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Fault Tolerance Control of Wind Turbine

(FTC-WTG)

Final Bachelor Degree Thesis

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3 Aim

The aim of this project is to develop a controller for wind turbines, that can be used to generate power in suboptimal conditions that usually might lead to critical failure of the system or a shutdown of the system. The fault case scenarios are considered and some of the control strategies are implemented to withhold the degradation of the system whilst providing the maximum power that is possible for the system.

4 Scope

The controller deals with the fault scenarios that are encountered in the Gearbox. The Gearbox being one of the critical systems; any faults in it could lead to the complete shutdown of the system. The no fault scenario is simulated and the baseline correlations are established. Upon simulations of fault scenarios, the variation in the parameter is observed and the resulting effects can be predicted. This data is then used to make a control strategy that can be utilized to have a much smoother and safer operation of the turbine without sacrificing on the other economical or environmental factors. The control strategy is developed only in the power production region of the wind turbine.

So the Scope is:

- Set – Up a simulated model on FAST v8
- Performance analysis on steady state conditions for different wind regimes
- Simulate fault conditions on the Gearbox
- Performance analysis under fault condition
- Proposal for a Fault tolerant control

5 Specifications

The default 5MW wind turbine developed by NREL for simulation and testing of FAST v8 is utilized. It is a virtual turbine developed by NREL based on previous research and existing turbines due to the lack of open source data available for each turbine [1].

The Wind turbine is a conventional three-bladed upwind variable speed variable blade-pitch-to-feather-controlled horizontal axis wind turbine. Some of the specification are given in Figure 1: General specification of the default wind turbine

Control simulations will be done by using Matlab Simulink.

Rated Power	5MW
Rotor Orientation, Configuration	Upwind, 3 Blades
Control	Variable Speed, Collective Pitch
Rotor Diameter	126 m
Hub Height	90 m

Cut-in, Rated, Cut-out Speed	3 m/s, 11.4 m/s, 25 m/s

Figure 1: General specification of the default wind turbine

Control simulations will be done by using Matlab Simulink.

6 Justification

The Last decade has been characterized by a substantial shift toward renewable energy production that in 2018 was the 26.2% (2,378 gigawatts) [2] of the global power generation capacity.

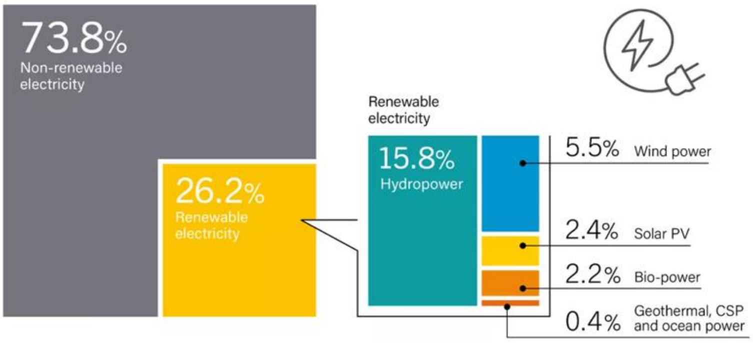

Figure 2: Estimated Renewable Energy Share of Global Electricity Production, End 2018

Wind energy is one of the most sustainable and important sources of energy accounting for 21% (591 GW) of the total renewable electricity. Due to technological advances made in the last decade, wind power has become more competitive with traditional power prices. However, wind energy needs to solve several challenges that don't allow it to be equated or to, or respected like, traditional energy sources or renewable energies like hydropower and Solar PV, which have been the most installed renewable energy in the last three years. The main challenges are:

1. Cost reduction in the operation and maintenance is required to make wind energy more competitive: In average 3% of the production time turbines have downtime due to breakdowns and maintenance issues. In some parks, these figures are even higher at 10-15% and can be at 30% in extreme cases (especially the oldest ones). The global average downtime is 1–7 days. [2]

   Breakdown and maintenance incidents lead to production losses in the sector of over €15 billion worldwide annually. On average, 60% of wind turbine downtime is unplanned; this of course includes many early turbines that are approaching the end of their life. [2]

2. The aging of turbines and the Lifetime extension decision: Nowadays, there are 184.4 GW wind power cumulative capacity operating with wind turbines between 10 and 20 years old (approximately 92,524 wind turbines). This represents 32% of the

Global wind power cumulative capacity in 2019.

This situation means that many operators anticipate that the future of their assets will be affected by rising O&M costs.

The service life of some of the wind turbines' main components such as gearboxes, tower and blades are the first to be affected. Fatigue failures can damage some parts of the structure leading to, in some cases, a sudden collapse of the machine. These increasing failures jeopardize the original business case as the potential solutions are costly and are not covered either by manufacturer's warranties or customers' insurance.

The end-of-life situation requires, by operators and owners, to make a choice between lifetime extension of the old wind farm, repowering with a new set of wind turbines, and decommissioning of the site. However due to financial constraints, and technical and legal impediments, the last two options (repowering with a new set of wind turbines, and decommissioning of the site) are economically unfeasible for most.

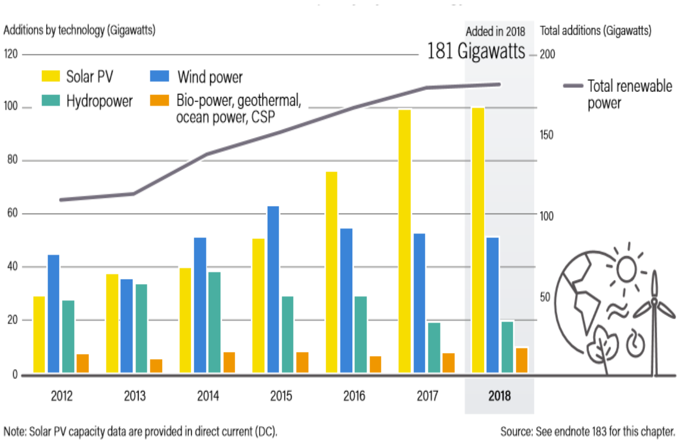

Figure 3: Annual Additions of Renewable Power Capacities

The real challenge exists in the strict O&M the turbines to make the wind farms secure and profitable beyond their original useful lifetime, without the need for any incentives

7 FAST

FAST is a Computer Aided Engineering Tool (CAE) designed by NREL for the analysis and testing of wind turbines. FAST stands for Fatigue, Aerodynamics, Structures, and Turbulence and performs various operations in relation to them. Due to its industry wide presence it has come to be one of the trusted tools for the same.[3] It works by the help of utilizing subsystems to facilitate certain tasks that when combined and executed in conjuncture with each other lead to a complete analysis of the system. The subsystems can be run independently of each other to only obtain certain results that might be necessary for any form of study or analysis. FAST is essentially a 'glue-code' for the subsystems.[4] It can be used to perform Aerodynamic, Hydrodynamic, Control Systems, Electrical Systems, Structural and sub-structural analyses. It can be used to conduct various tests on different configurations of wind turbines, but is limited to only two bladed and three bladed horizontal axis wind turbines.

The FAST subsystems are:

1. AeroDyn
2. BeamDyn
3. ElastoDyn
4. InflowWind
5. ServoDyn
6. HydroDyn
7. MoorDyn
8. SubDyn
9. IceFloe
10. IceDyn

Out of these subsystem only the first 5 subsystems were utilized in this project as we are dealing with an onshore wind turbine.

HydroDyn and MoorDyn are utilized for offshore wind turbine simulations as they provide data about the surrounding waters and its effects of the structural subsystems of an offshore wind turbine.

SubDyn is utilized whist taking into consideration the wind turbines that are placed on certain platforms for various reasons. It is used for both onshore and off shore wind turbines. It is again a structural module for calculation stress, strain and other parameters of the platforms.

IceFloe and IceDyn are utilized for analysis of wind turbine that are placed in region where the temperature is low and the local atmosphere is prone to snowing. It is a feature available in FASTv7. It helps in analysis of aerodynamics with snow and other factors taken into consideration.

