Optimal Modelling of A 720KW Wind Turbine Using Matlab/Simulink

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Abstract- Wind energy is a vital component of sustainable power generation, and modeling wind turbine generators accurately is crucial for optimizing their performance. This project focuses on the optimal modeling of a wind turbine generator using MATLAB SIMULINK, emphasizing key aspects such as MATLAB as a versatile modeling platform, the critical parameter of Tip Speed Ratio (TSR) for determining optimal rotational speed, the significance of modeling Pitch Controller algorithms to regulate blade angles and ensure safe operation, and the consideration of environmental effects, including wind speed, turbulence, and wind direction, to assess their impact on energy production and turbine loads. These elements collectively contribute to the comprehensive understanding and optimal modelling of the 720KW wind turbine systems with pitch controller for enhanced energy efficiency, reliability, and longevity, making this research vital for sustainable wind energy generation.

Keywords: Optimal, Wind Energy, Wind Turbine, MATLAB, Simulink.

I. INTRODUCTION

Recent studies have shown that about 770 million people live without access to electrical power, mostly in Africa and Asia (Bouckaert, et al., 2019). As electricity is the backbone of today's industrial and consumer economies, for there to be increased per capita income, electrification of transport, use of electronic device and demand for customer and industrial products, power must be generated. Power generation is the process of producing electrical energy from various sources, such as coal, natural gas, nuclear, wind, solar, hydro, and geothermal Power generation is a crucial component of modern society as it provides electricity for homes, businesses and industries. The method of power generation can have significant environmental and societal impact, and there is a growing emphasis on developing sustainable renewable sources of energy to meet the world's growing energy demand.

The increasing demand for renewable energy sources has led to the development of wind turbine generators as a viable source of clean energy. The design and optimization of wind turbine generators is crucial to ensure their efficiency and effectiveness in converting wind energy into electrical power. In this project, we used MATLAB/SIMULINK software to model and design a wind turbine generator system. The purpose of this report is to present the results of the simulation and analysis of the wind turbine generator's performance, including its power output and efficiency, as well as to evaluate the impact of various design parameters on its performance. Through this project, we aim to provide insights into the design and optimization of wind turbine generators, which can aid in the development of more efficient and cost-effective wind energy systems.

Wind turbine generators come in different sizes, configurations, and designs, and their performance is affected by a variety of factors, including the wind speed and direction, the blade design, and the generator's control system. Therefore, designing and optimizing wind turbine generators is crucial to ensure their efficiency and effectiveness in harnessing wind energy.

II. RESEARCH ELABORATIONS

REVIEW OF PREVIOUS WORK

(Bossanyi, 2003) paper titled Wind Turbine Control for Load Reduction, audits strategies for the control of wind turbines during power production. Pitch control is utilized essentially to restrict power in high winds; however, it additionally critically affects underlying burdens. Especially as turbines become bigger, there is expanding interest in planning regulators to relieve loads beyond what many would consider possible. Torque control in variable-speed turbines is utilized essentially to maximize energy capture when wind speed is less than rated wind speed, and to restrict the torque above rated, however it can likewise be utilized to decrease specific loads. Extra sensors, for example, accelerometers and load sensors can likewise assist the regulator with accomplishing its targets efficiently. By independently controlling the pitch of each blade, accomplishing significant further decreases in loading is likewise conceivable. It is vital to have the option to evaluate the advantages of any new regulator. Although programmatic experiences are helpful, field preliminaries are likewise crucial. The changeability of the wind implies that specific consideration is required in the plan of the preliminaries.

(Rassul Abbas & Abdulsa, 2010) Simulation of Wind Turbine Speed Control by MATLAB. The output frequency of the self-excited induction generator (SEIG) driven by the wind turbine is controlled. Static load is supplied by the wind turbine. Principle connections of wind conversion are discussed. Dynamic modeling and linearization of wind turbines are derived. PID controller used for the turbine rotor speed regulation and frequency regulation is discussed. Block diagram of the speed control system proposed which includes speed controller and actuator model, and turbine linearized model is simulated using MATLAB-SIMULINK.

(Qi & Meng, 2012) titled The Application of Fuzzy PID Control in Pitch Wind Turbine, the theory of fuzzy control and PID control is applied to control the generator speed and blade pitch. In the initial stage, a fuzzy controller was used to improve the responsiveness of the system and reduce overshoot. Once in the steady-state control period, a PID controller was used to minimize the steady-state error by controlling the proportional, derivative, and integral parameters of the system. Perform MATLAB simulations based on a mathematical model of a variable-pitch wind turbine. The results show that this method allows the generator to operate at maximum power before it is connected to the grid and at rated power after operation.

