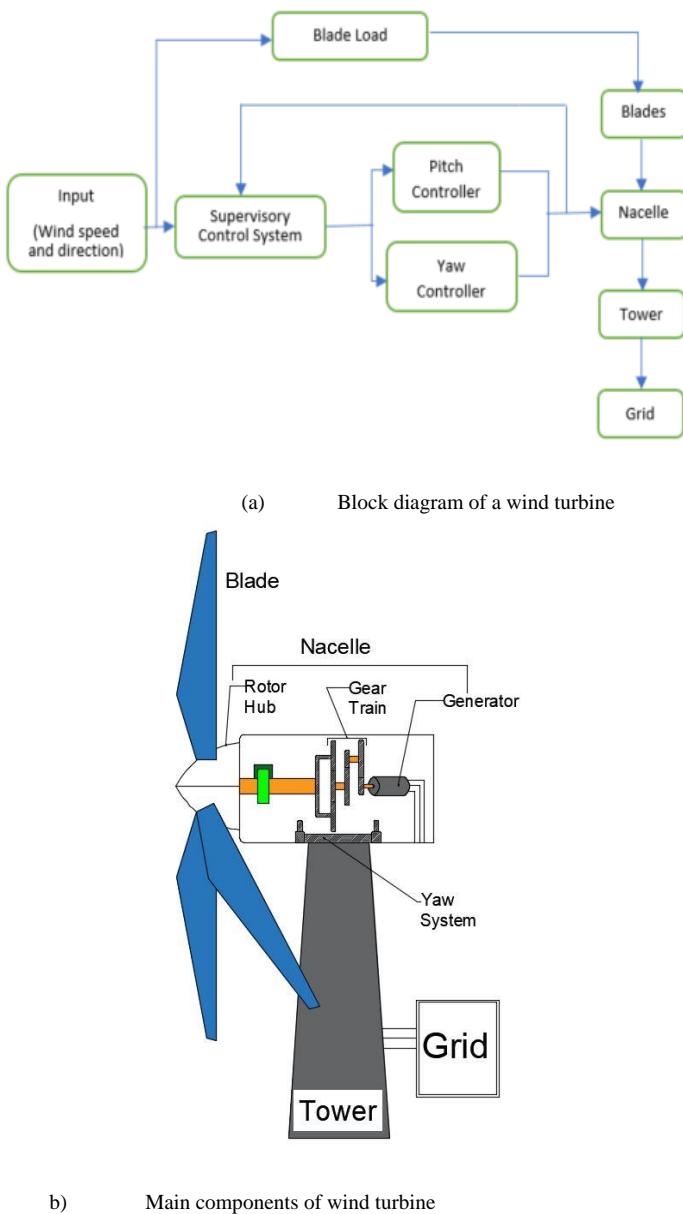


Figure 1: Basic structure of Wind Turbine

The fundamental equation of wind power answers the most basic quantitative question-how much energy can be generated by a wind turbine per unit time. The power of the wind is the rate of wind energy flow through an open window. Wind energy depends on three factors- a) amount of air (the volume of air in consideration), b) speed of air (the magnitude of its velocity), c) mass of air (related to its volume via density). In other words, wind power is the rate of kinetic energy flow. Using the fluid mechanics concept, the fundamental equation in power analysis can be derived [5].

$$P = \frac{1}{2} \cdot \rho \cdot A \cdot v^3 \quad (1)$$

Where P = available power of wind; ρ = density of air; A = swept area by the wind; v = velocity of the wind. It exhibits a highly nonlinear cubic dependency on wind speed. Wind

turbines reach the highest efficiency at a wind speed between 10 and 15 ms⁻¹. Above this wind speed, the power output of the rotor must be controlled to reduce driving forces on the rotor blades as well as the load on the whole wind turbine structure [6]. High winds occur only for short periods and hence have little influence in terms of energy production. All wind turbines are designed with a type of power control. There are different ways to control aerodynamic forces on the turbine rotor and therefore limit the power in high winds in order to avoid damage to the wind turbine [7].

Advanced control strategies for wind turbines have been investigated over a few decades which are broadly classified into the classic control, modern control and intelligent control [8] as shown in Table I.

Table I Classification of Wind Turbine Control Strategy

Control theory	Classical control	Modern control	Intelligent control
Control objective	SISO, LTI system	SISO/SIMO/MIS O/MIMO, Linear/nonlinear time variant/invariant/univariate/multivariate, Discrete/continuous system	Large scale, Complex structure, Incomplete information, Multivariate system
Analysis method	Frequency domain approach	Time-domain approach	Time-domain approach
Mathematical model	Transfer function	State-Space equation	Subsystem
Mathematical tool	Laplace transform	Matrix Algebra, Vector-space theory	Cybernetics, Operation research, Artificial intelligence
Control method	PID Control	Optimal Control, Robust Control, Adaptive Control, Sliding Model Control, Predictive Model Control	Bayesian Control, Fuzzy Control, Neural network Control, Genetic Algorithm, Intelligent agents

In the partial load regime, the main control objective is to capture the maximum power available from the wind. The rotor speed and pitch angle should be controlled in a way such that

the maximum power point tracking (MPPT) is obtained. To achieve the MPPT, the classical PI controller is used which is simple and practical, but needs to tune the PI parameters repeatedly. In the full load regime, the main control objectives are to regulate both the generator power and speed at their rated values, respectively. These objectives can be achieved by manipulating the desired pitch angle and/or generator torque set-point.

Sometimes unwanted loads are caused by the wind at the blades such as sudden changes in wind direction, uneven loading of blades, wind turbulence and accumulation of dust on the blades. All these factors influence the generation rate of electric power. The basic formulation and governing equations regarding wind turbine modelling has been discussed in section 2 and 3D modeling of the whole project has been developed using various contents like *Simscape multibody*, *Simmechanics*, *Simhydraulics* in MATLAB. In section 3, the control schemes required for capturing maximum power from wind have been discussed named as pitch, yaw and supervisory control systems. The mechanical power of the wind turbine is controlled by the pitch angle adjustment of the blades. If the wind speed is greater than the rated wind speed, the pitching angle should be increased and if it's lesser than rated speed, the pitching angle should be reduced. For the sudden change in wind direction, the yaw action should occur i.e. move the whole nacelle in the direction to the upcoming wind. So, a single control system with four servo motors at 90° apart from each other has been considered which should operate simultaneously. After that, an overall supervisory control system is required to monitor the state of the turbine in case of emergency or during the time of maintenance and to identify statutory constraints of the turbine like whether its running on rated speed or not, generator becomes saturated or not etc. Different types of simulations using MATLAB are performed and results have been discussed in section 4 and 5. Simulation parameters have been given in the *Appendix (Part B)*. Finally, the paper concludes with a generic discussion and suggestion about future scopes of work.

WIND TURBINE MODELING

Modeling is a basic tool for analysis such as optimization, design and control. Wind energy conversion systems are very different in nature from conventional generators and therefore dynamic studies must be addressed in order to integrate wind power into the power system. Models used for steady-state analysis are extremely simple while the dynamic models for various types of analysis related to system dynamics: stability, control system and optimization. Modern wind turbine generator systems are constructed mainly as systems with a horizontal axis of rotation, a wind wheel consisting of three blades, a high speed asynchronous generator (also known as induction generator) and a gear box. Asynchronous generators are used because of their advantages, such as simplicity of construction, possibilities of operating at various operational conditions and low investment and operating costs. A typical wind energy conversion system is displayed in Fig. 2.

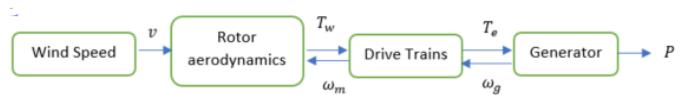


Figure 2: Wind turbine energy conversion scheme

B. Modeling of Blades

The forces that are acting on rotor blades which are generated from the wind speed during the conversion of the kinetic energy of the wind into mechanical power then converted into electrical power is described by the aerodynamic system [9]. There are mainly two forces on the blade which cause the moment in the blades, the forces are lift and drag force. The torque and thrust force are resolved from the tangential component and an axial component respectively. The forces acting on the blades are shown in Fig. 3.