7.1.1 AeroDyn

AeroDyn is a subsystem that can work independently of FAST but requires Inflow to provide the input wind. Its basic function is to carry out aerodynamic analysis on the wind turbine. The input file of AeroDyn consists of the cross-sections of the various components of the wind turbine that might be subjected to aerodynamic loading, i.e. the Blades, Nacelle, & Tower. It interpolates the cross-sections between the given cross-sections and the CFD analysis is carried out. It treats the system as a collection of two dimensional sections that are independently subjected to the wind profile as defined by the user via InflowWind. It can also calculate the effect of the wind turbine on its wake and can be used to optimize the total power production of the whole wind farm.

7.1.2 BeamDyn

BeamDyn is a subsystem that deals with the loading upon the blades. It mainly deals with the Twisting and Flapping of the blades. It is used with AeroDyn and InflowWind to get a better picture of the Aerodynamic loading; whereas it is used in conjuncture with ElastoDyn to get a better understanding of the dynamics of the blade along with all the fatigue and fracture analysis. This subsystem is also very useful for wind farm optimization as blade dynamics affect the wake dynamics of the turbine. The blade is treated as a cantilever for the most part and the uniformly varying load is applied.

7.1.3 ElastoDyn

This subsystem is responsible for the Fatigue and structural analysis of the turbine. It provides data as to the loads and failure of certain components. The input file consists of Young's modulus, Poisson's ratio, etc. for analysis regarding the loads and the corresponding stress that might be induced and all its further effects. FAST uses the data from the other subsystems along with ElastoDyns to get a better understanding on the components of the wind turbine.

7.1.4 InflowWind

This subsystem is used to create input wind profiles. It can create a simple step input wind profile, a user defined wind profile, and a turbulent wind profile based on random seeds. This subsystem drives most of the analysis of the wind turbine. The user defined wind profile can be generated by giving a wind velocity profiles at certain points in time and InflowWind interpolated the wind profile in the intermediate time region and provides fast with a binary file that is used as input for the various subsystems.

7.1.5 ServoDyn

ServoDyn is a subsystem that works with only FAST. It is used to control the pitch, system dampening, torque, yaw, and brakes of the wind turbine. The ServoDyn module can be switched off to study the effects of certain inputs on the functioning of the wind turbine. It uses Fortran code developed by NREL as a baseline turbine control. User defined control systems can also be implemented by interfacing it with Simulink and Matlab. The initial conditions of the wind turbine are defined in ServoDyns input file. It is basically responsible for the control and analysis of the drivetrain of the wind turbine, which include highly crucial components such as the Gear box and the Generator. Various fault case scenarios also can be modelled with the help of ServoDyn.

Figure 4 shows the interaction of FAST and its components and how the input and output files of various subcomponents interact with each other.

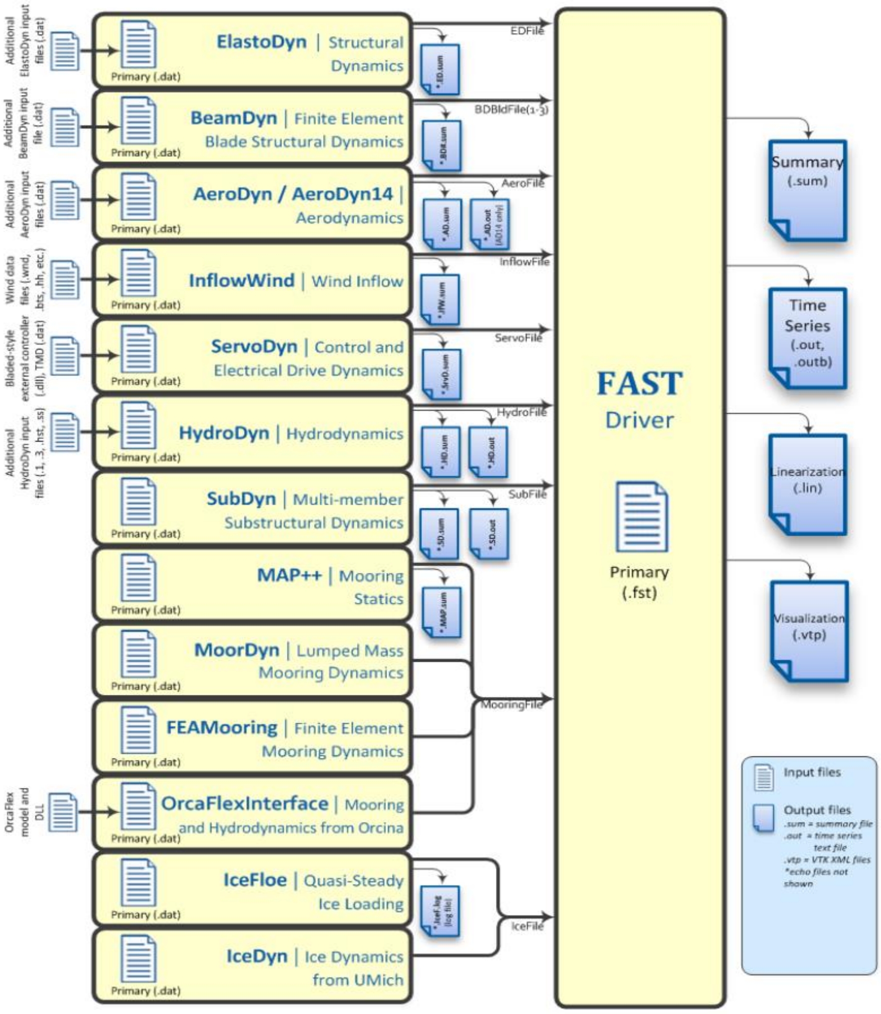

Figure 4: The interactions of FAST and its subsystems

8 FAST Wind Turbine Modelling

The default wind turbine is utilized in this paper. It is a 5MW turbine that was developed by NREL in 2004 and has come to be used as an industry standard model for multiple studies. It was based off the publically available data from the development of Multibird M5000 and Repower 5MW wind turbines. The data available from WindPACT, RECOFF, and DOWEC projects was utilized. In actuality there is not working 5MW onshore wind turbine.[5]

The positive x-axis of this coordinate system is directed nominally downwind with the origin located at the base of the tower, the y-axis is directed transverse to the nominal wind direction with the positive y-axis being to the left side of the incident wind, and the z-axis is directed vertically from the tower base to the yaw bearing, with positive z-axis being above the connection between tower and the ground. The actual wind turbines use a built in prebend in the blades to prevent collision of the blades with the other components of the turbine. Due to the complexity of this geometry and it aerodynamic effects a regular upwind precone angle of 2.5˚ is introduced; reducing the effective diameter of the rotor to 125.88 m.[6]

To conduct the aerodynamic testing, 11 nodes are taken along the length of each blade. The blades used belong to the DOWEC catalogue and all the properties of these airfoil cross-sections are taken from various studies conducted before. The DOWEC blades were chosen as they were designed taking into consideration the design and operation of Wind Turbines unlike NACA airfoils. Various properties such as the blade stiffness, moment of inertia, edge stiffness, flapping stiffness, etc. were taken from the data obtained from the DOWEC study. DU40, DU35, DU30, DU25, DU21, and NACA64 airfoils were used with slight changes to the coefficients of lift and drag.[1]

Node (-)	**RNodes (m)**	**AeroTwst (º)**	**DRNodes (m)**	**Chord (m)**	**Airfoil Table (-)**
1	2.8667	13.308	2.7333	3.542	Cylinder1.dat
2	5.6	13.308	2.7333	3.854	Cylinder1.dat
3	8.3333	13.308	2.7333	4.167	Cylinder2.dat
4	11.75	13.308	4.1	4.557	DU40_A17.dat
5	15.85	11.48	4.1	4.652	DU35_A17.dat
6	19.95	10.162	4.1	4.458	DU35_A17.dat
7	24.05	9.011	4.1	4.249	DU30_A17.dat
8	28.15	7.795	4.1	4.007	DU25_A17.dat
9	32.25	6.544	4.1	3.748	DU25_A17.dat
10	36.35	5.361	4.1	3.502	DU21_A17.dat
11	40.45	4.188	4.1	3.256	DU21_A17.dat
12	44.55	3.125	4.1	3.01	NACA64_A17.dat
13	48.65	2.319	4.1	2.764	NACA64_A17.dat
14	52.75	1.526	4.1	2.518	NACA64_A17.dat
15	56.1667	0.863	2.7333	2.313	NACA64_A17.dat
16	58.9	0.37	2.7333	2.086	NACA64_A17.dat

17	61.6333	0.106	2.7333	1.419	NACA64_A17.dat

Figure 5: Wind Turbine Physical Model

Initially the hub of the wind turbine is located 90 m above the base of the tower and 5 m upstream of the wind. The hub weight is taken to be 56,780 kg its inertia about the shaft, which is tilted by 5˚ with respect to the horizontal, is 115,926 kg*m^2. The nacelle is given a mass of 240 metric tons. [1], [6]

Following the data from REpower 5MW wind turbine, the default WT is specified to have rated rotor speed of 12.1 rpm, rated generator speed of 1173.7 rpm, and gearbox ration of 97:1. [1] The gearbox is of multistage variety with null friction taken into account in its components. This assumption makes the simulation of faults in gearboxes challenging as many of the faults in the gearbox can be identified by the change in operation temperature. The default generator efficiency is taken to be 94.4%, but this value can be easily modified based on the users' needs.