(Civelek, et al., 2016) paper titled Intelligent Automation & Soft computing, this paper presents a study on a set of PID parameters for a wind turbine blade pitch controller using fuzzy logic algorithms. Three separate control methods were used to control the pitch angle of the wind turbine. These control methods are traditional PI, fuzzy, and fuzzy PID. Using these control methods, we were able to protect the system from damage that could occur in high wind speed areas and ensure changes in the rated output power. The objective was to control the angle of attack of the wind turbine blades at different wind speeds and keep the output power stable at the set point by simulating the controller in MATLAB/Simulink software. The performance of the control system was measured and compared with each other by evaluating the steady-state time of the output power and the steady-state error obtained from the simulation results. As a result of these simulation comparisons, the performance of the fuzzy PID controller is better than his PI controller and fuzzy controller.

(Babu, et al., 2014) Modelled and Simulated Wind Turbine Generator using MATLAB/SIMULINK, the authors developed a MATLAB SIMULINK model of a squirrel cage induction generator (SCIG) wind turbine. This model was used to study the effects of different wind speeds and different loads on the performance of a wind generator. Research has shown that SCIG can generate electricity over a wide range of wind speeds.

(Roshen & Abdul-Hassain, 2017) Paper Modelling and Simulation of Wind Turbine Generator using MATLAB-SIMULINK model of a wind turbine generator with induction generator is done. This paper describes modeling and simulation of wind turbine generators using MATLAB-SIMULINK using a model of a wind turbine generator with an induction generator. This model was used to study the effects of different wind speeds, different loads, and different grid conditions on the performance of a wind turbine generator. Research results have shown that Doubly Fed Induction Generator (DFIG) can operate more efficiently than squirrel cage induction generator (SCIG) even with varying wind speeds.

In the paper titled Modelling and Simulation of Wind turbine driven permanent magnet generator with new Maximum power point tracking (MPPT) algorithm, the authors developed a MATLAB SIMULINK model of a wind turbine generator with a permanent magnet synchronous generator (PMSG). This model was used to study the effects of different wind speeds, different loads, and different grid conditions on the performance of wind generators and to maximize the efficiency of the wind energy conversion system. Compare MATLAB/SIMULINK results with laboratory setup (Bharanikumar, et al., 2010).

In the paper, Modelling and Simulation of Different Wind Energy Conversion System (WESC) using different generators, in order to examine the generators' efficacy, modeling and simulation of several wind energy conversion systems (WESC) employing various generators running under the same conditions will be done in the article using MATLAB/SIMULINK. Although all of them eventually approach the same efficiency, PMSG has demonstrated to be more effective than SCIG and DFIG for lower wind speeds. Efficiency of SCIG, DFIG and PMSG for rated wind speed are 66.25%, 69.38% and 71.88% respectively (Chong, et al., 2020).

III. METHODOLOGY

In this paper, the following methodology is followed

1. The necessary data and parameter for the wind turbine model is obtained. This includes the wind turbine's power curve, aerodynamic characteristics, mechanical properties, and electrical properties (Junyent-Ferre, 2011).
2. Wind speed and direction data is incorporated into the model in SIMULINK to simulate the dynamic behavior of the wind turbine generator system under various environmental conditions.
3. The performance of the wind turbine generator system is evaluated in terms of power output, efficiency, under different wind conditions and operational scenarios.
4. The effects of control strategy on the performance of the wind turbine generator system is explored for the most effective methods for maximizing power output and maintaining system stability in the MATLAB/SIMULINK model with the use of a pitch controller.

IV. MODELLING OVERVIEW

This section explains the optimal modelling of the wind turbine generator as it engages several areas of knowledge including aerodynamic studies, mechanical workings, electrical engineering and control as well as awareness related to environmental factors. Figure 1 below represents the block diagram of the wind turbine generator model, it shows how the various components are connected.

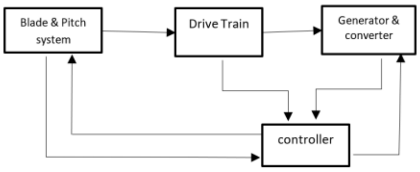


Figure 1: Block diagram of the wind turbine generator

The wind turbine generator consists of aerodynamic block, the mechanical block and the electrical block. The modelling of the wind turbine generator will analyze two blocks which comprises the aerodynamic block and the mechanical block. The electrical block will not be studied because it is not relevant to the objective of the paper as it would be an implementation that would not provide any relevant information to the subject of study, the model blocks is as shown in the figure 2 below:

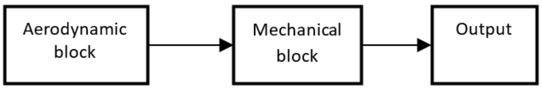


Figure 2: Optimal turbine block model

The equations used in the design model for each block are derived and analyzed. The Aerodynamic block is responsible for the extraction of power from the wind in the form of kinetic energy necessary to propel the blades. The mechanical block then converts this kinetic energy into mechanical energy used to drive the generator which in turn is converted into electrical energy.

