CONTROL APPLICATIONS OF WIND TURBINES AND RELATED SYSTEMS

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Abstract

Compared to conventional fossil fuels generators, renewable energy is being seen as a much more suitable alternative across the globe. This is because of the challenges caused by climate change and the depletion of fossil fuel reserves and the negative impact of such fuels on the environment. Wind energy continues to be an important renewable source and is the most deployed of all the renewable energy sources. Although the wind turbines (WTs) used to harvest wind energy present their own potential set of hurdles to overcome (high installation costs, additional costs of transmission lines, noise pollution, adverse effects on wildlife, intermittent power production due to variable wind speeds, etc.) they also have low operating costs, make efficient use of land space, and are a great energy harvester as a result of technology advancements. These points, along with the fact that wind itself is a clean, free source of fuel, makes research in this area more popular than ever. But the efficiency and cost effectiveness of a WT system with regards to wind application absolutely depends on its control. This report briefly discusses various control techniques available for WTs, followed by an implementation of the pitch angle control technique of WTs with the help of Simulink models, as well as any future scope of work, or other developments in this area.

1. Introduction

Wind Turbine (WT) control schemes aim to provide stability for grid integration, mitigate static and dynamic mechanical loads, maximize power production and ensure continuous power supply to the grid. To achieve these objectives, optimally controlling the WT generator torque and blade pitch angles is crucial.

Torque control of the generator allows varying the speed of the turbine rotor by applying MPPT strategies to achieve the maximum possible extraction of wind power. As wind speed changes the rotor torque increases or decreases, so the generator torque must be the shock absorber for the turbine to turn at optimum speed while the pitch angle control achieves smooth power production by controlling the input torque of wind **[1]**. Advances in power electronic systems have also contributed to various improvements in the control of WT systems especially considering the quality of the WT system. For a stable grid integration and variable speed operation of any wind energy system, the power electronics components of the WT play a critical role.

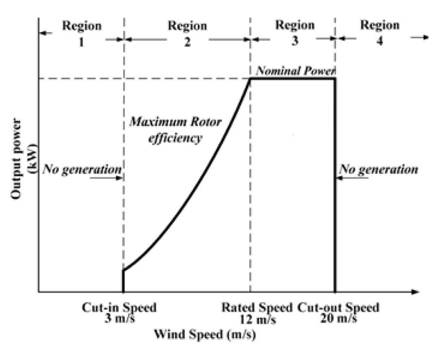

Figure 1: Wind turbine operating regions **[1]**

A common expression for power extracted by the WT is

$$P_w = 0.5\ \rho A C_p V^3 \tag{1}$$

P_w being the power extracted from wind, ρ the air density, and A is the rotor area. The power coefficient C_p depends on tip speed ratio (TSR) λ and pitch angle β. V is the wind speed, and λ is expressed as a relationship between V and linear velocity on the tip blade given as

$$\lambda = \frac{\omega R}{V} \tag{2}$$

ω being rotor speed and R the rotor radius.

Each control system and its unique control method depends on the operational region (shown in the previous graph) and the control objectives of WTs. In region 1, there is no power generation as the wind speed is too low to rotate the WT rotor. The WT in this region is idle and rotor rotation only begins at the point where the wind speed exceeds the cut-in wind speed of the WT. In region 2, the WT can generate power within a range of wind speeds but not at nominal power. In this region the maximization of power production is the primary focus. As seen in (1), the wind power content varies with the cube of the average wind speed. The rotor speed is varied to ensure that the λ is kept at an optimal level with changes in the wind speed to ensure the production of maximum power.