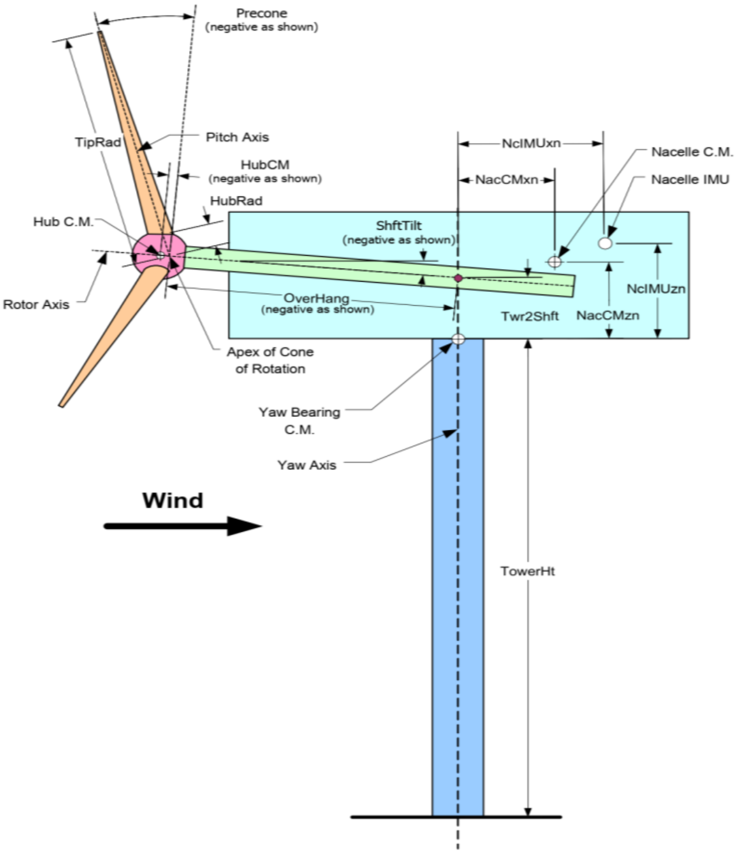

Figure 6: Layout of a conventional, upwind, three-bladed turbine

The operation region is split into 3 main operating regions based on the input wind speed.

- Region 1
  This region starts when the Generator Speed is 0 rpm and lasts till it reaches 430 rpm. There is no production of power in this region and is used purely for the startup procedure. There are no considerable loads on the drivetrain components and hence the effects of any faults can be overlooked. The Generator Torque is zero. After 430 rpm is achieved a very small change in the Pitch is made that is just enough to overcome any friction in the bearing of the drivetrain leading to the startup of the operation of the Turbine.

- Region 2
  This region starts when the Generator Speed is 450 rpm and till it reached 1700 rpm. In this region the main objective of the controller is to maximize the power output. The main criteria for this is to maintain a good tip speed ratio. The coefficient of power to the tip speed ratio is predetermined and the controller tries to maintain a certain tip speed ratio by varying the pitch of the blades. The plots for a few cases can be seen in Figure 7. The tip speed ratio is maintained until the rated power of the Wind turbine is reached upon which the control shifts to the Pitch actuators. The main control on Region 2 is done by the control of the Torque.

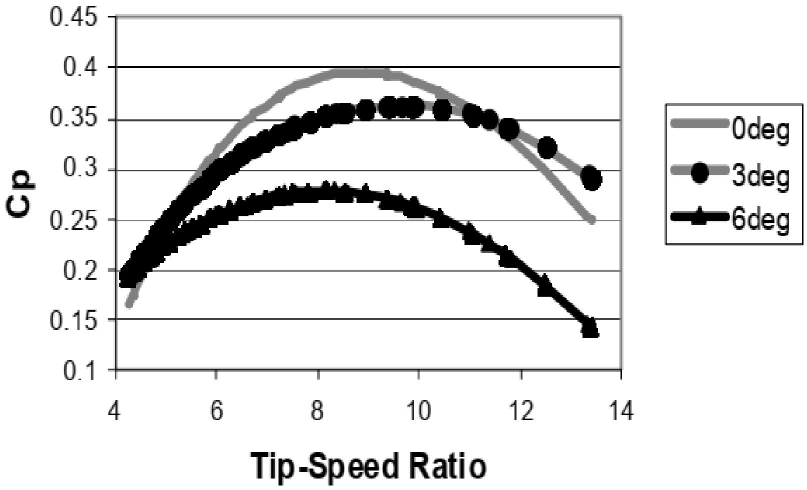

Figure 7: Plot of Power Coefficient Vs. Tip speed ratio

- Region 3

  This region starts when the Generator Speed is at 1800 rpm and stop at the cutoff wind velocity of 25 m/s. The main objective of the controller in this region is to have a safe operation of the wind turbine without causing any form of damages; it does this in addition to maintaining the rated power of the Turbine (5 MW). In this region the Pitch Actuators are utilized to carry out this function. Any faults in this operating region could lead to immense damages to the drivetrain or the Wind Turbine as a whole. The Pitch actuators are utilized to in this region is to decrease the load on all the subsequent parts of the drivetrain.

A transitional region called 2½ is kept between region 2 and region 3. If the trend seen in Region 2 were to follow till the Generator started outputting the rated power, then the Tip speed ration would be very high leading to high noise and premature wear and tear of the blade. The premature wear and tear of the blades might lead to catastrophic failures down the line if not checked on a regular basis. Hence by introducing this region the causes of failure can be reduced by a certain amount. A summary of the operating regions of the wind turbine can be found in Figure 8. [1], [3], [5], [7]

Region Name	**Generator Torque**	**Generator Power**	**Description**
Region 1	0	0	This region is used to startup the rotation of the blades without applying any load
Region 1½	0	0	This region is used for linear transition from Region 1 to Region 2. It is also utilized to define the lower limit of the generator speed to limit operations
Region 2	α (Filtered Generator Speed)^2	Generator Torque X Generator Speed (rad/s)	This region is used to maximize the power capture
Region 2½	-	-	This region is used to for linear transition from Region 2 to Region 3 whilst defining the top limit of the tip speed
Region 3	α (1/ Filtered Generator Speed)	5000 MW	This region is utilized to keep a constant power output whilst using the actuators to