A flow chart of the operation of the turbine is represented in figure 3 below

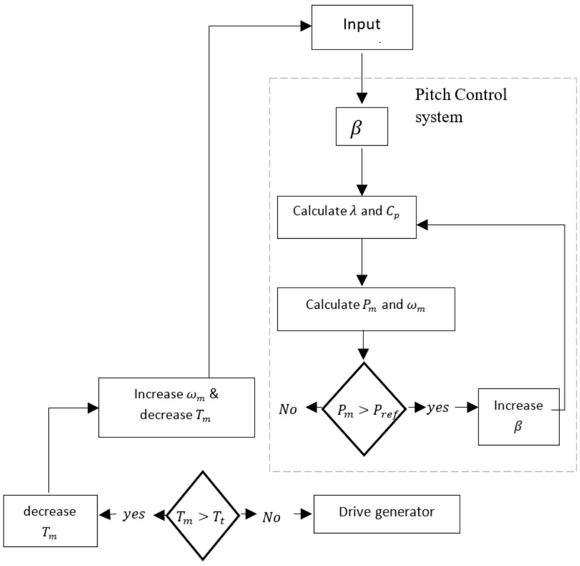


Figure 3: A flowchart of the operation of the wind turbine

V. AERODYNAMIC SUBSYSTEM MODELLING

This system models the interaction of the wind and the blades of the turbine. The blades of the turbine rotate due to the kinetic energy from the wind which is determined by the speed of the wind. An object of mass (m) moving with a velocity (v) has a kinetic energy given by

$$E = \frac{1}{2} \times m \times v^2 \tag{1}$$

The power contained in the blade assuming moving with constant velocity is obtained by the derivative of kinetic energy with respect to time is given as

$$P_w = \frac{dE}{dt} = \frac{\Delta KE}{t} \tag{2}$$

$$P_w = \frac{1}{2} \times \frac{m}{t} \times v^2 \tag{3}$$

$$P_w = \frac{1}{2} \times \dot{m} \times v^2 \tag{4}$$

Where $\dot{m}$ is the mass flow rate

When the air crosses the area A brushed by the blades of the rotor the power in the air can be calculated as

$$P_w = \frac{1}{2} \times v^3 \times A \times \rho \tag{5}$$

The efficiency of the turbine with respect to the power is C_p referred to as performance coefficient of the rotor, which shows how efficiently a turbine converts the energy in the wind to electricity.

$C_p(\lambda, \beta)$ is a function of the tip speed ratio (TSR) "λ" and the blade pitch angle "β(in degrees)". The blade pitch angle refers to the angle between the propeller blade chord and the plane of rotation of the propeller. (Chong, et al., 2020) shows a blade pitch angle of $\beta = 0$, has a high-performance coefficient leading to a highly efficient wind turbine. For this project $\beta = 0$ will be used.

$$Efficiency\left(C_p(\lambda, \beta)\right) = \frac{Power\ output}{Power\ input} \tag{6}$$

$$C_p(\lambda, \beta) = \frac{P_{blade}}{P_w} \tag{7}$$

$$P_{blade} = \frac{1}{2} \times v^3 \times A \times \rho \times C_p(\lambda, \beta) \tag{8}$$

Where:

$A = \pi \times R^2$ is the swept area of the blade.

v is the velocity of wind in $\frac{m}{s}$

ρ is the density of air, $\rho = 1.225kgm^{-3}$ at sea level at temperature $298°K$

$C_p(\lambda, \beta)$ is the performance coefficient of the turbine = 0.593 (Betz law)

The TSR is expressed as

$$\lambda = \frac{\omega_r \times R}{v} \tag{9}$$

ω_r is the angular velocity of the rotor

R is the radius of the turbine blade

$C_p(\lambda, \beta)$ can be expressed as

$$C_p(\lambda, \beta) = C_1 \times \left(\frac{C_2}{\gamma} - C_3\beta - C_4\beta^{C_5} - C_6\right) e^{\frac{-C_7}{\gamma}} \tag{10}$$

$$\frac{1}{\gamma} = \frac{1}{\lambda + 0.02\beta} - \frac{0.03}{1 + \beta^3} \tag{11}$$

Where

$C_1 = 1, C_2 = 110, C_3 = 0.4, C_4 = 0.002, C_5 = 2.2, C_6 = 9.6, C_7 = 18.4$ are the characteristic parameter of the turbine. These values are derived through statistical analysis of actual turbine and finite element simulations. (Junyent-Ferre, 2011)

γ is the tip speed ratio at the ith time step

The Rotor Torque is defined by the

$$T_w = \frac{P_{blade}}{\omega_r} \tag{12}$$

Based on the amount of research data available on the HWP 33/330 wind turbine model, Specification of the suggested wind turbine (Junyent-Ferre, 2011)