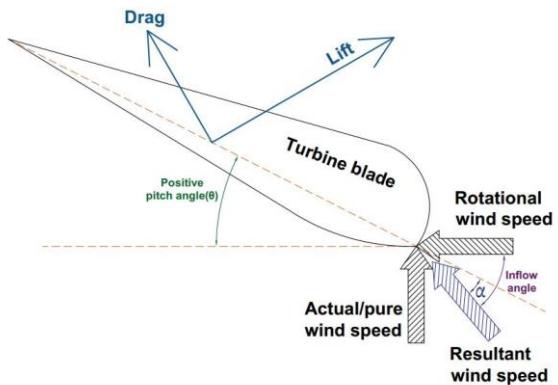


Figure 3: Forces acting on the blade

$$\text{Lift force} = \frac{1}{2} \cdot C_L \cdot \rho \cdot A \cdot v^2$$

$$\text{Drag force} = \frac{1}{2} \cdot C_D \cdot \rho \cdot A \cdot v^2$$

$$\text{Rotational wind speed}(v_r) = \text{Rotor speed}(\omega) \times \text{Radius}$$

$$\text{Inflow angle} = \tan^{-1} \left[\frac{\text{Initial wind speed}(v_{int})}{\text{Rotational wind speed}(v_r)} \right]$$

$$\text{Angle of attack}(\alpha) = \text{Inflow angle} - \text{Pitch angle}$$

Where,

C_L = coefficient of lift; C_D

= coefficient of drag and they depend on angle of attack(α)

As mentioned earlier in (1), the turbine blades extract kinetic energy in the wind and transform it into mechanical energy. The kinetic energy in air of an object of mass m moving with speed v is equal to,

$$E = \frac{1}{2} \cdot m \cdot v^2 \quad (\text{II.A.1})$$

The power in the moving air (assuming constant speed velocity) is equal to,

$$P_w = \frac{dE}{dt} = \frac{1}{2} \cdot m \cdot v^2 \quad (\text{II.A.2})$$

Where m is the mass flow rate per second. When the air passes across an area A (e.g. the area swept by the rotor blades), the power in the air can be computed by using (1). The air density ρ can be expressed as a function of the turbine elevation above sea level H ,

$$\rho = \rho_0 - 1.194 \times 10^{-4} \cdot H \quad (\text{II.A.3})$$

Where $\rho_0 = 1.225 \text{ kgm}^{-3}$ is the air density at sea level at temperature, $T = 298K$.

The power extracted from the wind is given by

$$P_{\text{Blade}} = C_p(\lambda, \beta) \cdot P_w = C_p(\lambda, \beta) \cdot \frac{1}{2} \cdot \rho \cdot A \cdot v^3 \quad (\text{II.A.4})$$

The power factor, C_p has a maximum theoretical value equal to 0.593 and a function of the tip-speed ratio (λ) and the blade pitch angle (β) in degrees. The blade pitch angle is defined as the angle between the plane of rotation and the blade cross-section chord. The tip-speed ratio is defined as,

$$\lambda = \frac{\omega_m \cdot R}{v} \quad (\text{II.A.5})$$

Where ω_m is the angular velocity of the rotor and R is the rotor radius (blade length).

The rotor torque T_w can be computed as

$$T_w = \frac{P_{\text{Blade}}}{\omega_m} = \frac{C_p(\lambda, \beta) \cdot \frac{1}{2} \rho \cdot A \cdot v^3}{\omega_m} \quad (\text{II.A.6})$$

The power coefficient C_p can be defined as a function of the tip-speed ratio and the blade pitch angle as follows:

$$C_p(\lambda, \beta) = c_1 \left(c_2 \cdot \frac{1}{\gamma} - c_3 \cdot \beta - c_4 \cdot \beta^x - c_5 \right) e^{-c_6 \cdot \frac{1}{\gamma}} \quad (\text{II.A.7})$$

With γ defined as

$$\frac{1}{\gamma} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{1 + \beta^3} \quad (\text{II.A.8})$$

While the coefficients $c_1 \sim c_6$ are proposed as equal to: $c_1 = 0.5$, $c_2 = 116$, $c_3 = 0.4$, $c_4 = 0$, $c_5 = 5$, $c_6 = 21$ ('x' is not used here as $c_4 = 0$)

An example of the power coefficient [$C_p(\lambda, \beta)$] characteristics computed taking into account (II.A.7, II.A.8) and the parameters $c_1 \sim c_6$ for a given rotor diameter, rotor speed and for various blade pitch angles (β) is presented in Fig. 4 [10]. The 3D modeling of the blades has been given in the Appendix (Part C).

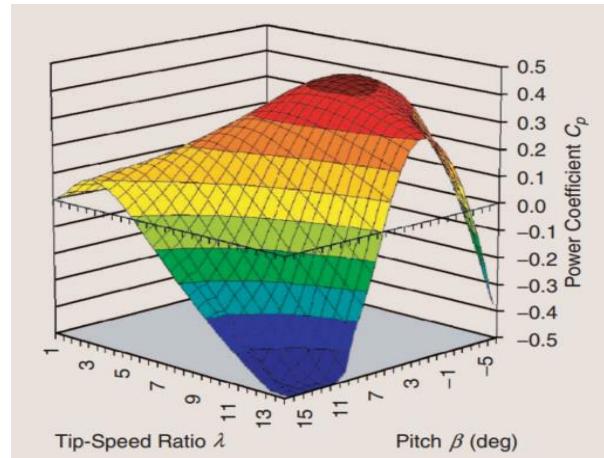


Figure 4: Analytical approximation of $C_p(\lambda, \beta)$ characteristics

C. Modeling of Drive-train

The drive train of a wind turbine system generally consists of a blade pitching mechanism, a hub with blades, a rotor shaft and a gearbox with generator. The drive train model presented in this paper includes the inertia of both the turbine and generator. The moment of inertia (MOI) of the wind wheel (hub with blades) is about 90% of the drive train total moment, while the generator rotor MOI is equal to about 10%, the generator represents the biggest torsional stiffness. The structure of the model is presented in Fig. 5 [11].

The equations of motion of the induction generator is given by

$$H_g \cdot \frac{d\omega_g}{dt} = T_e + \frac{T_m}{n} \quad (\text{II.B.1})$$

Since the wind turbine shaft and generator are coupled together through a gearbox, the turbine shaft system should not be considered stiff. To account for the interaction between the wind turbine and rotor, an additional equation describing the motion of the wind turbine shaft is adopted.

$$H_m \cdot \frac{d\omega_m}{dt} = T_w - T_m \quad (\text{II.B.2})$$

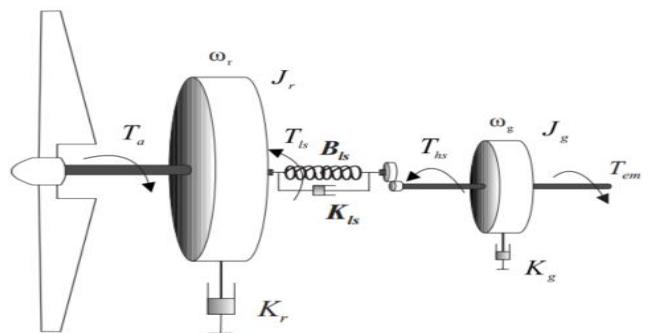


Figure 5: Drive train dynamics

The mechanical torque T_m can be modelled with the following equation,

$$T_m = K \cdot \frac{\theta}{n} + D \cdot \left(\frac{\omega_g - \omega_m}{n} \right) \quad (\text{II.B.3})$$

$$\frac{d\theta}{dt} = \omega_g - \omega_m \quad (\text{II.B.4})$$

Where n is the gear ratio, θ is the angle between the turbine rotor and the generator rotor; ω_m , ω_g , H_m and H_g are the turbine and generator rotor speed and inertia constant, respectively. K and D are the drive train stiffness and damping constants; T_w is the torque provided by the wind (from section A) and T_e is the electromagnetic torque. The 3D modeling of the gear train system has been given in the *Appendix (Part C)*.

D. Yaw System Modeling

Yaw system plays an important role in wind turbine generator because of the direction and intensity of wind is time-varying. Yaw system consists of yaw control system and yaw drive system which mainly make the wind wheel track the wind direction and unwind the cables automatically when it is winded in a certain amount of rings [12]. The yaw movement differential equation is given below:

$$J \frac{d^2\alpha}{dt^2} + k_a \cdot \frac{d\alpha}{dt} = F_v \quad (\text{II.C.1})$$

Where α is the yaw rotational angle; J is the nacelle inertia; k_a is the air friction constant and F_v is the wind force, as follows:

$$F_v = F_0 \cos \alpha; F_0 = k_v \cdot v^2 \quad (\text{II.C.2})$$

Where k_v is a constant and v is the wind velocity.