			avoid any form of damage to the system and its components

Figure 8: The operation regions of the Wind Turbine

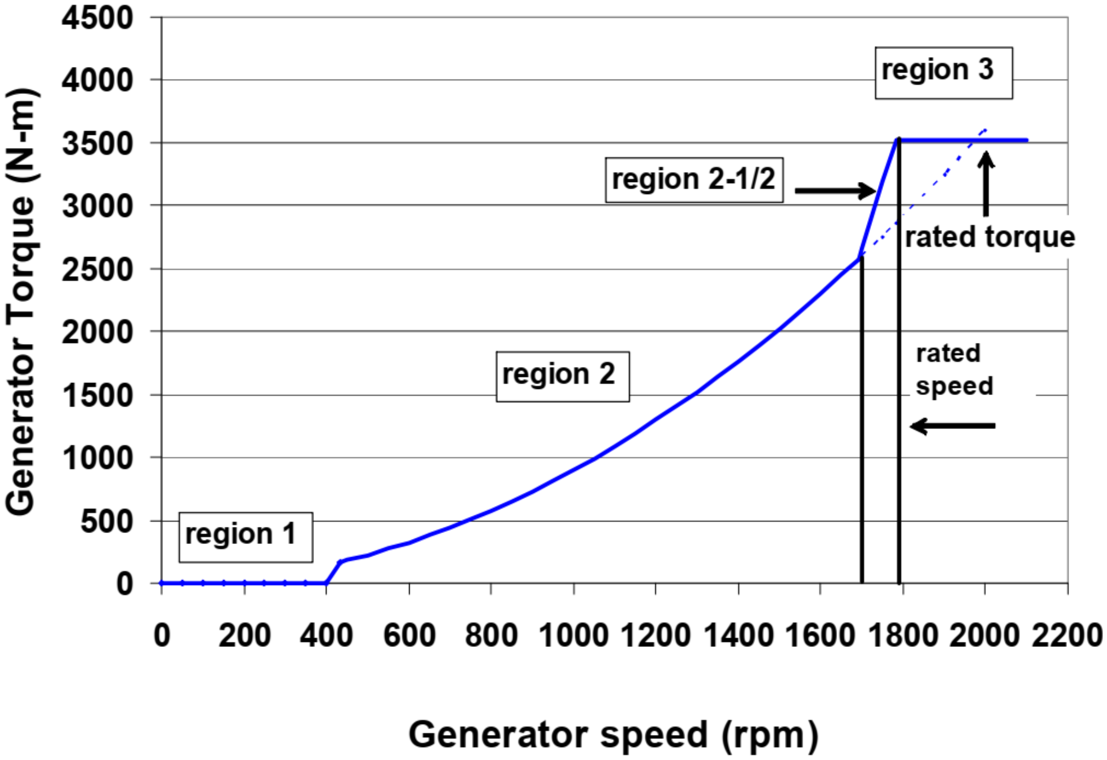

Figure 9: Generator Torque Vs. Generator Speed characteristics

10 Control System

The default control system was designed by NREL laboratories. It involves the control of the Collective Pitch of the blades as well as the Torque Control but excludes control of the vibration of the whole turbine, fault detection, and many other scenarios.[5] Due to the main goal of the controller being the safe operation of the Turbine whilst extracting the maximum power available in the wind. The control strategies are developed and implemented based on the operation regions defined by the designers as seen in the previous section.

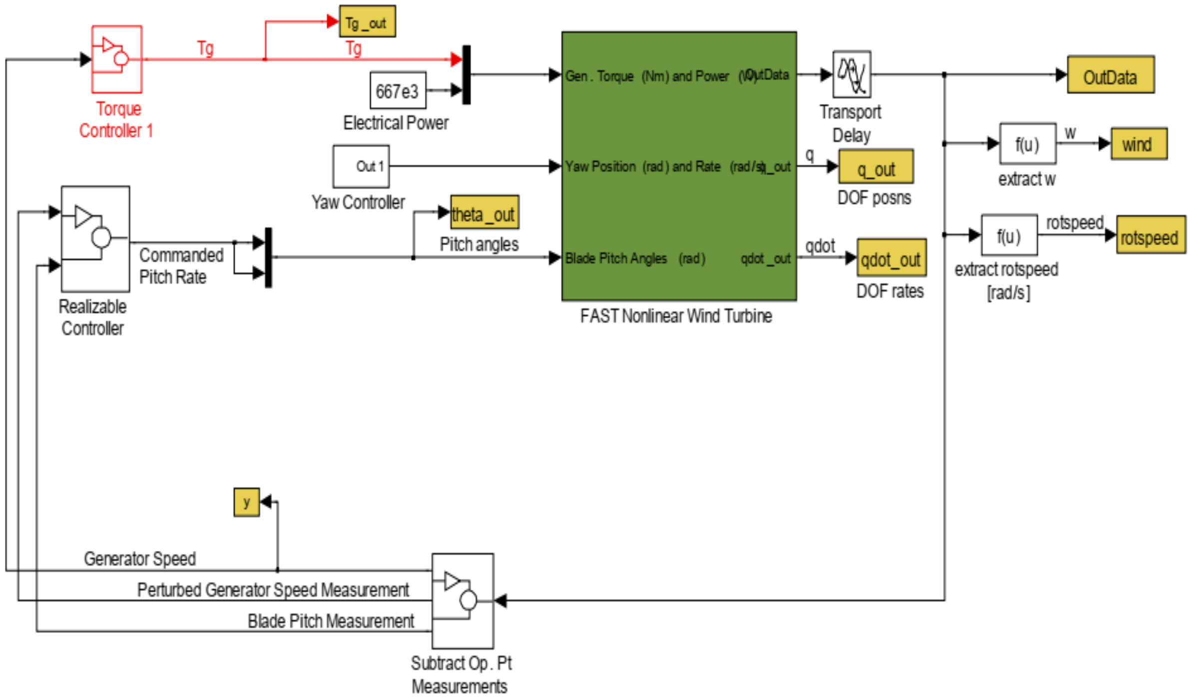

Figure 10: Baseline Torque and Collective PI Pitch controller for CART Model in Simulink

10.1 Torque Control

The torque control of the wind turbine is carried out in Region 2. The main goal being the maximization of power output. The sole input for this control is the filtered generator speed. This default controller controls the torque in the high speed shaft with no regards to the operation conditions of the low speed shaft.

The torque is controlled by a simple formula

$$Generator\ Torque\ (\tau_{gen}) = k * (\Omega)^2$$

Equation 1

Where,

k=(0.5* ρ* π* R^5 * $C_{P\ max}$) / $(\lambda_{opt})^3$

Equation 2

ρ stands for Air Density

R stands for Rotor Radius

$C_{P\ max}$ stands for the maximum power coefficient for a certain pitch angle and tip speed ratio

λ_{opt} stands for optimal tip speed ratio for maximum power production

Ω stands for filtered Generator Speed

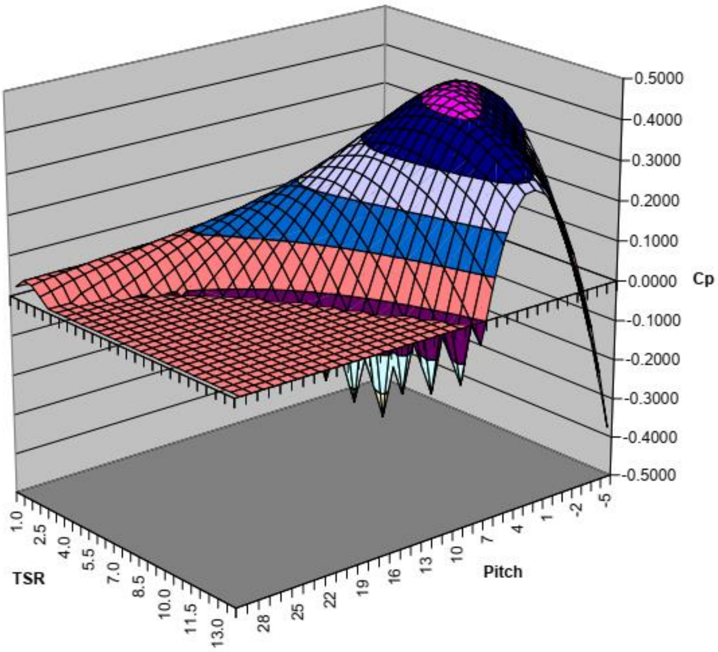

Figure 11: Cp Vs TSR and Pitch

The data obtained from the CART study can be used to find the ideal combination of Tip speed ration and pitch for maximum power production as shown in Figure 11.

Region 2½ is provided so that the transition from Region 2 to Region 3 is smooth and the rated power output can be achieved. If the trend of Region 2 were to be carried till the desired speed is achieved, the output power would be lower; as the controlling criteria for the controller is the speed and the torque in the shafts.