For a 720KW,

Table 1: Specification of 720KW wind turbine

Rotor Diameter	66m
Swept Area (A)	$3421.2m^2$
TSR ($\boldsymbol{\lambda}$)	5.83
Blade Pitch angle ($\boldsymbol{\beta}$)	0°
Performance coefficient ($\boldsymbol{C_p(\lambda, \beta)}$)	0.442
Rotor Angular velocity ($\boldsymbol{\omega_r}$)	2.39 rad/sec
Density of air	$1.225kgm^3$
$\boldsymbol{Torque}$	$3.2 \times 10^3 Nm$

The maximum efficiency of the turbine is determined through the differentiation of the power coefficient equation as a function of lambda (λ) then finding the root of the equation. Therefore,

$$C_{P_{opt}} = \frac{c_1 c_2}{c_7} e^{-\frac{c_2 + c_6 c_7}{c_2}} \tag{13}$$

$$\lambda_{opt} = \frac{1}{0.03 + \frac{c_6}{c_2} + \frac{1}{c_7}} \tag{14}$$

The overall simulation schematic of the aerodynamic model is shown in figure 4:

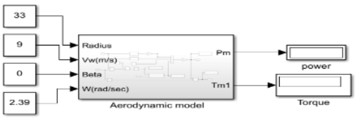


Figure 4: Wind Turbine Model

Figure 5 is the interior of the wind turbine shown below:

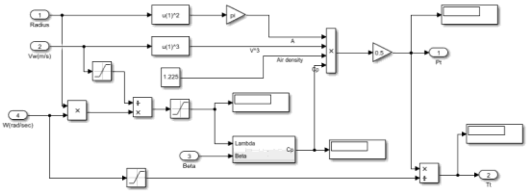


Figure 5: Interior of the wind turbine model

All equations that have been discussed above have been presented in form of blocks and can be seen in the figure 5 above. Saturators are added to the blocks to ensure that there are no division by zero (0) to prevent the system from collapsing during simulation.

The interior of the power coefficient (C_p) is also shown below

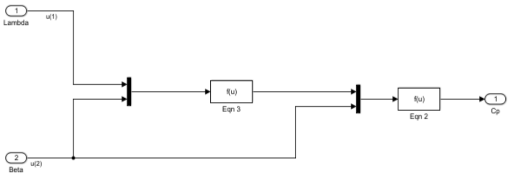


Figure 6: The interior of the power coefficient (Cp)

VI. MECHANICAL SUBSYSTEM MODELLING

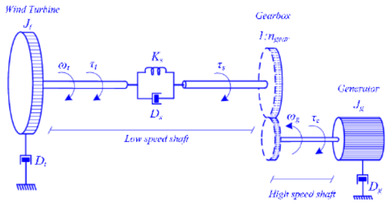


Figure 7: Two mass drive train *(Rolan, et al., 2010)*

The mechanical subsystem modelling will be based on the following equation of the two-mass drive train due to the need to deal with flexible modes because of low-speed shaft stiffness, also accounting for transient loads and vibration. Since the wind turbine shaft and generator are linked utilizing a gearbox, the shaft of the turbine is not seen as stiff, there will be movement in the shaft. The coupling between the masses has a stiffness coefficient (k), a damping constant (c) and also a transformation gear ratio (v). Applying newton's law of rotation, the dynamic equation of the system can be obtained in state space.

Using state space equation,

$$\dot{x} = Ax + Bu$$
$$y = Cx + Du \qquad (15)$$

The parameter x represents the state, u represents the inputs, and y represents the output of the system. The equation of this system is shown in the matrix below:

$$\begin{bmatrix} \dot{w}_m \\ \dot{w}_t \\ w_m \\ w_t \end{bmatrix} = \begin{bmatrix} \frac{-c}{v^2 J_m} & \frac{c}{vJ_m} & \frac{-k}{v^2 J_m} & \frac{k}{vJ_m} \\ \frac{c}{vJ_t} & \frac{-c}{J_t} & \frac{k}{vJ_t} & \frac{-k}{J_t} \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} * \begin{bmatrix} w_m \\ w_t \\ \theta_m \\ \theta_t \end{bmatrix} + \begin{bmatrix} \frac{1}{J_m} & 0 \\ 0 & \frac{1}{J_t} \\ 0 & 0 \\ 0 & 0 \end{bmatrix} * \begin{bmatrix} T_m \\ T_t \end{bmatrix} \quad (16)$$

$$[w_t] = \begin{bmatrix} 0 & 1 & 0 & 0 \end{bmatrix} * \begin{bmatrix} w_m \\ w_t \\ \theta_m \\ \theta_t \end{bmatrix} + \begin{bmatrix} 0 & 0 \end{bmatrix} * \begin{bmatrix} T_m \\ T_t \end{bmatrix} \quad (17)$$

$w_t = Angular\ Velocity\ of\ turbine$
$w_m = Angular\ velocity\ of\ generator$
$\theta_m = Angular\ position\ of\ generator\ shaft$
$\theta_t = Angular\ position\ of\ turbine\ shaft$
$T_t = Torque\ of\ Turbine$
$T_m = Torque\ of\ generator$