$$\tau_g = K.\ \omega^2 \tag{3}$$

K is an aerodynamic constant of the wind turbine defined as follows:

$$K = 0.5\ \rho\ \pi\ R^5\ \frac{C_{p.opt}}{\lambda_{opt}^{\ 3}} \tag{4}$$

Here, ρ is the air density, $C_{p.opt}$ the optimal power coefficient, and R the blade radius. After reaching rated speed the WT goes into region 3, regarded as the full load region. Here the wind speed is between the rated and cut-out speed, the pitch angle controller controls the rotor rotation at nominal speed and the generator gives rated power. Here the desired control objective is to limit power production, opposite of region 2. This is achieved by limiting both torque and rotor speed of the WT generator, thus ensuring that constant rated power is obtained from the wind. Proportional-integral-derivative (PID) control is deployed in this region for pitch blade control to regulate the WT speed under varying wind conditions. The increment $\Delta\theta$ to the initial pitch of the WT is calculated as

$$\Delta\theta(s) = \left(K_P + \frac{K_I}{s} + \frac{K_D.s}{s.\ \tau + 1}\right)\Delta\omega \tag{5}$$

$\Delta\omega$ represents the generator speed error, K_P, K_I and K_D are gains chosen for the desired controller closed loop characteristics. The WT switches off in region 4 to avoid catastrophic failures due to high wind speeds that can mechanically damage the turbine, so no power is produced and the WT is out of operation.

In summary, the control targets of the WT operational regions are as maximal power production keeping the load and constraints of WT components in mind, safe operation of the WT, providing the required power quality at point of grid connection, preventing extreme loads and minimizing damages arising due to fatigue.

2. Wind Turbine Power Control Techniques

2.1 Commonly used WT control techniques

WTs are not typically designed for extreme wind speeds or rotational torques. In such conditions, the force on the WT blades is large and can tear the turbine apart. To avoid this, WTs are always designed with a cut-out speed above which brakes slow the turbine to a halt. However, there is a range of wind speeds before the cut-out speed where the WT employs various control strategies to deal with high wind speeds that would otherwise pose a threat to the turbines. Thus, all WTs are designed with some power control technique. This can either be stall or pitch control. Stall control is further classified as passive and active stall control.

<u>Passive stall controlled</u> WTs have their blades bolted to the hub at a fixed angle. The rotor blade profile is aerodynamically designed ensuring that turbulence is created at high wind speeds on the rotor blade side not facing the wind. This stall prevents the rotor blade's lifting force from acting on the rotor. The rotor blade in this control is slightly twisted along its longitudinal axis, ensuring a gradual rather than abrupt stalling of the rotor blades when the wind speed reaches its critical value.

<u>Active stall controlled</u> WTs, on the other hand, are fitted with active power control mechanisms and pitch-able blades similar to pitch controlled WTs. This method is popular with larger WTs rated 1 MW and above and can also be applied to fixed speed WTs mainly operating at high wind speeds. During low wind speeds the blades are pitched in steps to get large torque. To prevent the overloading of the WT generator at its rated power, the active stall controlled WT increases the angle of attack of rotor blades in order to make the blades go into a deeper stall rather than decreasing the angle of attack to reduce the lift and rotational speed of the blades.

<u>Pitch control</u> uses an electronic controller to sense the WT output power several times per second. The generated electronic signal pitches the turbine blades out of the wind when the power level goes above the prescribed safe level. The turbine blades are pitched/turned back into the wind at an optimal angle of attack to catch the wind when the power level gets lower. Minimal power loss is achieved by pitching the WT blades, resulting in the captured power being equal to the electrical power produced by the wind generator. These WTs have an active control system that varies the turbine blades' pitch angle to decrease torque and rotational speeds. This control method is usually employed only where high rotational speeds and aerodynamic torques can damage the equipment.

The difference between stall and pitch control is mostly noticeable in high wind speeds. While the stall controlled systems rely on aerodynamic designs of the blades to control the aerodynamic torque/rotational speed of the turbine in high wind speeds, the pitch controlled systems use an active pitch control for the blades, allowing the pitch controlled system to have a constant power output above the rated wind speed unlike the stall controlled system. The pitch control and active stall control of WTs are both based on the rotating actions on the WT blade. But while pitch control turns the blade away from the wind in order to reduce the lift force on the turbine blades, the active stall control of the WT turns the turbine blades into the wind.