The Simulink model for the Torque controller can be seen in Figure 13. The input parameter is the generator speed. Based on the design of the Wind Turbine, the operating parameters are decided. These parameters are the basis of the operation of the controller itself. The important parameters being cut-in speed, cut-out, speed, rated power, region 2 end speed, etc. Based on these values the value of "k" in Equation 1 can be calculated.[4] When plotted on a graph, the trend of the graph becomes the deciding factor for the operation of Region 2½.

The controller takes the input generator speed, decides the operation conditions to be implemented based on operation region and then calculated the Generator Torque and the Generator Power. This output is then fed into FAST module and the whole process continues. As the system has high dampening capabilities, there is no need for design of a controller provided the operation is ideal and faultless.

The values shown in the Simulink model of CART model differ to that of the default 5MW wind turbine. These values can be found in Figure 12. The values in this table were obtained by simulation the default 5MW wind turbine to a constant wind velocity of 8m/s.

C_p	0.482
λ_{opt}	7.55
Pitch	0°
Gear Ratio	97:1
"k" in Region 2	0.0255764 Nm/s
Rated Generator Speed	1173.7 rpm
Rated Electric Power	5 MW
Rated Generator Torque	43,093.55 Nm
Generator Efficiency	94.4%
Rated Mechanical Power	5.29961 MW

Figure 12: Design Parameters of Default 5MW wind turbine

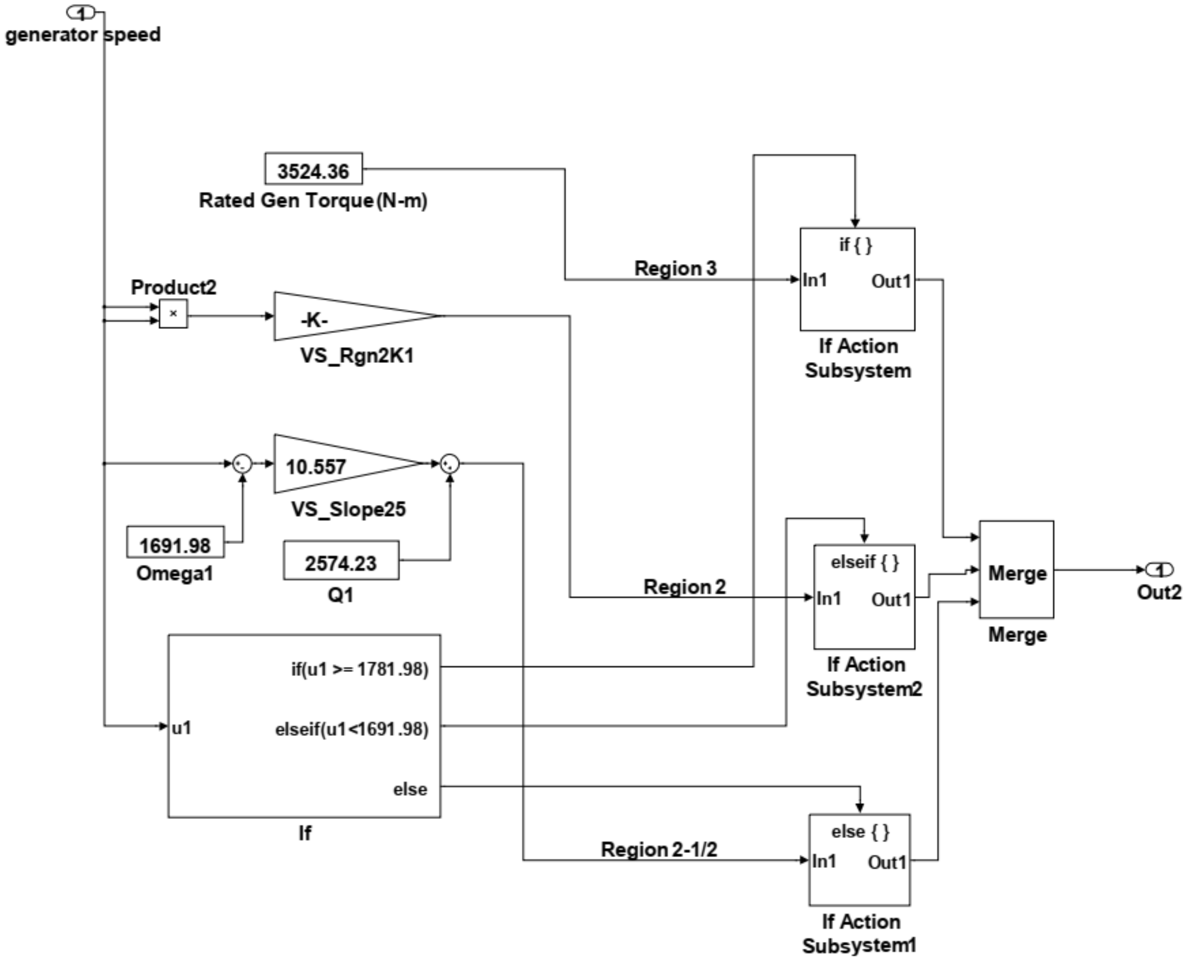

Figure 13: Baseline Torque Controller of CART Model

10.2 Baseline Blade Pitch Controller

The other control surface of the wind turbine is the pitch control of the blades. This system offers a safer approach for the control of the turbine in the fault case scenarios as all the forces can be controlled from the very beginning of the drivetrain. The Pitch controller has collective pitch control, i.e. the pitch of each blade of the turbine is the same at any given moment of time. A gain scheduled PI controller is used and it controls based on the error between the filtered generator speed and the rated generator speed. The main goal of this controller being the control of the Generator speed. A single degree of freedom, rotation of the shaft, model is used. The equation of motion of the system can be seen in Equation 3.

$$T_{aero} - N_{gear}T_{gen} = \left(I_{rotor} + N_{gear}^2 I_{gen}\right)\frac{d}{dt}(\Omega_0 + \Delta\Omega) = I_{drivetrain}\Delta\dot{\Omega}$$

Equation 3

Where,

T_{aero}	LSS Aerodynamic Torque	I_{gen}	Generator Inertia
T_{gen}	HSS Torque	Ω_o	rated LSS speed
N_{gear}	Gear Ratio	$\Delta\Omega$	small changes in speed LSS
$I_{drivetrain}$	Drivetrain Inertia	$\Delta\dot{\Omega}$	LSS rotational Acceleration
I_{rotor}	Rotor Inertia	t	simulation time

As we have the rated power of the wind turbine, the generator torque and the Aerodynamic torque can be evaluated and the results can be used to tune the PI controller.

$$T_{gen}\left(N_{gear}\,\Omega\right) = \frac{P_0}{N_{gear}\,\Omega} \qquad T_{aero}(\theta) = \frac{P(\theta,\Omega_0)}{\Omega_0}$$

The pitch control is given by the equation below

$$\Delta\theta = K_{\,P} N_{gear}\Delta\Omega + K_I\int_0^t N_{gear}\Delta\Omega dt$$

Where,

$$K_P = \frac{2\,I_{drivetrain}\,\Omega_0\zeta\omega}{N_{gear}(\frac{-\partial P}{\partial\theta})} \qquad K_I = \frac{I_{drivetrain}\,\Omega_0\omega^2}{N_{gear}(\frac{-\partial P}{\partial\theta})}$$

$$\omega = 0.6\,rad/s \qquad \zeta = 0.6\ to\ 0.7$$

The term $\frac{\partial P}{\partial\theta}$ is termed as blade-pitch sensitivity. It is the measure of how the blade changes with relation to change in its pitch. It is dependent on the geometry of the blade and its aerodynamic properties.[4][5] The values were determined by conduction simulations on the wind turbine at rated rotor speed for different wind velocities using AeroDyn and FAST. The value of these results can be found in the Figure 14.