The modelling parameters for a 720KW wind turbine are seen in the table 2 below from (Junyent-Ferre, 2011)

Table 2: Modelling parameters of a 720KW wind turbine

Parameters	Value	Units	Description
V	90		Gear ratio
J_t	3.6×10^6	kgm^2	Two mass turbine inertia
J_m	49.38	kgm^2	Two mass generator inertia
J_g	4×10^6	kgm^2	One mass turbine inertia
c	10^6	$Nm\,s\,rad^{-1}$	Damping ratio
k	6×10^7	$Nm\,s\,rad^{-1}$	Stiffness
w_m	215.17	$rad\,s^{-1}$	Angular velocity of generator
T_m	3.2×10^5	Nm	Nominal torque of the generator

The factor that affects power extraction by wind turbines is the average wind that comes in contact with the blade. It is complex to measure wind speed

because in practice wind speed is not constant due to many variations. To extract maximum power from the turbine that is for optimal power, the maximum power point tracking must be implemented. A basic technique is the constant tip speed ratio (Hwas & Katebi, 2012).
The control action for this method is given as

$$T_m^* = \frac{1}{v} K_{cp} {w_t}^2 \tag{18}$$

T_m^* is the generator torque reference value while K_{cp} is

$$K_{cp} = \frac{1}{2} \rho A R^3 \frac{c_1 (c_2 + c_6 c_7)^3 e^{\frac{c_2 + c_6 c_7}{c_2}}}{{c_2}^2 {c_7}^4} \tag{19}$$

(Junyent-Ferre, 2011)

This above formulation is guided by speed control law and aerodynamic curve of the wind turbine (Hwas & Katebi, 2012) and they are non-linear, making them linearized about a nominal point. For a perfect control,

$$T_m^* = T_m \tag{20}$$

VII. MODELLING OF WIND TURBINE WITH ONE MASS DRIVE TRAIN

For a one mass drive train, the damping and stiffness factors are set to infinity, using the already stated formulas. The model is designed in MATLAB Simulink as shown below. The constant nominal value of w_t is shown. With the drive train implemented, the aerodynamic model is connected with the mechanical system and a loop of w_t is created and recalculated in the time interval. At time $t = 0$sec, the value of w_t is not defined, therefore the nominal value of w_t is given to the system as the initial value, the figure below shows the overall aerodynamic and mechanical model of the wind turbine with one mass drive train.

The schematic simulation using MATLAB Simulink is shown below in Figure 8

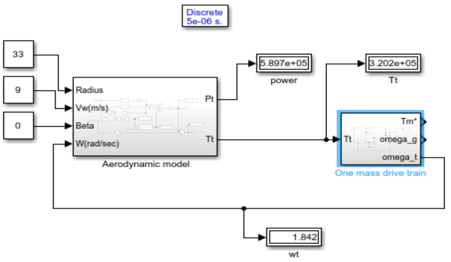


Figure 8: Wind Turbine with one mass drive train

From the above, it can be seen that the value of w_t stabilizes at $1.84\ rad\ s^{-1}$ for a wind speed of $9ms^{-1}$ because of the load torque, the load being the one mass drive train. Below is interior of the one mass drive train system as seen in Figure 9.

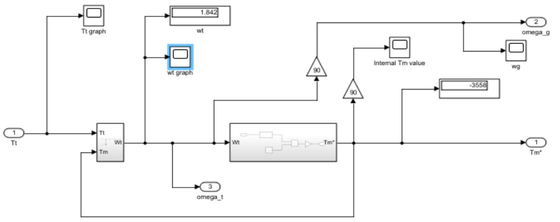


Figure 9: Interior of the one mass drive train

The subsystem below as part of the one mass drive train shows T_m and T_t as the inputs and has w_t which refers to the internal mechanical system and is fed back into the aerodynamic model. The integrator present is given the nominal value of w_t as the initial value, so the system does not fail when simulated. The value of T_m that the system receives as input is calculated as the reference mechanical torque which is stated by equation (17)

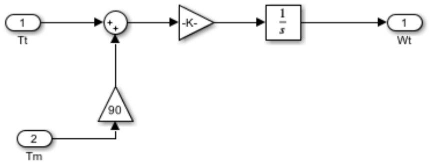


Figure 10: Internal mechanical system

The subsystem shown below shows the reference optimal mechanical torque which will be used to calculate the mechanical power obtained by the turbine given by equation 20.