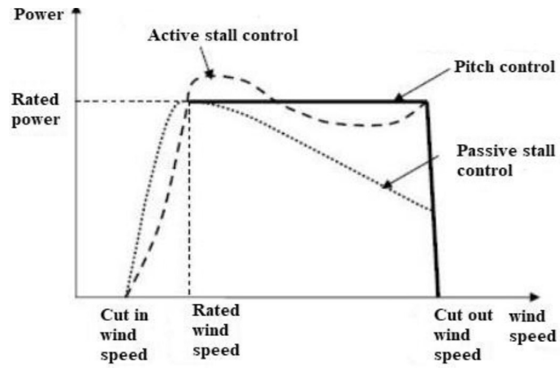

Figure 2: Power control of WTs **[1]**

Table I: Summary of passive, active and pitch control of WTs **[1]**

Control method	***Advantage***	***Disadvantage***
Passive Stall	Simpler, lower complexity, Lower cost and cheaper and more robust than other control systems. It has a faster response to wind gusts than other control systems.	Not suitable for large WTs. Less efficient in low wind speeds. It causes variations in the maximum steady state power due to variations in grid frequencies and air density.
Active Stall	Higher power production than passive stall as blade angle of the WT is optimized according to the wind speed. Better and more accurate control of power output. We can counteract power peaks very efficiently without changing rotational speed. Lower load and power peaks than pitch control.	Forced reduction of the generator rotor speed to stall the rotor blades during an increase in wind speed.
Pitch Control	Efficient power control. Assisted start up. Emergency stop.	High power fluctuations in high wind speed conditions. Extra complexities and increased costs as a result of the pitch mechanism.

Pitch control of WTs is classified into two control methods: collective pitch control (CPC) and individual pitch control (IPC). Both control methods can be implemented using an electric or a hydraulic controller.

<u>Collective Pitch Control (CPC)</u> is implemented in most commercial WTs by collectively implementing the same control for all the WT blades in a wind energy system **[2]**. Each WT blade is pitched the same way regardless of the existence of independent servomechanisms. CPC relies on traditional proportional-integral (PI) control laws - its main objective being regulation of rotor speed to limit the power captured from wind by adjusting the pitch angles. Here the controlled variable is collective blade pitch while error is the difference between nominal rotor speed reference and its actual value. This is expressed as:

$$\beta_c = K_p\left(1+\frac{K_i}{s}\right)(\omega_{ref}-\omega) \tag{6}$$

Here β_c is the collective demand on blade pitch angles, K_p and K_i are the proportional and integral controller gains respectively, ω_{ref} is the rotor speed reference and ω the actual speed measured at the rotor axis. This control is implemented in region 3. The constant need for load reduction has motivated various researches in modern CPC approaches. Adaptive and robust techniques have been introduced to overcome modeling uncertainties **[3]**. The setback of CPC is the erroneous assumption that all the WT blades have similar physical attributes and are subjected to equivalent aerodynamic loads when in operation. This results in the exposure of the rotor disk to unbalanced loads, inducing stresses on the WT and can lead to eventual WT failure.

Individual Pitch Control (IPC*)* individually controls the pitch angles, reducing mechanical loads. The IPC is a very recent development, and, though well researched over the last decade, has not been fully realized on a commercial scale in WTs. It is believed that results of current research being carried out in this area will be validated in the next generation of WTs with larger and more flexible blades **[4]**. This method allows for the measurement of variables like tower displacement, reducing fatigue damage and mechanical loads. As the name implies, IPC operates by controlling each WT blade individually using additional sensors. Its aim is reducing the blade root moment or damping structural modes by adjusting the WT pitch angle. Since additional sensors and individual pitch commands are required for each blade, it makes the WT control system an inherently multiple-input-multiple-output (MIMO) system. A major challenge of this control method is the sensors' reliability, as most modern WTs have blades already fitted with individual pitch actuators. The majority of research carried out on the IPC of WTs focuses on reducing the rotor blade load using Coleman transformation, which expresses the bending moment of the rotor blade with respect to the fixed direct-quadrature (d-q) axes. Two independent PI-control loops are then designed to suppress loads on the d-q axes.