The yaw angle is the angle between the direction of the oncoming wind speed and the rotor axis and the turbine power is multiplied by the cosine of the yaw angle. When there is a non-zero yaw angle, the wind does not strike the leading edge of the blade orthogonally. Hence, the blade does not generate the same lift forces as it would generate with orthogonal inflow. Therefore, for the calculation of turbine power, only the orthogonal component of wind should be used. So, (II.A.4) can be written as [13],

$$P_{\text{Blade}} = C_p(\lambda, \beta) \cdot \frac{1}{2} \cdot \rho \cdot A \cdot v^3 \cdot (\cos \alpha)^3 \quad (\text{II.C.3})$$

In reality, the simulation is complex. To obtain the real power that is produced by the rotor accurately, a detailed study using computational fluid dynamics (CFD) should be performed. It is beyond the scope of this work to perform such calculations.

E. Modeling of the Asynchronous Generator

The mechanical power of the wind turbine is converted into electrical power by an AC or DC generator. The AC generator can be either a synchronous or an induction (asynchronous) machine. The latter is the most widely used in wind power

industry and was selected for this project. The electrical machine works on the principle of action and reaction of electromagnetic induction. The resulting electromechanical energy conversion is reversible. As we have focused on control systems of the turbine and dynamic modeling is beyond the scope of this paper, the fixed speed induction generator has been considered which is discussed in [14], [15].

CONTROL SYSTEMS

For the proper operation of wind turbine, we have considered three control systems namely pitch, yaw and supervisory. Pitch control will help to monitor the blade position by adjusting angle of attack. Yaw control will assist to determine nacelle movement as per requirement and finally supervisory control system will govern the overall state of the turbine.

F. Blade Pitch Control System

Let us consider, the wind turbine has three blades. To control the pitch angle of the blade, hydraulic actuator is used for each blade and all the three hydraulic actuators should act simultaneously. The blade of wind turbine can rotate around one axis. To rotate the blade, we have a mechanical linkage which is attached to a blade and a hydraulic cylinder. The hydraulic cylinder can extend or contract in order to rotate the blade. To control the piston position i.e. flow of the hydraulic fluid inside the cylinder, hydraulic valves are used. The actuator controller will control the position of the spool of the valve. For this actuator controller to work, it has to know measured pitch angle and actual pitch angle command. Actuation is based on deviation from a commanded value. The mechanical power which has to be delivered to the generator must be limited when the turbine reaches the rated power. In our design, the cut-out speed of wind turbine is 25ms^{-1} , the rated wind speed is 12.5ms^{-1} and the cut-in wind speed is 3ms^{-1} . Rated power of the generator will be attained at 12.5ms^{-1} . Hence, after this rated speed, the generator will be saturated i.e. it will rotate with an over speed, so it has to be controlled. The controlling of the over speed of generator is done by adjusting the pitch angle through the control system loop [16]. We have a desired rotor speed and from that we have to determine the pitch angle command. The control system will compare the actual rotor speed to the desired rotor speed to determine the desired angle of attack. Then we compare the desired angle of attack with the inflow angle, the angle at which the wind strikes the blades, finally to determine pitch angle command. The other control system is involved to determine the state of the turbine. This is called event-based control where system changes mode based on event or in other words named as supervisory control. Fig. 6 shows the control structure of pitch controller.

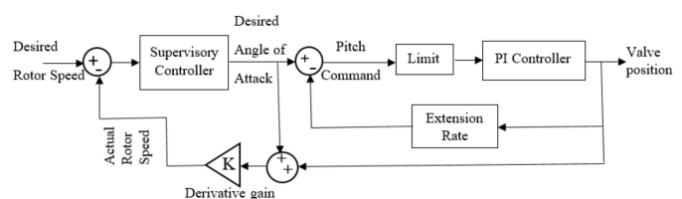


Figure 6: Control structure for pitch control system

A traditional approach to design commonly used linear controllers such as PI controller requires that the non-linear turbine dynamics be linearized about a specified operating point by using root-locus and Bode Plot methods as well as control system tool box in MATLAB. Linearization of the turbine equation would yield:

$$J_t \Delta \omega_t = A \Delta \omega_t + B \Delta v + C \Delta \beta \quad (\text{III.A.1})$$

Where J_t is the MOI of the turbine rotor, ω_t is the rotor speed and linearization coefficients A, B and C are given by,

$$A = \left(\frac{\partial T_m}{\partial \omega_t} \right)_{op} = \frac{1}{2} \rho A v_{op}^3 \cdot \frac{\partial}{\partial \omega_t} \left[C_p(\lambda, \beta) \right]_{op} = K_{11} + K_{12} + K_{13} \quad (\text{III.A.2})$$

$$B = \left(\frac{\partial T_m}{\partial v} \right)_{op} = \frac{1}{2} \rho A \frac{1}{\omega_{top}} \cdot \frac{\partial}{\partial v} \left[C_p(\lambda, \beta) \cdot v^3 \right]_{op} = K_{21} + K_{22} + K_{23} \quad (\text{III.A.3})$$

$$C = \left(\frac{\partial T_m}{\partial \beta} \right)_{op} = \frac{1}{2} \rho A \frac{v_{op}^3}{\omega_{top}} \cdot \frac{\partial}{\partial \beta} \left[C_p(\lambda, \beta) \right]_{op} = K_{31} + K_{32} + K_{33} \quad (\text{III.A.4})$$

$$\text{Where } \lambda_{op} = \frac{\omega_{top} R}{v_{op}}$$

$K_{11}, K_{12}, K_{13}, K_{21}, K_{22}, K_{23}, K_{31}, K_{32}$ and K_{33} are written in the appendix (Part A). $\Delta \omega_t, \Delta v$ and $\Delta \beta$ represent deviation from the chosen operating point ω_{top}, v_{op} and β_{op} respectively.

Selection of the operating point is critical to preserving aerodynamic stability in this system. For theoretical analysis, the desired operating point of rotational speed, wind speed and blade-pitch angle is selected as 1200 rpm, 12.5 ms⁻¹ and 90 respectively.

After Laplace Transformation (III.A.1) becomes:

$$J_t s \Delta \omega_t = A \Delta \omega_t + B \Delta v(s) + C \Delta U(s) \quad (\text{III.A.5})$$

The turbine rotor shaft speed can be represented as

$$\Delta \omega_t = \left[\frac{B}{J_t} \Delta v(s) + \frac{C}{J_t} \Delta U(s) \right] \cdot \frac{1}{\left(s - \frac{A}{J_t} \right)} \quad (\text{III.A.6})$$

Equation (III.A.6) describes the linearize model of the wind turbine.

As mentioned above the movements of the blades are achieved by using double-acting hydraulic actuators and the mathematical modelling of the actuation system can be found in [17].

The PI controller is used for controlling the rotor speed. The transfer function between the input rotor speed ($\Delta \omega_t(s)$) and the output pitch angle command ($\Delta U(s)$) can be described as follows:

$$T(s) = \frac{\Delta U(s)}{\Delta \omega_t(s)} = \frac{K_p s + K_I}{s} \quad (\text{III.A.7})$$

By using Simulink Control System Toolbox, we have tuned the PI controller by observing step responses adjusting Root Locus and Bode Plots at a particular operating point and found the proportional (K_p) and integral (K_I) gain values which are given in the appendix (Part B).

G. Nacelle Yaw Control System

The angle of attack will be affected by changing the yaw angle of a wind turbine. Thus, the different aerodynamic behavior of the blade can be resulted, so the performance characteristics of the wind turbine can be varied with respect to the yaw angle [18].

The nacelle sits on a tower. Inside the nacelle, there is a gear called ring gear, attached to the tower and it does not rotate. On the side of the ring gear, there are yaw gears, these gears can rotate. When they rotate, pushing against the fixed ring gear allowing the nacelle to rotate about its axis. We have to design a control system which will determine the torque requirements for the yaw actuator (servo motors) to rotate the yaw gears and adjust the nacelle position facing to the incoming wind direction. The yaw controller will determine a yaw command and with that it will determine how much torque the yaw actuator will need to provide to turn the gears in order to rotate the nacelle. The controller will compare the yaw command with nacelle yaw angle and then the controller will determine a yaw rate command [19]. Part of our requirement is the nacelle is allowed to rotate faster than 0.5 degrees per second. So, in our control logic we will put a limit on that yaw rate command and again will compare with the actual yaw rate and that control loop will determine what will the torque should be. Fig. 7 shows the control structure of yaw control system.