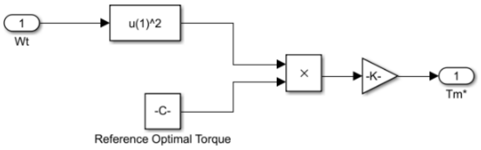
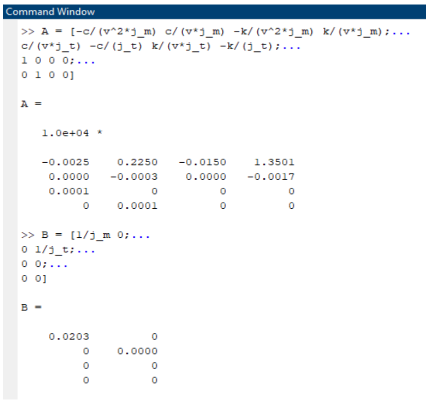


Figure 11: Optimal Reference mechanical torque

VIII. MODELLING OF WIND TURBINE WITH TWO MASS DRIVE TRAIN

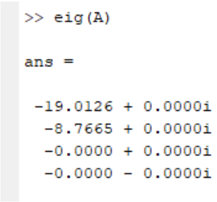
The two-mass drive train is more complex than the one mass drive train as it puts into consideration the damping coefficient and stiffness of the system. This system is modelled using the state space approach as stated in equation 14. The inputs to the state space equation that is matrix A and B are shown below in Figure 12:



```
>> A = [-c/(v^2*j_m) c/(v*j_m) -k/(v^2*j_m) k/(v*j_m);...
c/(v*j_t) -c/(j_t) k/(v*j_t) -k/(j_t);...
1 0 0 0;...
0 1 0 0]

A =

   1.0e+04 *

   -0.0025    0.2250   -0.0150    1.3501
    0.0000   -0.0003    0.0000   -0.0017
    0.0001         0         0         0
         0    0.0001         0         0

>> B = [1/j_m 0;...
0 1/j_t;...
0 0;...
0 0]

B =

    0.0203         0
         0    0.0000
         0         0
         0         0
```

Figure 12: State Space Matrices A and B

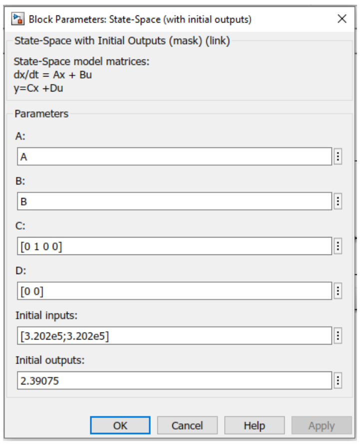
To determine the stability of the system, the eigen value method of matrix A used, the result is shown below, as it can be seen the eigen value has two negative real part indicating that the system is indeed stable.



```
>> eig(A)

ans =

  -19.0126 + 0.0000i
   -8.7665 + 0.0000i
   -0.0000 + 0.0000i
   -0.0000 - 0.0000i
```

Figure 13: Eigen Value of Matrix A

The inputs are passed into the state space block with initial condition as shown below.



State-Space with Initial Outputs (mask) (link)

State-Space model matrices:
dx/dt = Ax + Bu
y=Cx +Du

Parameters

A: A

B: B

C: [0 1 0 0]

D: [0 0]

Initial inputs: [3.202e5;3.202e5]

Initial outputs: 2.39075

Figure 14: State Space block with initial input

In the one mass system, the initial condition is defined in the integrator so that the system does not collapse on simulation, it is also necessary that the state space two mass model have initial condition so that the simulation has a starting point. The initial conditions here for T_m, T_t and w_t are the nominal values stated in table 2

In the state space block, it can be seen that the block only supports one input and one output, therefore, to provide both inputs it is useful to place a MUX with two inputs. Here, the first input corresponds to T_m and the second T_t. Figure 15 shows the interior Simulink model of the two-mass drive train.

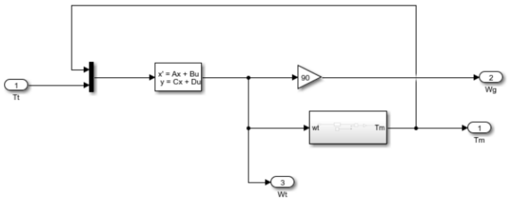


Figure 15: Interior of two mass drive train

Figure 16 is the complete Simulink model of the wind turbine with the two-mass drive train at $9ms^{-1}$

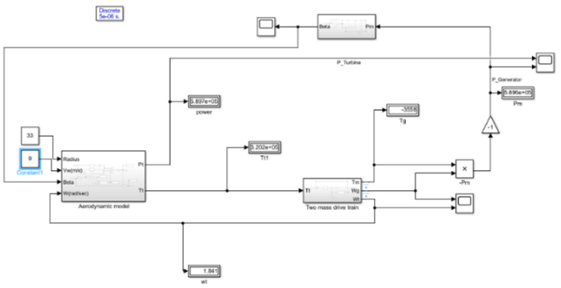


Figure 16: Simulink model of the wind turbine with the two-mass drive train at 9m/s

IX. MODELLING OF THE PITCH ANGLE CONTROL

It is best to incorporate a pitch angle controller into the system while running a wind turbine in turbulent or variable-speed environments to maintain the pitch angle at the ideal operating level. The power coefficient C_p demonstrates that in high wind speed regions, the power collected may be constrained by the pitch control, resulting in an extremely inefficient operation of the turbine. (Muljadi & Butterfield, 1999). When the wind speed is high, the pitch controller kicks in because the generator would overload if it tried to regulate the rotor by increasing produced power. The pitch controller is supplied with input power that the turbine is extracting (P_m), and based on the value compared with the reference power, the blades change their angle to match P_m to P_{ref}, then the pitch angle will change correspondingly to be fed back into the aerodynamic model.