$$\begin{pmatrix} M_d \\ M_q \end{pmatrix} = {}^2\!/_3 \begin{pmatrix} \cos(\psi) & \cos\left(\psi + \frac{2\pi}{3}\right) & \cos\left(\psi + \frac{4\pi}{3}\right) \\ \sin(\psi) & \sin\left(\psi + \frac{2\pi}{3}\right) & \sin\left(\psi + \frac{4\pi}{3}\right) \end{pmatrix} \begin{pmatrix} M_1 \\ M_2 \\ M_3 \end{pmatrix} \tag{7}$$

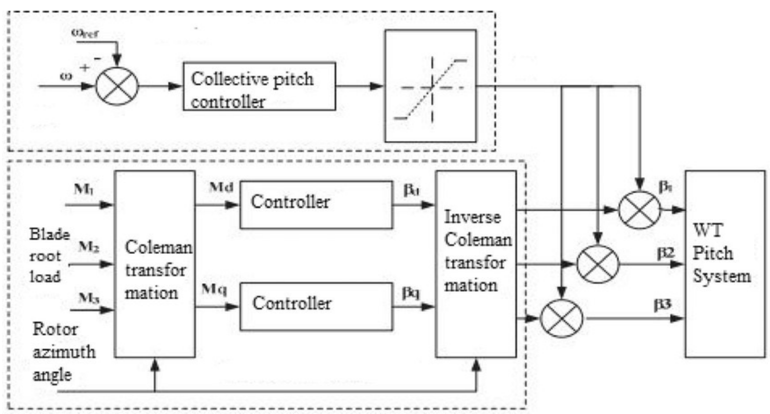

Figure 3: Block diagram of IPC of WTs **[1]**

M_1, M_2, and M_3 are the blade root load which can be found either by estimation or detection. These are transformed into two orthogonal d-q axes signals M_d and M_q. To generate the corresponding required pitch angle, the Coleman transformation is inverted by transforming the desired d-q pitch angle β_d and β_q respectively into pitch angle increments $\Delta\beta_1$, $\Delta\beta_2$ and $\Delta\beta_3$ for the three wind turbine blades.

$$\begin{pmatrix} \Delta\beta_1 \\ \Delta\beta_2 \\ \Delta\beta_3 \end{pmatrix} = {}^2\!/_3 \begin{pmatrix} \cos(\psi) & \sin(\psi) \\ \cos\left(\psi + \frac{2\pi}{3}\right) & \sin\left(\psi + \frac{2\pi}{3}\right) \\ \cos\left(\psi + \frac{4\pi}{3}\right) & \sin\left(\psi + \frac{4\pi}{3}\right) \end{pmatrix} \begin{pmatrix} \beta_d \\ \beta_q \end{pmatrix} \tag{8}$$

2.2 Electric and hydraulic pitch controllers

Electric pitch controller comprises of an electro-mechanical actuator controling the WT blade. Other components include the energy storage (a power source for the pitch controller in case of power failure), a gear box (adjusts the motor speed) and a power supply unit. It has a fast response time and higher efficiency than the hydraulic controller, but is more expensive due to high installation costs and the need for a power back up. They are grouped into four categories: robust controller, soft computing controller, conventional controller and hybrid electric pitch controller.

Robust Controllers have high efficiency, can compensate for uncertainties and provide system stability **[5]**. However, its drawbacks are the complexity of its control scheme and the increase in the mechanical stress of the WT due to sudden changes in control variables. The use of the robust controllers depends on prior insight of the WT system and its mechanical model. This controller integrates feed forward feedback system and the sliding mode control (SMC) to improve the robustness of pitch angle control in WT systems.