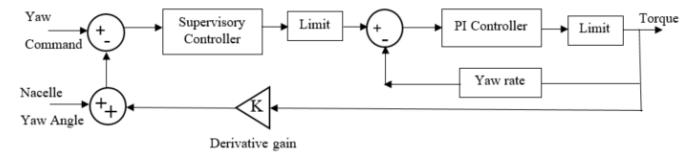


Figure 7: Control structure for yaw control system

Like the pitch controller, the yaw control system also includes a PI controller to control the preferred torque required for the nacelle movement. The non-linear wind turbine model described above has been used and extensive trial and error iteration based on guess and check are carried out [20]. Using Integral of Time-weighted Absolute Error (ITAE) criterion [21] as a performance index measure. The proportional action acts as the main controller where integral action refines it. The controller gain, K_p , is adjusted with the integral gain, K_I held at minimum, until a desired output (rise time) is obtained. The tuning K_I for best transient response while maintaining K_p at its pre-selected value. The proportional (K_p) and integral (K_I) gain values are given in the appendix (Part B).

The yaw moment of the wind turbine should be zero for a zero-degree yaw angle. The yaw momentum about the tower for yaw angle 0° , 10° , 20° and 30° when it is located in upstream. The turbine which is operating with the positive yaw angle which will be in order of 2° to 4° . The yaw momentum about the tower for yaw angle 0° as for yaw angle 10° , 20° and 30° when it is located in downstream, the turbine which is operating with the negative yaw angle will be in order of -2° to -4° .

H. Supervisory Control Using State Machine

We will define several states like the first one is ‘Park’ state where the parking brake is turned on, pitch brake is turned off and the generator is not connected to the grid. When the wind velocity gets above the certain speed i.e. the cut-in speed, we will move to the ‘Startup’ state releasing the parking brake and leave the other two systems at their previous states. When the turbine reaches the minimum operating speed, we will then connect the grid with the generator and the turbine will be in ‘Generating’ state. Under number of different operating conditions, we may have to stop the turbine, so we need a ‘Brake’ mode to slow down the turbine to stop by activating pitch brake and when it reached slow enough speed, it will put the turbine in Park mode. By using *Stateflow* in MATLAB, we have created the event-based supervisory controller that sets the state of the brake, generator, pitch and yaw angle based on turbine’s different operating conditions. The coding of state machine is done by using C language.

SIMULATION DIAGRAMS OF THE CONTROL SYSTEMS

The above mentioned three control systems named as pitch, yaw and supervisory control system are simulated by using MATLAB. Fig. 8 represents the control structure of each individual system. In Fig. 8a, pitch command is the input defining how pitch should vary, angle of extension is used to determine how much pitch angle has to be changed for the next instant. Extension rate is the rate at which the angle has to be extended and required actuation force is the output from this control loop which is the inner loop of the pitch control system. The outer loop which incorporates the wind and preferred rotor speed as input and with the help of inner loop, the rotor speed is calibrated as per the desired angle of attack, as shown in Fig. 8b. Fig. 8c represents the yaw control system where yaw command is the input and the required torque at which the nacelle rotates is the output. In both the control loops, we have used PI controller for less overshoot and to avoid sudden change in actual pitch or yaw angle. We have used *Simulink design optimization* toolbox to tune the controller parameters automatically until it meets system requirements. Fig. 8d introduces the event-based supervisory control system to maintain proper balance with each and every component and turn on/off the primary or auxiliary parts of the turbine.

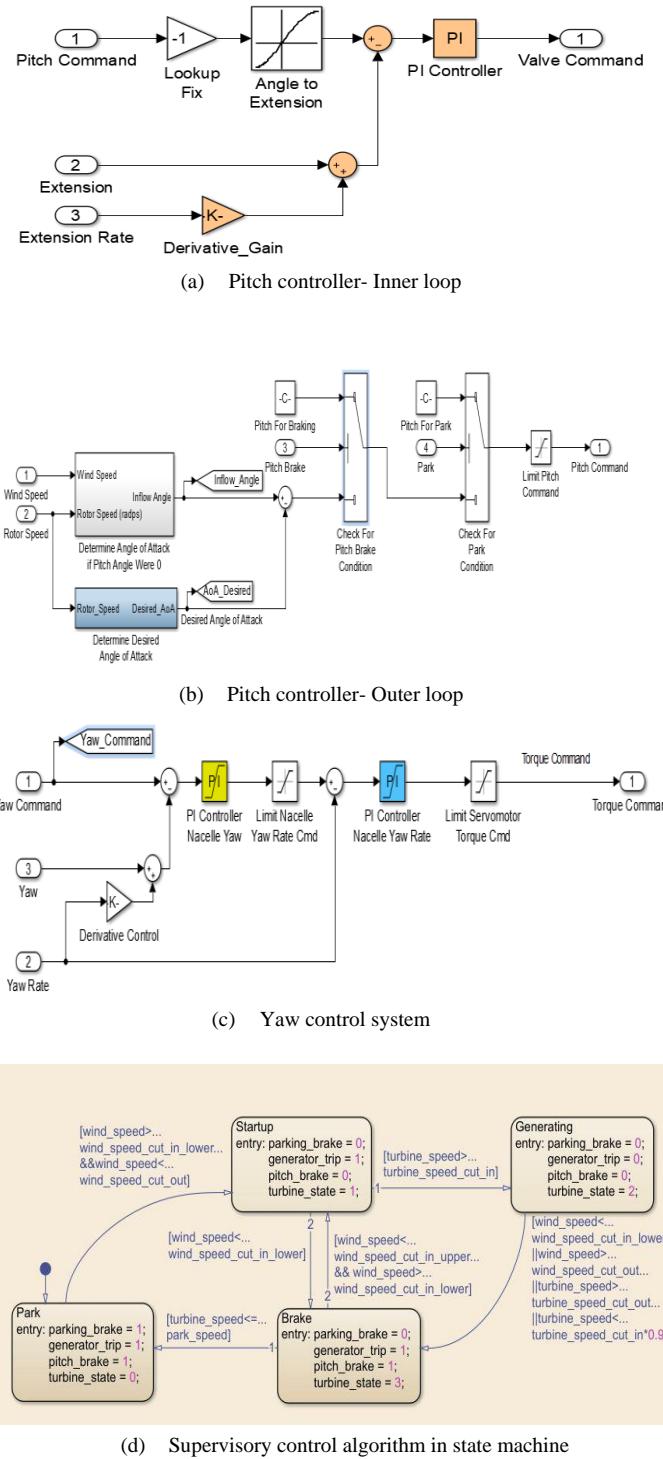


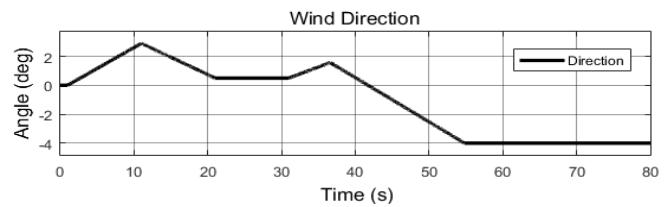
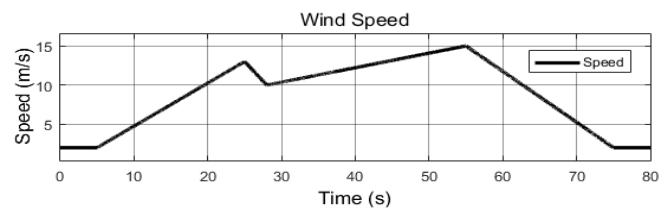
Figure 8: Simulation diagrams in MATLAB SimulinkTM