To prevent the rotor speed from rising too high, the blade pitch angle is altered to reduce the rotor's aerodynamic efficiency. There is an ideal pitch angle where the power generated is at its highest depending on the wind speed. (Pandey, et al., 2016). It should be noted that the minimum pitch angle is 0° and the maximum pitch angle should be 45° as the former refers to the blades' surface being parallel to the direction of the wind and the latter to the blades' surface being perpendicular to it. This angle restriction is based on the mechanical limitations of the system; the blades' pitch angle cannot change instantly since it is not physically feasible. The speed of the pitch angle is the output of the Proportional Integral (PI) controller, which is used to regulate pitch angle, and it is always restricted up to $5°/s$ for normal operation (Singh, et al., 2013).

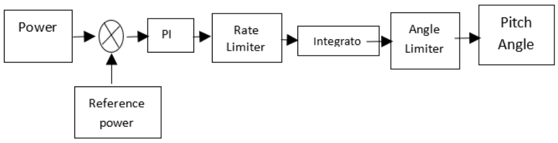


Figure 17: Pitch angle controller model *(Singh, et al., 2013)*

This model is implemented using MATLAB SIMULINK, is shown below the overview can be seen that P_m is the input and β as the output.

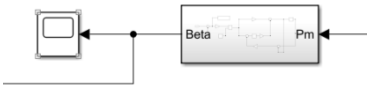


Figure 18: Overview of pitch angle controller

For the correct functioning of the pitch controller, a system that functions when extracted power is more than the rated power. A PI controller, a saturator, a step function, an anti-windup system and operators is utilized. Figure 19 below shows the interior of the controller.

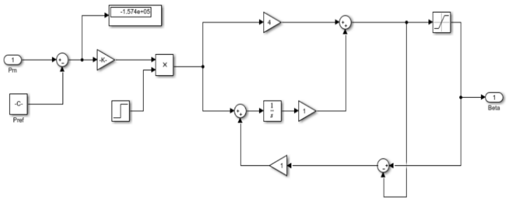


Figure 19: The interior of the controller.

The pitch controller works based on error computation, at the start of the simulation, the regulator receives the input power P_m and the reference power P_{ref} which is then subtracted from each other by means of an adder block. The reference power is the rated power of the wind turbine, and the absolute error is obtained by means of subtraction. The unitless relative error is then created by dividing the absolute error by the reference power. This relative error is then passed via the proportional integral controller. (Hwas & Katebi, 2012).

$$e_{rel} = \frac{P_m - P_{ref}}{P_{ref}} \tag{21}$$

The regulator does not begin to operate at the start of the simulation, thus a step block with a final value of 1 is placed to multiply the relative error by a multiplier block. That is until the step has a value of one (1) the relative error is multiplied by zero (0). This allows the system to stabilize before the controller must function. If this is not done, the system collapses, giving false results.

The PI type controller contains an integral parameter K_i and a proportional parameter K_p. These parameters allow for system adjustment so as to balance the system and its corresponding change. The equation of the PI controller is given below in equation 22

$$PI = K_p + \frac{1}{s} * K_i \tag{22}$$

K_p: this parameter multiplies the error. The lower the value, the slower the system response and the higher the error in the system in stationary state. Making K_p too large can destabilize the system, thus the appropriate value should be determined for this system.

K_i: this parameter has an integrator, which integrates the error, the higher the value, the lower the error in stationary state, it also makes the system unstable by increasing the response velocity.

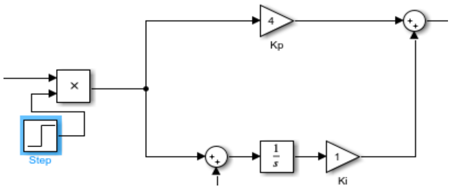


Figure 20: PI controller with step input

In this paper, the value of K_p and K_i is determined by trial and error method with the help of Simulink, at the beginning both value of K_p and K_i must be initialized to zero and the proportional part of the system is increased until there is an oscillation of the system then the value is left there, the iteration is done for the integral part and with same process when the system begins to oscillate based on the system's constraint. From the process, the value of K_p and K_i obtained are 4 and 1 respectively.

To meet the other system constraint stated previously, the saturator is placed at the end of the controller as the pitch angle should not exceed 45°. The limits of the saturator set to 0° and 45°.