Soft computing controllers are based on artificial techniques offering quick, predictive and efficient response to overcome uncertainties in the wind energy system occurring from variations in environmental conditions. The most commonly used techniques with these controllers are metaheuristic algorithms, fuzzy logic control (FLC) and artificial neural networks (ANN). FLC is gaining popularity due to its adaptability and simplicity. We can change the controller parameters of fuzzy logic controllers quickly to respond to changes in system dynamics without parameter estimation. But its strength depends on the user's knowledgeability. The need for memory allocation in FLC techniques is its major setback. Various researches have been carried out with FLC based controllers such as: improving the performance of a micro grid **[6]**, analyzing the various operating regions of a low speed wind system by generating a reference power from the WT and studying the difference between the reference power and the actual generator power (only disadvantage being the cost involved) **[7]**, smoothing wind power fluctuations occurring below rated wind speeds, selecting the targeted output based on available wind speed **[8]**. ANN is also a very popular **[9]** control technique for estimating the nonlinear characteristics of WTs. Variables like rotor speed, output torque, wind speed, pitch angle and terminal voltage or a combination of these can be used as input variable(s) to the controller. ANN is suitable for WT control for optimizing power at wind speeds above the rated wind speed. GA based pitch angle controllers are the most commonly used metaheuristic algorithms deployed for system stability during low wind speed conditions allowing maximal extraction of wind power by the pitch angle from available wind speed. Usually the reference speed is used as a control signal in controlling generator speed to optimal speed.

Conventional Controllers have also been well researched **[10, 11]** and are most suitable for, and most commonly used in, small wind energy conversion systems. They usually consist of a PID/PI controller for rotor speed and generated power control. Conventional controllers derive their pitch angle reference from parameters like wind speed, generator power and rotor speed. Its response time is higher than other controllers. The most efficient and reliable conventional controller is the rotor speed and generator power based pitch angle controller. The control performance of a system with non-linear characteristics can be improved by conventional controller using gain scheduling. This method is often used to overcome the sensitivity of the aerodynamic torque to the pitch angle since it is dependent on the varying of output power to the pitch angle. The relationship between the system sensitivity and the controller gain is inversely proportional, thus making conventional controllers with gain scheduling more reliable than ones without gain scheduling.

Hybrid Controller combines robust control and soft computing control and was developed in response to the challenges associated with conventional controllers to maximize the power from the WT system. This controller improves dynamic performance of the WT system by reducing the system complexity and improving stability. Its main advantage is the reliable solution it provides for nonlinear systems while its major drawback is the addition of extra costs to the WT system.

Table II: Comparison of electric pitch controllers **[1]**

Controller	***Complexity***	***Performance***	***Reliability***
Robust Controller	High	High	Moderate-High
Soft Computing Controller	Low	Moderate-High	High
Conventional Controller	Low	Low	High
Hybrid Controller	High	High	Moderate

Hydraulic Pitch Controllers control wind turbine blades using a hydraulic actuator placed alongside an accumulator tank for providing the required linear movement of the blades. The energy needed to rotate the WT blades is provided by the hydraulic pump situated in the nacelle of the WT. Different researches have been done on these controllers, however the most recent ones have focused on detailed dynamic analysis, efficient control strategies, modeling and reliability **[12–14]**. From these, we find that hydraulic pitch controllers can smoothen output power of WTs by eliminating drive train torque fluctuations. We can also diagnose fault occurrences using online fault compensation techniques. Compared to electromechanical controller, hydraulic pitch controller is safer to operate and more robust towards the non-linear characteristics of wind speed. The cost of initial installation of this controller is lower when compared than electromechanical controllers. Other unique features of this control system are its adaptability to work under extreme weather conditions and its ability to operate without power supply from external sources under emergency control situations. Furthermore, it is not sensitive to vibrations and highly reliable. But, this controller has high maintenance and operation costs.

2.3 Maximum Power Point Tracking (MPPT) control strategies

MPPT control algorithms are necessary in WT systems to extract maximum available wind energy based on wind speed. These algorithms help stabilize the power output if and when wind speed exceeds the rated wind speed, protecting the wind generator from overloading and surges. Various MPPT algorithms are available for WTs, however the choice of algorithm depends on user proficiency. Each algorithm has its own merits and demerits. Different MPPT algorithms are classified into two broad categories: direct power control (DPC) and indirect power control (IPC). The DPC algorithms directly maximize output electrical power (P_o) while IPC algorithms maximize captured mechanical wind power (P_{wind}). The relationship between P_o and P_{wind} is as follows:

$$P_o = \eta_g \eta_c P_{wind} \tag{9}$$

Where $\eta_g \eta_c$ represents the generator efficiency and converter efficiency respectively varying with rotor speed. So, the optimal P_o cannot be guaranteed even when optimal P_{wind} is obtained.