SIMULATION RESULTS

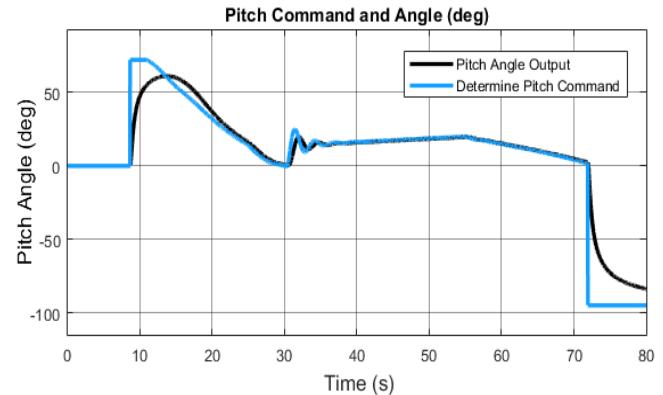
The simulation results of these three control systems are shown in Fig. 9a to 9l. Fig. 9a shows turbine input which is the wind in terms of speed and direction (inflow angle) by using signal generator. There are four types of inputs generated in the input block- normal wind, cut out wind, high speed wind and varying

wind. To make the simulation more practical, we made variation in both wind speed and direction with time and chose the ‘varying wind’ block as input. Fig. 9b shows pitch control waveforms where the blue color indicates the input command and black color indicates the output which is following the pitch command. To find out the hydraulic actuator requirements, at first we have used ideal actuator in the pitch system. Fig. 9c shows the behavior of ideal actuator i.e. pitch angle variation with the input command and actuation force. The hydraulic actuator should be designed as per these results. Fig. 9d depicts the cylinder piston velocity for both ideal (black) and hydraulic (blue) actuators where the piston is linked with the blades. The performance is nonlinear in nature. A comparison between the performance of ideal and hydraulic actuator is shown in Fig. 9e. The hydraulic actuator force is quite acceptable as it remains almost similar with the ideal actuation force curve and finally we can keep the pitch control system with that performance in hand. Now we will focus on yaw control system and likewise pitch control we will use an ideal actuator to determine yaw torque requirement for our system. The torque curve for ideal actuator is shown in Fig. 9f. Fig. 9g indicates the nacelle’s yaw movement as per given yaw command and nacelle yaw rate (degree per sec) which is below 0.5 degrees complies with design requirements. Now with these two data sets, we can find out the required torque for servomotor actuation. Fig. 9h shows a comparison between two yaw actuators- ideal (red) and servomotor (black) actuator. The generated torque by using servomotor actuators are pretty good as following the nature of ideal actuator. Fig. 9i interprets the supervisory control system namely the states of the turbine- turbine startup, generator trip, parking and pitch brake which are pretty much convenient as per event-based control algorithm. Lastly, Fig. 9j shows our main control objective which is controlling the rotor speed with various operating conditions. It is evident from the curve that when time is zero, the rotor is at parking position. After sometime when wind strikes the blades it starts to turn slowly. When the wind speed exceeds the cut in speed after 30 seconds, the rotor has reached its maximum rotational speed which is approximately 15 rpm and remained steady up to next 30 seconds and goes to generating mode. After 70 seconds, the wind reached the cut-off speed, so the rotor needs to be stopped to avoid unnecessary damage and from the response curve, we can see, the rotor speed is gradually decreasing and finally reaches to zero i.e. in parking mode. From this region, maximum safe electrical power is given up to the cut-off speed, which is the speed of wind that is no longer safe to run the turbine [22]. Therefore, we can conclude that the supervisory control system is maintaining the desired linkage between pitch and yaw controllers, respectively. Fig. 9k shows the estimation of generated output power. As we can see, the rotor speed gets the steady value after 30 seconds and so as the power reaches its maximum value which is more than 2MW and keeps a steady state till 55 seconds, then decreases as the rotor speed slows down. Fig. 9l indicates the step response of two different iterative methods named as Lumped Parameter Model and

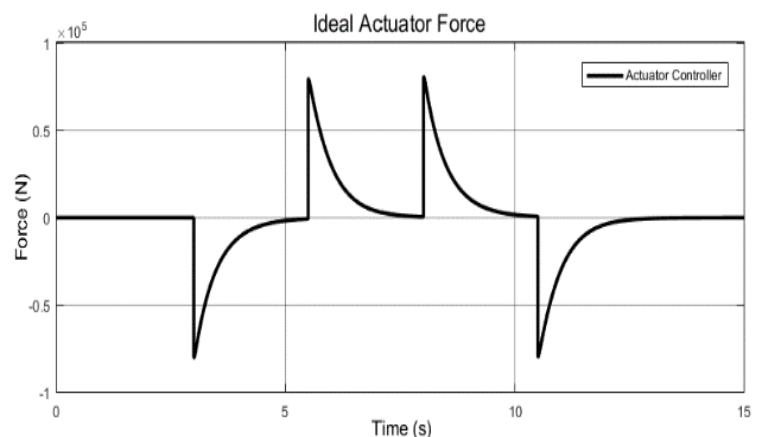
matrix based Finite Element Analysis (FEA) calculating the rotor speed and torque at the blade base and both results are identical. The rotor speed is showing steady with no overshoot, on the other hand torque curve is oscillatory in nature but bounded by the limiting values. Selecting an efficient control system requires doing tradeoff studies in early stages to determine which will provide enough force or torque while drawing the least power. The actuator must be developed together with the control systems and there may be multiple control loops that must interact with the actuation system.



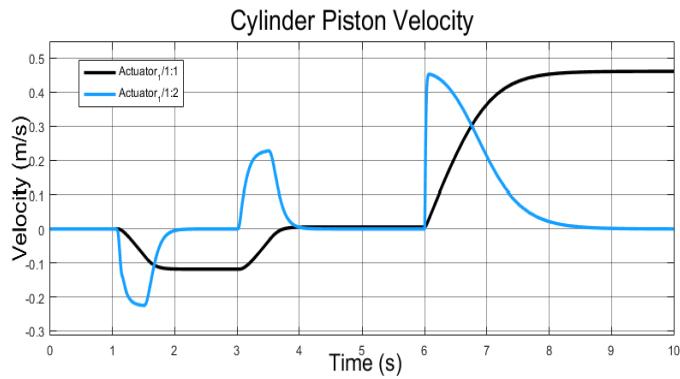
a) Input wind speed and direction



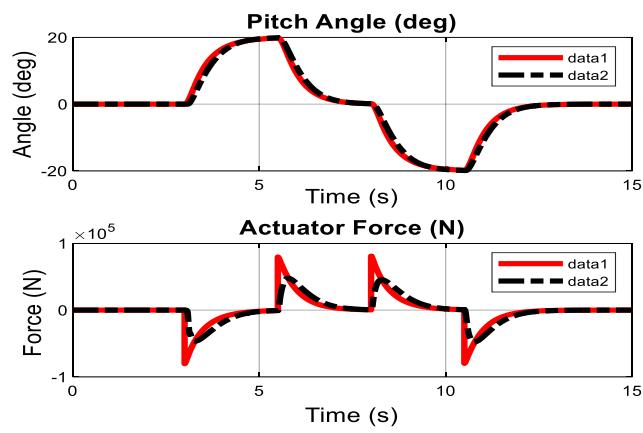
b) Pitch controller waveforms



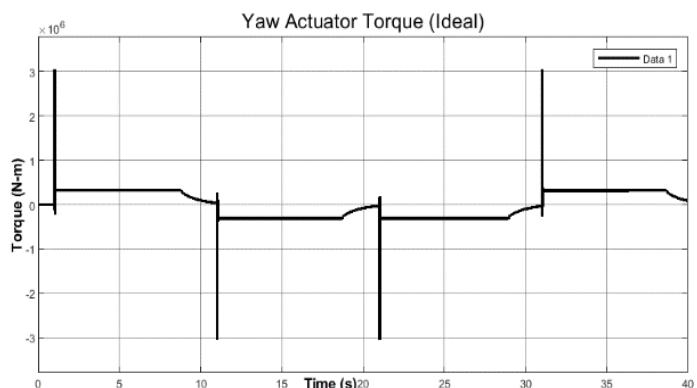
c) Behavior of Ideal Actuator (Pitch system)