Wind Speed (m/s)	**Rotor Speed (rpm)**	**Pitch Angle (º)**	***∂P /∂θ* (watt/rad)**
11.4 - Rated	12.1	0.00	-28.24E+6
12.0	12.1	3.83	-43.73E+6
13.0	12.1	6.60	-51.66E+6
14.0	12.1	8.70	-58.44E+6
15.0	12.1	10.45	-64.44E+6
16.0	12.1	12.06	-70.46E+6
17.0	12.1	13.54	-76.53E+6
18.0	12.1	14.92	-83.94E+6

19.0	12.1	16.23	-90.67E+6
20.0	12.1	17.47	-94.71E+6
21.0	12.1	18.70	-99.04E+6
22.0	12.1	19.94	-105.90E+6
23.0	12.1	21.18	-114.30E+6
24.0	12.1	22.35	-120.20E+6
25.0	12.1	23.47	-125.30E+6

Figure 14: Blade-Pitch Sensitivities

11 Faultless Performance Simulation

FASTv8 was used to carry out the simulations. To get the baseline results the wind turbine was subjected to multiple tests with unit step input wind velocities. The data was then tabulated and plotted to gain an understanding of the wind turbines operation and the defined safe loads that could be exerted on each component of the wind turbine.

Wind Velocity (m/s)	**Pitch (degrees)**	**Generator Power (kW)**	**Generator Speed (rpm)**	**Generator Torque (Nm)**	**Rotor Power (kW)**	**Rotor Speed (rpm)**	**Rotor Torque (Nm)**
3	0	28.83	674.5	432.4	30.56	6.953	41970
4	0	177.8	696.2	2587	186.3	7.17	244700
5	0	380.7	724.9	5303	402.6	7.473	513700
6	0	694.7	765.1	9179	735.5	7.887	889700
7	0	1129	815.1	14000	1195	8.403	135600
8	0	1684	873.1	19500	1782	9.001	1890000
9	0	2377	979.4	24540	2516	10.1	2380000
10	0	3233	1085	30140	3425	11.19	2923000
11	0	4278	1148	37700	4532	11.83	3657000
11.75	1.187	4995	1174	43050	5291	12.1	4175000
12	2.446	4979	1174	42910	5275	12.1	4162000
13	5.65	5000	1174	43090	5296	12.1	4179000
14	7.85	5000	1174	43090	5296	12.1	4179000
15	9.701	5000	1174	43090	5296	12.1	4179000

16	11.35	5000	1174	43080	5296	12.1	4179000
18	14.28	5000	1174	43080	5296	12.1	4179000
20	16.66	5000	1174	43080	5296	12.1	4179000
23	20.64	5000	1175	43080	5296	12.1	4179000
25	22.91	5000	1175	43080	5296	12.1	4179000

Figure 15: Baseline Results

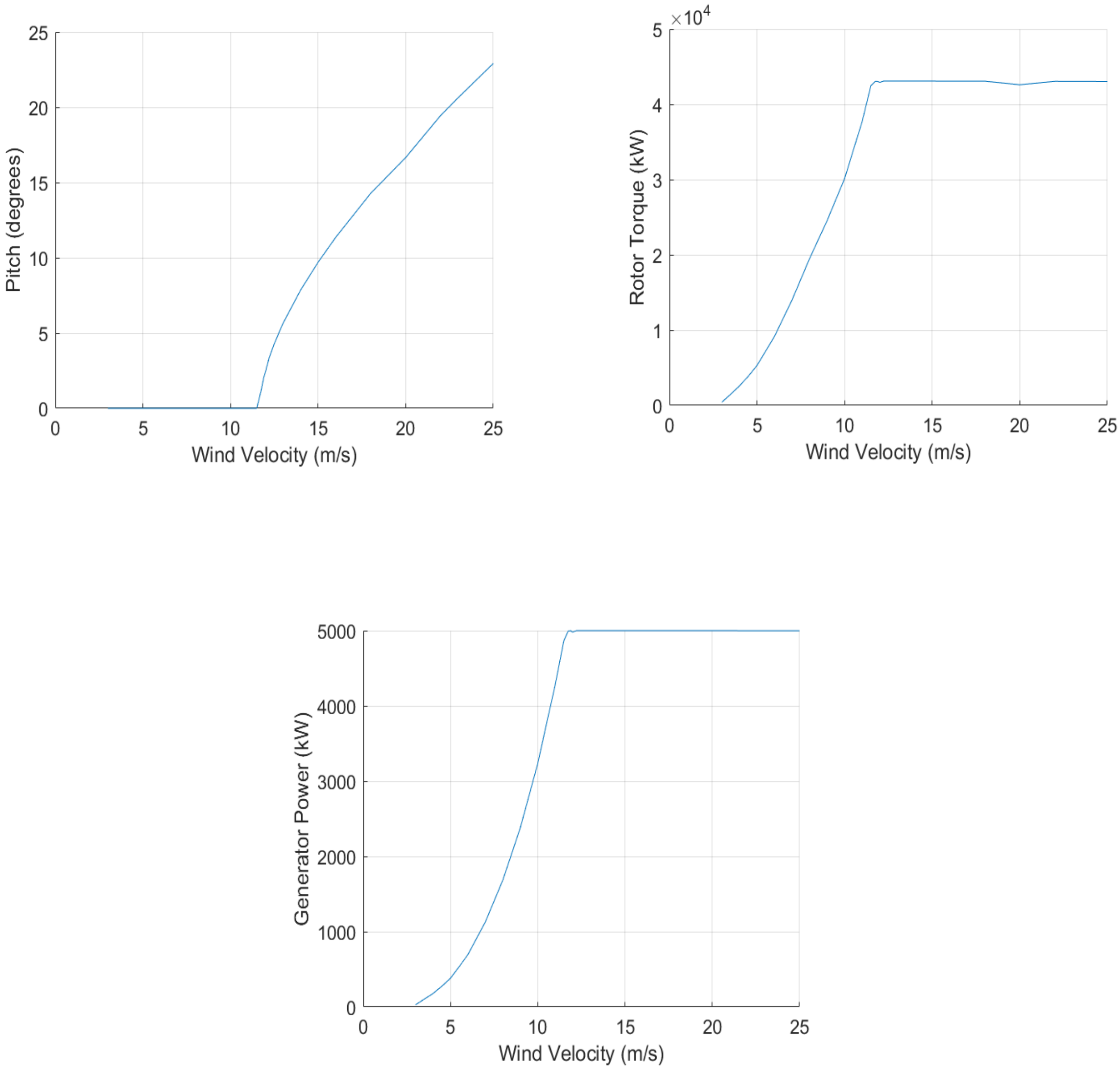

Figure 16: Baseline Result Plots

From the plots in Figure 16, it is observed that the generator power, after the rated wind speed of the turbine, remains constant at 5 MW although the wind speed keeps increasing, this is done by increasing the pitch and keeping the torque in the shaft constant. This control strategy could prove to be fatal in unpredictable cases like faults in the components of the drivetrain. The gearbox being one of the most integral parts and also costliest parts could suffer high amount of further damage until and unless the load is reduced. The load need to be reduced on the rotor side as the low speed shaft (LSS) carries more torque with lower speed than the high speed shaft. Any failure on the rotor shaft could lead the complete shutdown of the operation of the wind turbine.

With fault case scenarios like that of the wear and tear of the gear teeth, or insufficient lubrication; the damage to the subcomponents of the gearbox could be catastrophic. These failures could lead to the complete overhaul of the generator. Hence the torque needs to be limited in the input shaft itself. The default controller controls the torque in region 2 but this torque control is only limited to the torque of the high speed shaft; putting additional loads on the drivetrain components that are upstream. In region 3 of the operating condition the pitch is changed causing a change of load across the system. But this change in pitch doesn't not necessarily take into account the torque in the low speed shaft and operated on maintaining proper speed of the shaft.

12 Failure Performance Simulation

FAST does not have an inbuilt model for a gearbox for failure conditions to be modeled. One of the feasible options is to change the efficiency of the gearbox corresponding to certain faults. Any faults in the gearbox would lead to an eventual reduction in the power observed on the output shaft, i.e. the high speed shaft. Although most of the current failures in the gearbox are attributed to the bearing present in it, monitoring of the vibrations and oil temperatures could prove to be one of the leading the outliers that could point to a presence of fault. The main pointer being the discrepancy between the input and the output power of the wind turbine.