Various MPPT algorithms have been described in scientific literatures **[15, 16]**. The hill climb search (HCS), optimum relation based MPPT (ORB) and the incremental conductance (INC) are classified as DPC based MPPT algorithms. HCS, also known as perturb and disturb (P&O), is the most commonly used algorithm in this category due to its flexibility and simplicity. IPC based MPPT algorithms include optimal torque control (OTC), power signal feedback (PSF), and tip speed ratio (TSR) algorithms.

Hill climb search (HCS) is a very robust algorithm and is independent of prior knowledge of WT characteristics. It aims to locate the local maximal point of a given function. The control variable, the duty cycle, is implemented using a DC-DC converter. The algorithm works by disturbing the duty cycle in step. A modified HCS algorithm was designed that could create a uniformity between speed tracking and controlling efficiency **[17]**. The direction of the next perturbation and variable step size is determined by observing the distance between the operating point and optimal curve.

The optimum relation based (ORB) MPPT algorithm depends on the optimal relationship between quantities like power output of WTs, converter DC voltage, power, current and speed. Its advantage is its fast tracking speed compared to other MPPT techniques. However, a proper knowledge of the characteristics curves between turbine power and dc current at various wind speeds is needed since the MPP can be tracked by observing the optimum current curve **[18]**.

Incremental conductance (INC) algorithms are independent of sensor requirements and the wind turbine and generator specs. This reduces system cost and improves reliability. The operating point of the MPPT can be determined using the power-speed slope. A positive slope indicates the operating point lies on the right side of the speed-power characteristics and vice versa for a negative slope. A novel INC algorithm known as fractional order INC (FO-INC) is proposed in **[19]**. A variable step size is used in tracking the MPP for fast changing viable wind conditions ensuring a reduction in unnecessary power losses.

The optimal torque control (OTC) method adjusts the generator torque according to the reference torque of maximum power at any given wind speed as expressed in Eq. (4). A maximum power reference can thus be obtained by comparing the actual torque with an error signal fed into a controller to maintain the optimal torque of the generator. Therefore a change in wind speed is not reflected in the reference signal.

The power signal feedback (PSF) based MPPT strategy operates similar to OTC, except here a power control loop is utilized. Knowledge of the WT maximum power curve is required by the algorithm user. This curve is obtained by performing experimental tests on the individual WTs or by simulations. With this algorithm, optimal power can be generated by using the WT output power expression as shown in Eq. (1) (using the WT speed or wind speed as input power). The optimal power can also be generated using a pre-obtained power-speed curve.

Tip speed ratio (TSR) algorithms keep the ratio between the tip of the blade and the rotor speed to an optimal value where extracted wind power is maximized irrespective of the wind variations. An effective feedback controller is needed to feed the difference between the actual value and optimal value. The speed error generates a torque/power reference which then changes the speed to reduce the error.

Table III: Summary of MPPT control algorithms **[1]**

MPPT Strategy	***Advantages***	***Disadvantages***
Hill climb search (HCS)	Simple implementation, excellent performance under varying wind conditions and high flexibility.	It can cause stalling in smaller WTs. Under a rapid wind change, there is slow response and incorrect detection of direction for maximum power especially in large and medium inertia WTs.
Optimum relation base (ORB)	High accuracy and efficiency in maximum wind power tracking. Prior knowledge of the energy system is not needed.	Inability to track exact maximum power point under rapid wind changes.
Incremental conductance (INC)	Increased system stability and reduced costs. Easy implementation and ability to handle non-linearity.	High instability under variable speed wind conditions.
Power signal feedback (PSF)	The PSF provides a robust and cost effective maximum power control of WTs. It is also simple to use with a fast speed of convergence.	Low efficiency under varying wind conditions since it does not reflect variations in wind speed instantly.
Optimal torque control (OTC)	Very simple to use, fast convergence speed and high efficiency.	Just like the PSF, it lacks the ability to measure wind speed directly.
Tip speed ratio (TSR) measurement.	High efficiency and performance with a fast convergence speed. Its optimal point can be determined theoretically or experimentally.	High cost of operation especially for small WT systems. Impossible to have precise wind speed.