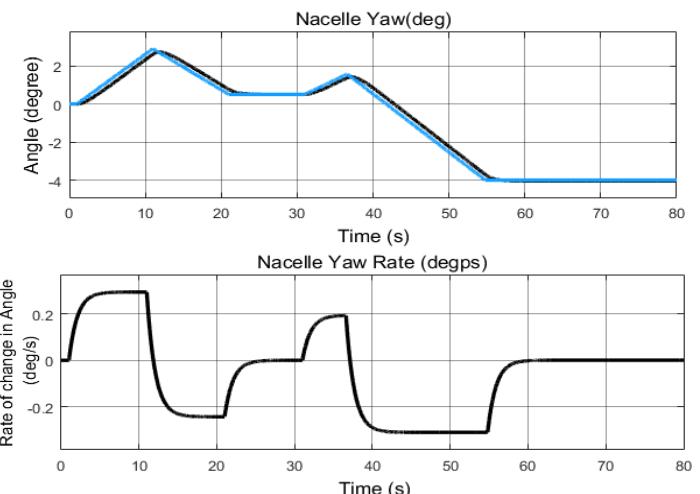
d) Cylinder piston velocity requirements for hydraulic actuator



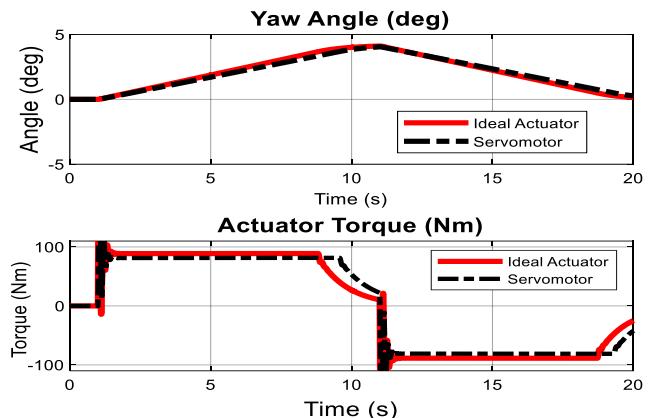
e) Comparison between ideal and hydraulic actuator performance (pitch control)



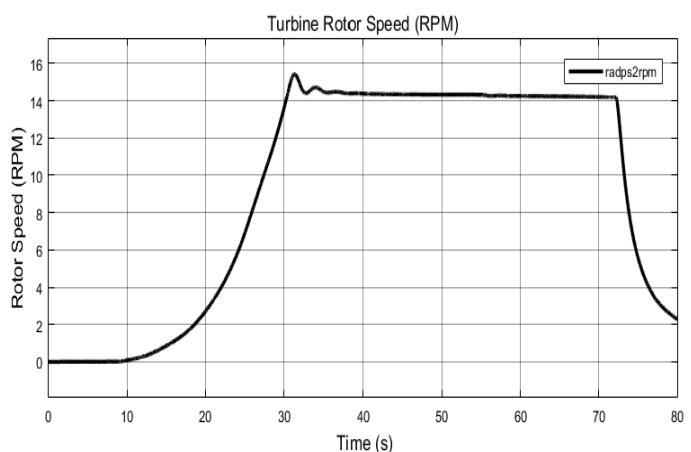
f) Torque requirement for Ideal Actuator



g) Yaw angle and rate of change of Nacelle



h) Comparison between ideal and servomotor actuation performance (yaw system)



i) Turbine rotor speed

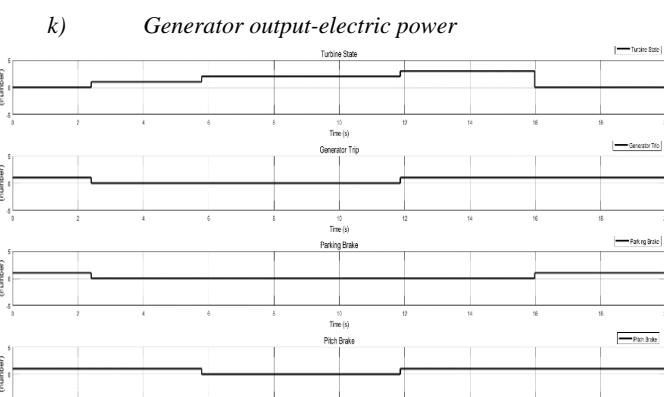
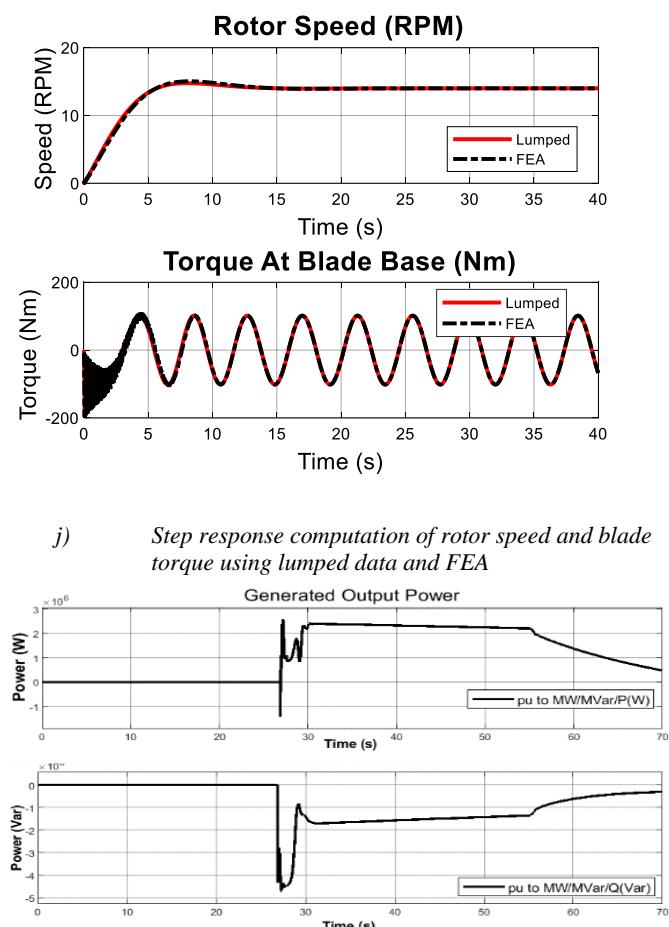


Figure 9: Simulation results for pitch, yaw and supervisory control systems

CONCLUSION

As the world is currently facing an energy and climate crisis, the development and utilization of alternative sources of energy has become an important challenge. Among the available renewable energy sources, wind energy proved to be one of the

cleanest and most reliable solutions for electrical energy production. The complexity of control systems in wind turbines is expanding rapidly and their design can be the difference between an immensely profitable system and a dormant or damaged system. Designing a robust control system requires an accurate model of the plant and tools that enable rapid iteration to find the best design. The control system must be optimized as possible while meeting multiple and sometimes conflicting system requirements. Pitch and yaw controllers must interact with supervisory logic controller in order to operate and protect the turbine under a wide range of environmental and statutory conditions. We have used linear control theory (Root locus, Bode plot, ITAE) to tune the controller parameters. After getting linearized model, we applied it to test the overall nonlinear model using Simulink design optimization. The simulation results show that the classical PI controller performs well, adjusts accurately the blade pitch angle so that the rotor turns at a sequential speed with the generator shaft and required yaw movement to change the nacelle position. To build this model in MATLAB, we have used *Simscape multibody*, *Simmechanics*, *Simhydraulics*, *Control system toolbox* and *State machine* [23]. It allows us the ability to simulate the physical systems such as mechanical, electrical, hydraulic and various control systems in a single environment. It enables engineers to incorporate requirements into the development process, design at the system level and to predict and optimize overall system performance without relying on only hardware prototypes as well as minimizing the cost.

FUTURE WORK RECOMMENDATIONS

The results obtained during this investigation are encouraging. It appears that the control methods allow the wind turbine to operate smoothly. A comparison of Fuzzy PI controllers with the classical PI controllers would be desirable to demonstrate if significant performance improvement of the classical PI controller approach over Fuzzy controlled PI controllers or using deep neural networks or PSO based algorithm is possible. Furthermore, validating the developed wind turbine model with real-time implementation on an actual turbine would be appreciated. This study is limited to the available data and further validation of the model with other wind turbines, other operating points and different disturbances would be advisable, For instance, this study can be improved by taking into account wind gusts and other practical problems. The insertion of the power electronics, converter, inverter, rectifier, capacitor and transformer would make the model more complete. Further research includes modeling and control of a group of interconnected wind turbines or wind farm as well as maintaining robustness requirements for controllers.