The wind turbine was subjected to identical conditions with the only changing variable being the change of the efficiency value in the ElastoDyn file. The wind turbine was subjected wind velocities ranging from 3 m/s to 17m/s, with the default pitch and torque controllers switched on. The efficiency of the gearbox was varied from 100% to 93% and the resulting power output and pitch angle values were observed for 3m/s, 8m/s, 12m/s, and 17m/s wind.

It was observed that with a decrease in the generator efficiency which would correspond to the increasing severity of the fault that might be present, the Rotor Torque value went up. This decreasing efficiency also lead to the increase in the Blade pitch. This is observed as the controller tries to maintain the rated power output of the wind turbine by controlling the speed of the shafts, i.e. the pitch of the blades to capture more power and increase the speed.

The increase in the torques in the shafts might lead to further damage to the gearbox reducing its efficiency more compounding any minute faults that might have been present initially. The increase in the pitch of the blades also could lead to the saturation of the actuators, which might cause further damage to the turbine components in case the input wind increases or any sudden and strong gusts that might occur. The results for of the simulation can be seen in Figure 17.

Gearbox Efficiency (%)	Wind Velocity (m/s)	Pitch (degrees)	Generator Power (kW)	Generator Speed (rpm)	Generator Torque (Nm)	Rotor Power (kW)	Rotor Speed (rpm)	Rotor Torque (Nm)
100	3.00	0.00	28.97	674.50	434.50	30.76	6.95	42240
100	8.00	0.00	1670.00	871.00	19400.00	1770.00	8.98	1883000
100	12.00	2.56	5000.00	1174.00	43090.00	5296.00	12.10	4180000
100	17.00	12.86	5000.00	1174.00	43090.00	5297.00	12.10	4180000
98	3.00	0.00	28.42	674.40	426.30	30.79	6.95	42290
98	8.00	0.00	1637.00	867.70	19080.00	1770.00	8.95	1890000
98	12.00	2.14	5000.00	1174.00	43090.00	5404.00	12.10	4265000
98	17.00	12.75	5000.00	1174.00	43090.00	5404.00	12.10	4265000

95	3.00	0.00	27.59	674.30	413.90	30.82	6.95	42340
95	8.00	0.00	1587.00	862.80	18610.00	1770.00	8.90	1901000
95	12.00	1.28	49996.00	1174.00	43040.00	5569.00	12.10	4395000
95	17.00	12.57	5000.00	1174.00	43090.00	5575.00	12.10	4399000
93	3.00	0.00	27.04	674.20	405.60	30.85	6.95	42380
93	8.00	0.00	1554.00	859.50	18290.00	1770.00	8.86	1908000
93	12.00	0.76	5000.00	1173.00	43120.00	5694.00	12.09	4497000
93	17.00	12.44	5000.00	1174.00	43090.00	5695.00	12.10	4494000

Figure 17: Results for Simulation at different Gearbox Efficiency

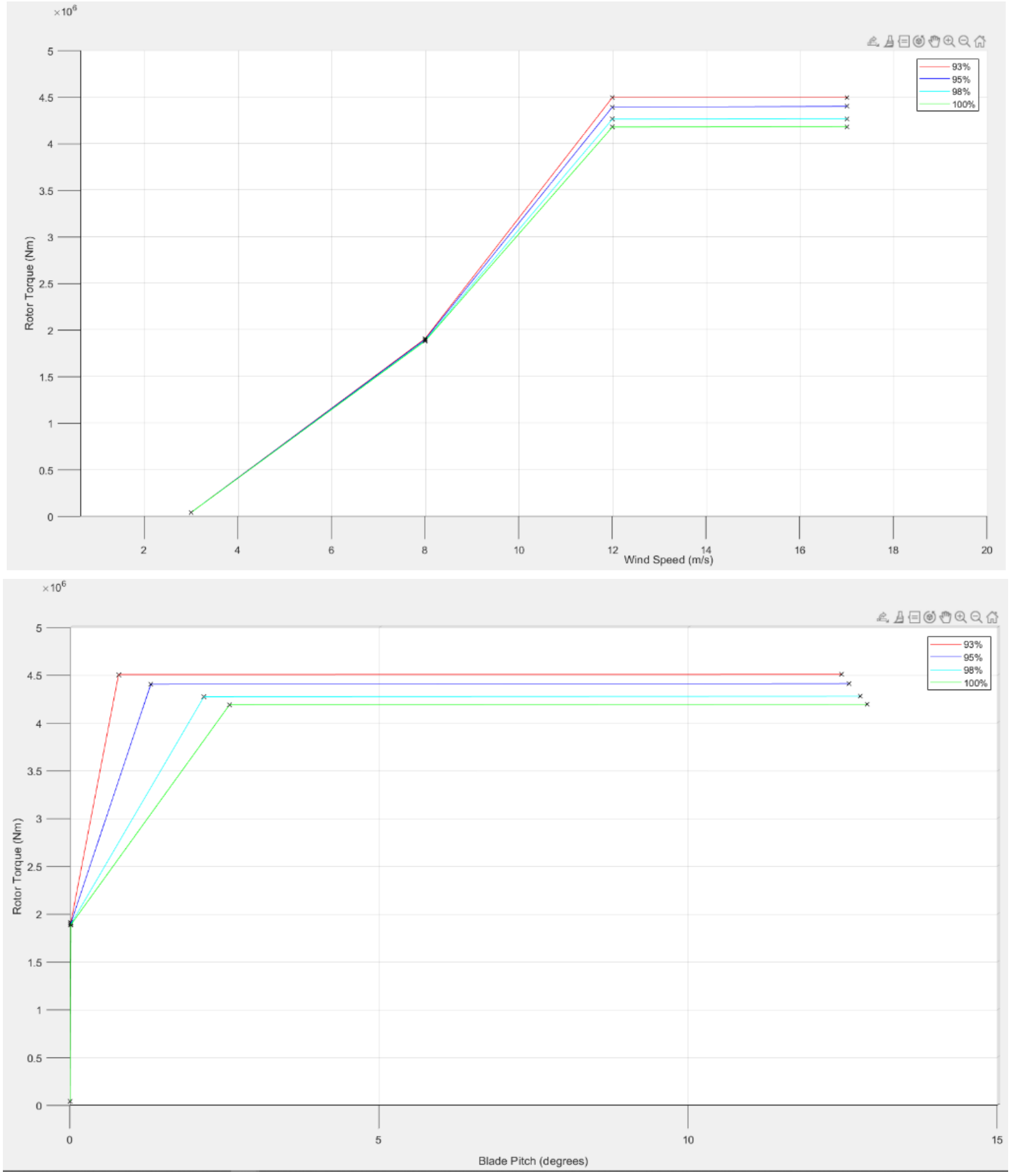

Figure 18: Plot of results for fault scenario

In Figure 18 it can be observed for any given blade pitch and wind velocity the corresponding rotor torque is higher for wind turbines with reduced gearbox efficiency. This increasing load could cause further damage to the drivetrain components making the operation of the wind turbine unsafe and uneconomical.

13 Fault Tolerant Control Strategy

Fault Tolerance Control is the design of a control strategy that incorporates the effects of the faults in a system and compensates for the same to maintain a desired level of operation without causing any form harmful effects a certain fault could have [8]. The main category that fault tolerance control can fall into is Active Fault Tolerance Control and Passive Fault Tolerance Control.

Active Fault tolerance control does not require the designer to specify the probable future faults and their consequences. It is highly dependent on fault detection and diagnosis and therefore the controllers' performance may vary on similar faults.

Passive Fault tolerance control requires the input of possible failure cases and their resulting effects. This approach is highly suited to conditions wherein the fault scenarios are well known and methods to combat them are well established.

Some of suggested Fault Tolerance Control Strategies are given below:

1. Pitch Reduction

The load on the Low Speed Shaft can be reduced by utilizing multiple technique. The most effective of these techniques can be the reduction of the pitch of the blades. This reduction in pitch, although might reduce the power output of the turbine extends the lifetime of the drivetrain components. Coupling this with the fault tolerance control strategy employed in the to combat the fault in the pitch actuator[9] , could lead to a more safe and reliable wind turbine. To check the effect of the pitch on the wind turbine, multiple simulations were carried out at 15m/s wind velocity (Region 2) with all variable remaining the same with slight changes to the collective pitch of the blades. The Pitch control component was switched off in these simulations.