For the anti-wind-up system, the error starts to build up from the beginning of the simulation, leading to errors in the controller and inaccurate data. The controller will not be able to act to stop each repeat of the accumulated mistake without the introduction of this anti-in up mechanism. Unity negative feedback is added to the system to prevent this.

X. RESULTS AND DISCUSSION

A summary of results of the simulation is shown below in Tables 3 and 4 below, with a wind speed of 9 ms^{-1} and pitch angle of 0°, the simulation is run for 150sec, the following are output of one mass and two mass drive train as seen in Table 3 below

Table 3: Turbine output for one and two mass drive train

Turbine parameter	One mass drive train	Two mass drive train
Turbine angular velocity	$1.84\ rads^{-1}$	$1.84\ rads^{-1}$
High speed angular velocity	$165.7\ rads^{-1}$	$165.7\ rads^{-1}$
Turbine torque	$3.2 \times 10^5 Nm$	$3558Nm$
Power output	589.6KW	589.6KW

When a pitch controller is integrated into the design the following is the output of the turbine as shown in Table 4

Table 4: Turbine output with pitch controller for different wind speed

Wind speed ($\mathbf{ms^{-1}}$)	Pitch angle (°)	Turbine Torque(Nm)	Two mass drive Torque(Nm)	Power (KW)
3	0	3.558×10^4	395.3	21.84
9	0	3.202×10^5	3558	589.6
16	20.61	3.682×10^5	4092	727.3
32	39.35	3.683×10^5	4092	727.3
33	0	1.269×10^6	84.65	2.164

During the analysis of the drive train model, 150sec is set as the simulation time, wind speed will be $9ms^{-1}$ and the pitch angle will remain at 0°. It is observed that in the stationary state, both models attain the same values, but due to complexity added by the two-mass model, it is seen that as the simulation decays exponentially without oscillating as there is no complex root in the eigen value of matrix A. If both models are analyzed, the difference is only noticeable at the beginning of the simulation. The steady state value is equivalent in both models and the oscillation at the beginning of the simulation are due to the position of poles of the system.

To confirm that the system is correctly modelled, the values of P_t and P_m must be identical.
In the case of the figure above, the wind speed at $3\ ms^{-1}$, $9ms^{-1}$ the pitch angle will remain at 0°, while it is observed that for a wind speed of $16ms^{-1}$(which is greater than the rated wind speed), the pitch controller adjusts to $20.61°$ and the power output is observed to stabilize at the rated speed of the turbine giving an output of 727.3KW.

XI. CONCLUSION

The primary goal of this study has been accomplished, which involved creating a wind turbine model capable of converting wind energy into usable power for an electrical grid. The critical components of the turbine, such as its aerodynamic design and gearbox, have been meticulously detailed, including the equations governing their operations. The incorporation of a pitch controller has enabled the creation of a dynamic system where the turbine can adapt to various wind speeds, making it self-regulating, especially during high and variable winds. Efficiency considerations for different wind conditions have also been discussed, crucial for project design and financing decisions. The model's behavior has been evaluated under different wind scenarios, including sudden changes, demonstrating its realistic and dynamic responsiveness. Real turbine system constraints were met, and a commonly used gearbox model was employed, making this model closely resemble real-world applications, fulfilling one of the study's objectives.

Creating models of this kind is truly a challenging endeavor, and it involves a lot of hard work. The world of wind turbine design offers a wide range of possibilities, allowing us to find the best solutions depending on where the turbine will be used. However, this abundance of choices can make the life of a designer quite tricky, as the way the turbine behaves can vary significantly depending on the design methods used.

Additionally, the various parts of the turbine have their own speed limitations, which is why control systems like the pitch controller developed in this project are necessary. All of these factors are part of the design process for a model, highlighting just how complex it can be at times. As a suggestion for future improvements, it would be beneficial to focus more on the electrical aspects of the turbine, as they play a crucial role in its real-world operation.

For the futuristic optimization of wind turbines, the following should be put into consideration:

i. Advanced Computational Fluid Dynamics (CFD): Utilize sophisticated CFD simulations to model the airflow around turbine blades accurately. High-performance computing can help in simulating turbulent flow and complex interactions, providing insights into blade design improvements.

ii. Machine Learning and AI: the use of Artificial Intelligence (AI) can be used to implement machine learning algorithms to analyze vast amounts of aerodynamic data. AI can help identify patterns and optimize blade design for different wind conditions.

iii. Data Validation and Calibration: Continuously validate and calibrate the model using real-world performance data. Adjust model parameters to align with observed turbine behavior, reducing the impact of data uncertainties.

iv. Data Collection Improvements: Investing in more accurate data collection methods and sensor technologies to reduce data uncertainty at the source. This includes improving the accuracy of wind speed measurements.

By implementing these solutions, we can enhance the accuracy and reliability of wind turbine models while effectively managing data uncertainties in the modeling process.

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