APPENDIX

Part A

Results of Linearization of the Wind Turbine Equation

$$K_{11} = \left[\frac{Kv_{op}^3}{R\omega_{top}} (0.44 - 0.0167\beta_{op}) \cdot \frac{\pi R}{v_{op}(15 - 0.3\beta_{op})} \right] \cdot \cos \left\{ \pi \left(\frac{\lambda_{op} - 3}{15 - 0.3\beta_{op}} \right) \right\}$$

$$K_{12} = -\frac{Kv_{op}^3}{R\omega_{top}^2} (0.44 - 0.0167\beta_{op}) \sin \left[\pi \left(\frac{\lambda_{op} - 3}{15 - 0.3\beta_{op}} \right) \right]$$

$$K_{13} = -0.00184 \left(\beta_{op} v_{op}^2 + \frac{3\beta v_{op}^3}{R\omega_{top}^2} \right) K$$

$$K_{21} = \frac{3Kv_{op}^2}{R\omega_{top}} (0.44 - 0.0167\beta_{op}) \sin \left[\pi \left(\frac{\lambda_{op} - 3}{15 - 0.3\beta_{op}} \right) \right]$$

$$K_{22} = -\frac{Kv_{op}^3}{R\omega_{top}} (0.44 - 0.0167\beta_{op}) \cdot \frac{\pi\lambda_{op}}{v_{op}^2(15 - 0.3\beta_{op})} \cdot \cos \left\{ \pi \left(\frac{\lambda_{op} - 3}{15 - 0.3\beta_{op}} \right) \right\}$$

$$K_{23} = -0.00184K \left(2v_{op}\beta_{op} - \frac{9\beta_{op}v_{op}}{\lambda_{op}} \right)$$

$$K_{31} = -\frac{0.0167Kv_{op}^2}{\lambda_{op}} \sin \left[\pi \left(\frac{\lambda_{op} - 3}{15 - 0.3\beta_{op}} \right) \right]$$

$$\begin{aligned} K_{32} \\ &= \frac{0.0167Kv_{op}^2}{\lambda_{op}} (0.44 \\ &\quad - 0.0167\beta_{op}) \left[0.3\pi \left(\frac{\lambda_{op} - 3}{15 - 0.3\beta_{op}} \right) \right] \cos \left\{ \pi \left(\frac{\lambda_{op} - 3}{15 - 0.3\beta_{op}} \right) \right\} \end{aligned}$$

$$K_{33} = \frac{0.00184K(\lambda_{op} - 3)v_{op}^2}{\lambda_{op}}$$

Part B

Wind Turbine Model and Simulation Parameters

1. Blade Requirements

Type description	AL 40
Blade length	40 m
Material	Carbon/wood/glass/epoxy
Standard color	RAL 7035

Gloss	Class 2: (30-70%) to be measured acc. to DS/ISO2813
Type of rotor air brake	Full blade
Blade profiles	FFA - W3, NACA 63.4
Twist	20°
Largest chord	3.08

2. Brakes Requirements

Mechanical	
Type description	Active Brake
Brake disc	Steel, mounted on high speed shaft
Number of calipers	2 piece
Brake Hydraulics	
Voltage	3 x 480 V
Working pressure range	140-150 bar
Oil capacity	11

3. Environment Requirements

Temperature interval for operation	-30 to +30°C
Temperature interval for structure	-40 to +50°C

4. Gear Train Requirements

Type description	1. step planet, 2. step helical
Gear house material	Cast
Ratio	1:84.3
Mechanical power	1800 kW
Bending strength acc. to ISO 6336	SF > 1.6
Surface durability acc. to ISO 6336	SH > 1.25
Scuffing safety acc. to DNV 41.	SS > 1.3

Shaft seals	Labyrinth
Oil sump	App. 250 l

5. Generator Requirements

Type description	1 speed generator, water cooled
Rated power	1650 kW
Apparent power	1808 kVA
Rated current IN	1740 A
Max power at Class F PFma	1815 kW
Max current at Class F IFmax	1914 A
No load current I0	430 A
Reactive power consumption at rated power (tolerance. acc to IEC 60034-1)	740 kvar
Reactive power consumption at no load (tolerance. acc to IEC 60034-1)	447 kvar
Number of poles P	6
Synchronous rotation speed n0	1200 rpm
Rotation speed at rated power nN	1214 rpm
Slip at rated power sN	0.0117
Voltage UN	3 x 600 V
Frequency F	60 Hz
Coupling	Δ
Enclosure	IP54
Insulation class/ Temperature increase	F/B

6. Main Controller Requirements

Annual average wind speed 8.5 m/s	8.5 m/s
Wind shear 0.20	0.2
Extreme wind speed	42.5 m/s (10 min. average)
Survival wind speed 59.5 m/s (3 sec. average)	59.5 m/s (3 sec. average)
Automatic stop limit 20 m/s (10 min. average)	20 m/s (10 min. average)
Re-cut in 18 m/s (10 min. average)	18 m/s (10 min. average)
Characteristic turbulence intensity	16% (including wind farm turbulence)
Maximum in-flow angle	8°

7. Nacelle Requirements

Material EN-GJS-400-18U-LT	EN-GJS-400-18U-LT
Standard colour RAL 7035	RAL 7035
Corrosion class, outside Acc. to DS EN ISO 12944:C5 I	Acc. to DS EN ISO 12944:C5 I
Rotor	
Number of blades 3 pieces	3 pieces
Tip speed (synchronous) 61.8 m/s	61.8 m/s
Rotor shaft tilt 5°	5°
Eccentricity (tower center to hub center)	3447 mm
Solidity (Total blade area/rotor area)	0.05
Rotor orientation	Upwind

8. Pitch Actuation Requirements

Hydraulic pressure	2e7 Pa
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Accumulator Capacity	0.1 L
Accumulator Preload Pressure	1.5e7 Pa
Accumulator Maximum Pressure	2.5e7 Pa

9. Pitch Controller Requirements

Track angle within	1 degree
Rise Time	3 seconds
Settling Time	5 seconds
Proportional Gain, K _P	92845
Integral Gain, K _I	307

10. Yaw Actuation Requirements

Type description	Planetary gear motor
Gear ratio of yaw gear unit	app. 1:1687
Voltage	3 x 480 V
Rotational speed at full load	1140 rpm
Number of yaw gears	4 pieces
Yaw Brake	Hydraulic disc brake
Number of Yaw Friction Units	6 pieces
Voltage	3 x 480 V
Working pressure range	140-150 bar
Oil capacity	App. 10 l.

11. Yaw Controller Requirements

Max Yaw Rate	0.5 deg/sec
Rise time	3 seconds
Settling time	5 seconds
Proportional Gain, K _P	300
Integral Gain, K _I	0.1

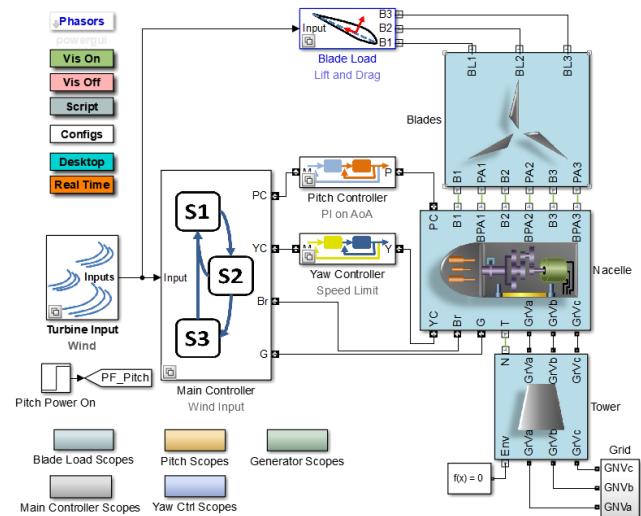
12. Tower Requirements

Type Description Conical, tubular	Conical, tubular
Material Welded steel plate	Welded steel plate
Corrosion class, outside Acc. to DS EN ISO 12944: C5 I	Acc. to DS EN ISO 12944: C5 I
Colour RAL 7035	RAL 7035
Access conditions	Internal, safety harness, ladder cage