Pitch (degrees)	**Rotor Speed (rpm)**	**Rotor Torque (Nm)**	**Generator Speed (rpm)**	**Generator Torque (Nm)**
5	24.97	2032000	2422	20880
10	11.34	4458000	1100	46020

15	7.577	4598000	734.9	47400
20	2.866	4493000	278	47400

Figure 19: Result of Pitch Changes

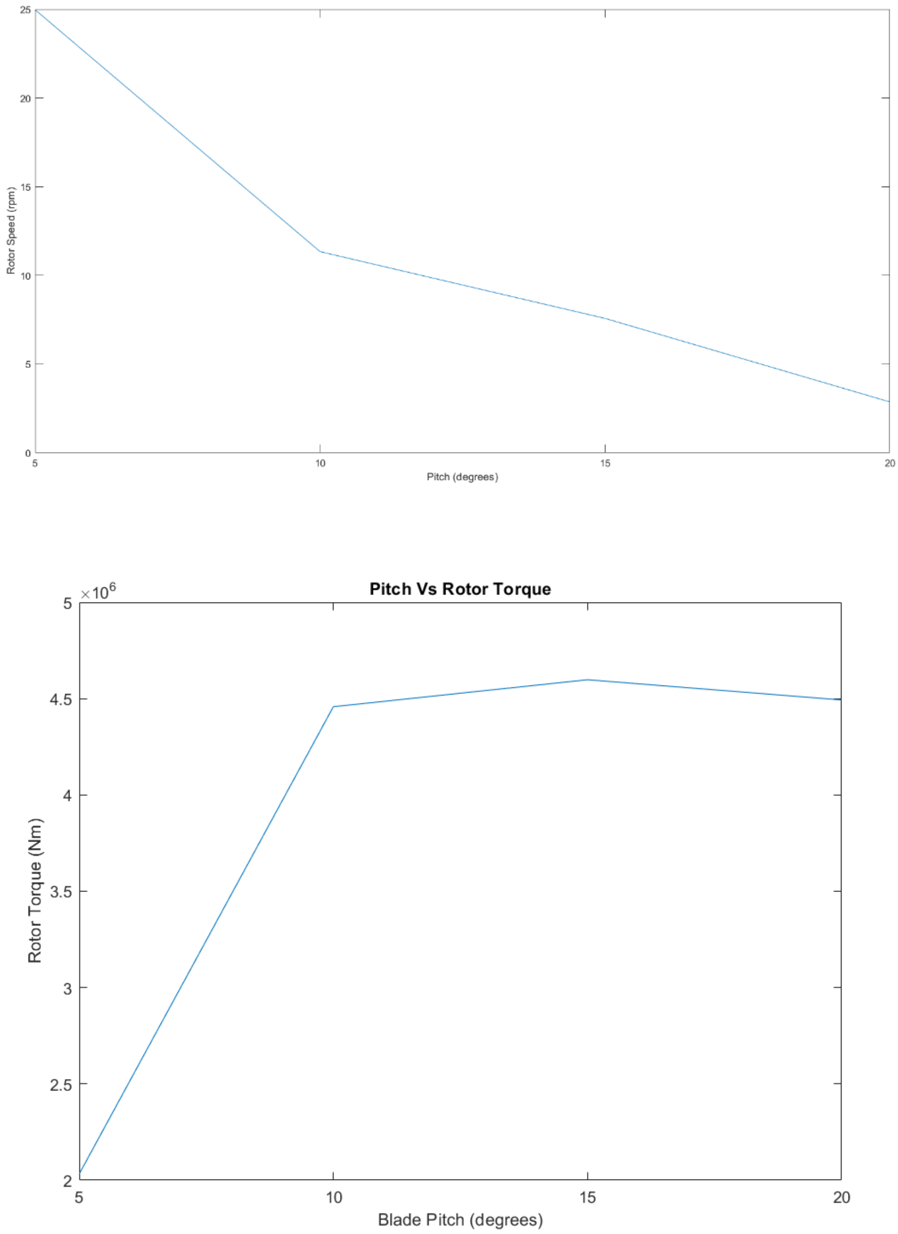

Figure 20: Plot of Pitch Change on Rotor Torque and Speed

It is observed from the results above that the torque on the LSS reduces with reduction on the pitch of the blades. This result can be utilized to reduce the loading on the gearbox provided the failure is not highly effected by the increase in speed that accompanies this reduction in pitch.

2. Yaw Angle

   Another approach the can be utilized is the changing of the Yaw of the nacelle of the wind turbine. This effectively reduced the incident amount of wind into the turbine therefore reducing the resulting torques in the shafts. This approach reduces the load on the drivetrain components but increases the loads on the structure of the turbine and also might add some additional stress on the Yaw actuators and the bearings. Additional results can be obtained by integrating the Yaw system to function with FAST. [10]

3. Utilizing Downdraft of Upwind Wind Turbine

   After wind passes through the blades of the Wind turbine it loses some of it energy, this downwind energy reduction which might prove to be an inefficiency in a perfectly working wind farm could be utilized to reduce the load on certain wind turbines. SOWFA, a tool developed by NREL that comes as a module of OpenFAST that is used for wake and turbulence studies of wind turbines, can be used to carry out further simulations regarding this approach.

   It was observed that the power reduction of downwind wind turbines reduced by up to 10% with a reduction of thrust force of up to 3% [11].

   This might cause certain instabilities in the wind turbine, which might have to be resolved by addition of further controller components.

14 Budget

Budget of the project is 32.125 € according Figure 21.

Concept	**Hours /quantity**	**Unitary cost**	**TOTAL**
Sohel Chungikar	360 h	25 €	9.000 €
Jordi Cusido	80 h	90 €	7.200 €
Matlab License	1	7.000 €	7.000 €
Computer Work Station	1	2.500 €	2.500 €
Indirect Costs		25%	6.425 €
TOTAL Cost			32.125 €

Figure 21: Budget Summary

15 Environmental Impact

The European Union is committed to becoming the first climate neutral continent by 2050. This requires the transformation of our energy system which accounts for more than 75% of our greenhouse gas emissions to be put at the heart of the EU recovery from the COVID-19 crisis.

Wind is already 15% of Europe's electricity and the International Energy Agency expects wind to become our number one source of power generation by 2027. Renewables-based electrification will be central to a climate neutral, competitive, and secure energy system.

With the right policies, the development of climate mitigation technologies can be a driver of jobs and growth as the basis of a just energy transition.

Wind can help ensure the Green Deal works for all Europeans and is the engine of economic growth in the aftermath of COVID-19.

Our proposal is aligned with the following topics of Green Deal as it is explained in the following lines:

Supplying clean, affordable, and secure energy: Wind energy is good placed to be the European Green Deal's technology of choice to restart the EU economy: it's scalable, sustainable, green and labour-rich. However, the cost reduction in the operation and maintenance is required to make wind energy more competitive respect to traditional energy sources or renewable energies like hydropower and Solar PV.

The average of the downtime production in wind farms due to breakdowns and maintenance problems are 10-15%, leading to production losses in the sector of over €15 billion worldwide annually.

FTC-WTG technology contribute to sustainable growth and energy transition by increasing the efficiency of Wind Power fleets. The demonstrated failure control allows to keep wind turbines spinning reducing 20% of OEM costs, increasing 10% of power production and extending the useful life up to 10 years. That leads up to 10TW energy increase, and 2,863 Mt CO2 reduction worldwide each year or 400 hectares of forest every year

16 Conclusion

Multiple simulation were conducted on the default 5MW wind turbine developed by NREL in both ideal conditions and fault conditions. It was observed that the predetermined operating loads could lead to unsuitable or inoperable conditions on the wind turbine under fault case scenarios. The simulations were done at constant speed to determined baseline results for both fault and faultless conditions. These results can be used to implement strategies to reduce loads on the drivetrain and therefore increase the operational lifetime of the wind turbine. Reductions in the collective pitch, Changing the Yaw of the Turbine, and Downwind Turbine optimization could help in the development of a more robust fault tolerance controller.

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