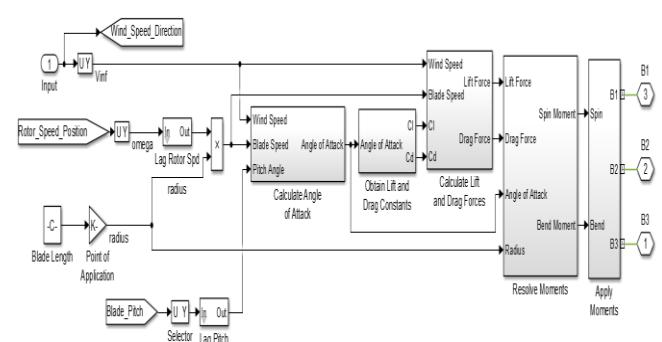
Part C

3D Modeling Structures built in Simulink™

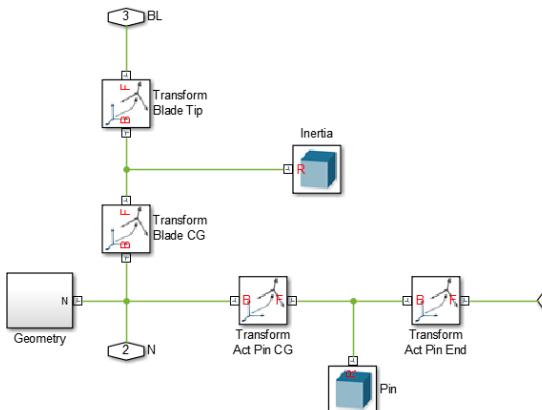
1. Overall Wind Turbine Model



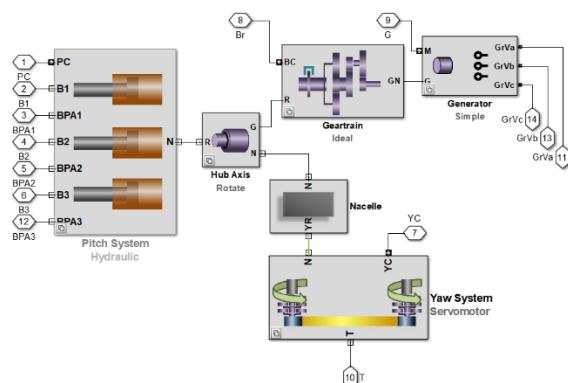
2. Blade Load Model



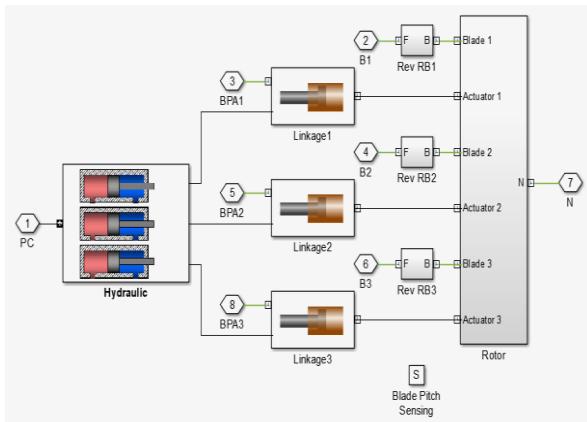
3. Blade Mechanics Model



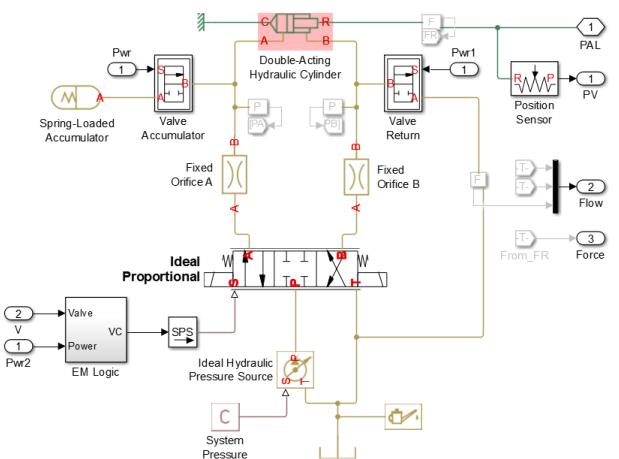
4. Nacelle Model



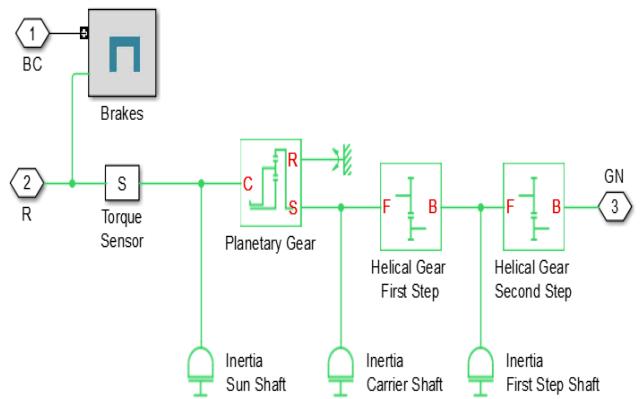
5. Pitch Mechanism Model



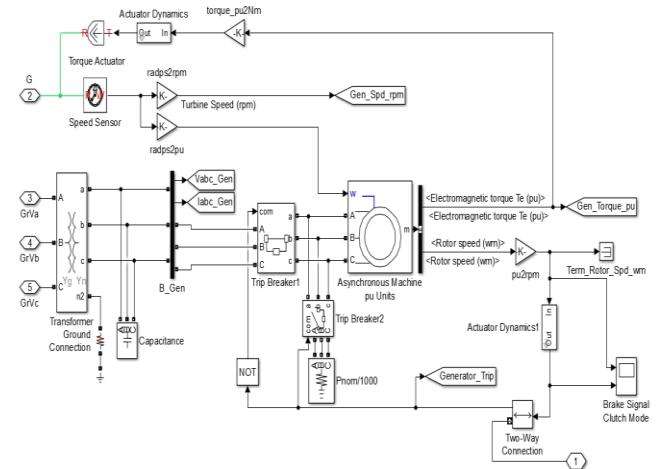
6. Hydraulic Actuator Model



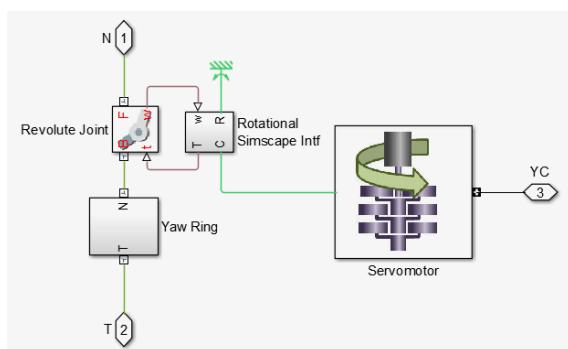
7. Gear train Model



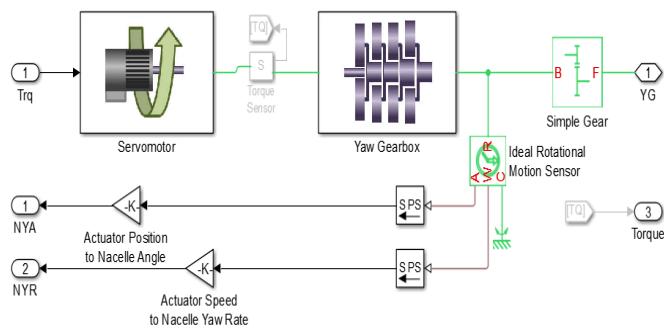
8. Generator Model



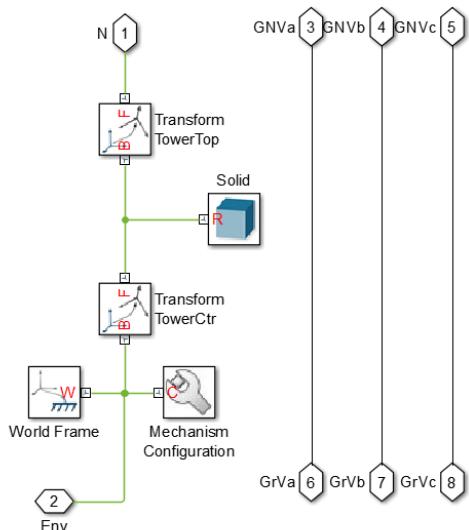
9. Yaw system Model



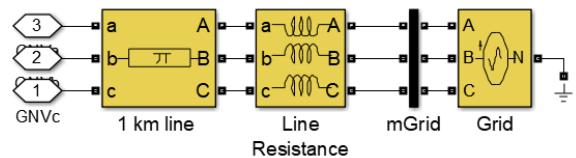
10. Servomotor Model



11. Tower Model



12. Grid Model



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