3. Developed Wind Turbine Pitch Control Models

3.1 Governing equations of the models

Normalizing equation (1) in the per unit (pu) system, the output power of the wind turbine is:

$$P_{m\_pu} = k_p c_{p\_pu} v_{wind\_pu}^3 \tag{8}$$

Here, P_{m_pu} is the power in pu of nominal power for particular values of ρ and A, c_{p_pu} the performance coefficient in pu of the maximum value of c_p, v_{wind_pu} the wind speed in pu of the base wind speed (the base wind speed is the mean value of the expected wind speed in m/s), and k_p the power gain for $c_{p\_pu} = 1$ pu and $v_{wind\_pu} = 1$ pu ($k_p \leq 1$).

A generic equation, based on the modelling characteristics of **[20]**, is used for modelling $c_p(\lambda,\beta)$. This equation is:

$$c_p(\lambda, \beta) = c_1(c_2/\lambda_i - c_3\beta - c_4)e^{-c_5/\lambda_i} + c_6\lambda \tag{9}$$

With

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \tag{10}$$

The various coefficients are: $c_1 = 0.5176$, $c_2 = 116$, $c_3 = 0.4$, $c_4 = 5$, $c_5 = 21$ and $c_6 = 0.0068$.

The maximum value of c_p ($c_{pmax} = 0.48$) is achieved for $\beta = 0$ degrees and for $\lambda = 8.1$. This particular value of λ is defined as the nominal value ($\lambda_{\_nom}$). The characterics plot of c_p versus λ is shown in the following figure, for different values of the pitch angle β

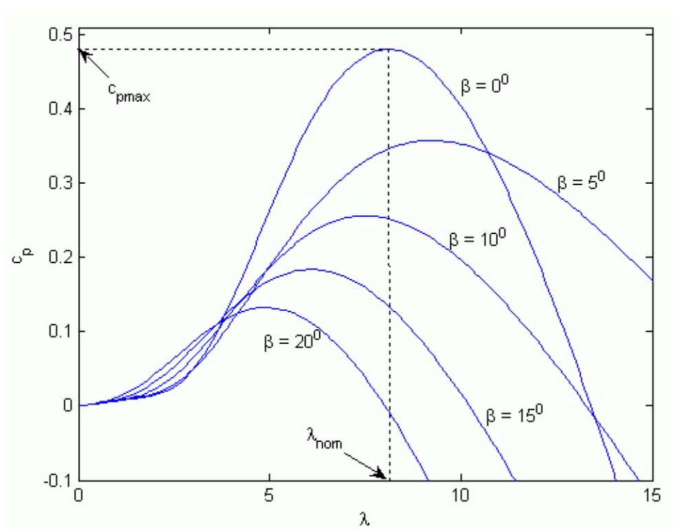

Figure 4: c_p-λ characteristics, for different values of the pitch angle β **[20]**

3.2 Initial developed WT control model

The initial WT pitch control model that I designed is shown as follows:

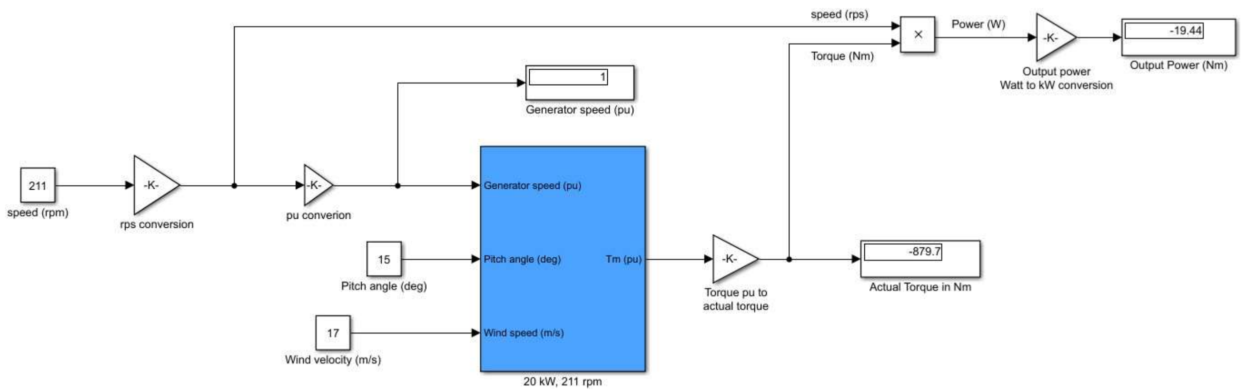

Figure 5: Initial WT control model

For this model, the WT block parameters were chosen as:

Nominal mechanical output power = 20 kW.

Nominal power of electrical generator coupled to the wind turbine = 20,000/0.9 VA. This parameter, also called base power of electrical generator is used to compute the output torque in pu of the nominal torque of the generator.

Base wind speed = 12 m/s. The mean value of the expected wind speed used in the pu system, it produces a mechanical power usually lower than the turbine nominal power.

Maximum power at base wind speed = 1 pu. It is the power gain k_p ($k_p \leq 1$) at base wind speed in pu of the nominal mechanical power.

Base Rotational Speed = 1 pu. It is the rotational speed at maximum power for the base wind speed, expressed in pu of the base generator speed. For a synchronous or asynchronous generator, the base speed is the synchronous speed. For a permanent-magnet generator, the base speed is defined as the speed producing nominal voltage at no load.

Pitch Angle = 0 deg. It is the pitch angle β (β ≥ 0), in degrees, used to display the power characteristics.

From Figure 5, we can observe that as wind speed increases above the rated value (17m/s, in this case), then by increasing the pitch angle (here, 15 degrees proves sufficient) we can control the output power of the turbine and maintain it close to the nominal value (20 kW, for this example), ensuring that it does not exceed that value (here, the output power obtained is 19.44 kW). The negative sign is due to Simulink and MATLAB convention.

The turbine power characteristics are shown in the following figure. It presents the turbine output power (as a pu of nominal mechanical power) plotted against the turbine speed (as a pu of nominal generator speed). The plots are taken at different constant wind speeds, and the pitch angle is kept as zero in each case. The maximum power obtained at base wind speed is also highlighted.

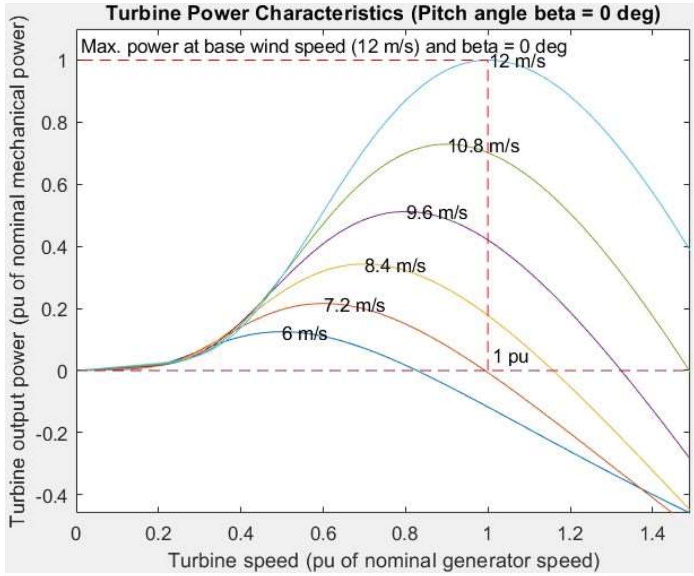

Figure 6: Turbine power characteristics of model

The interior modelling of the WT block/subset is shown in the following two figures. It simply takes the equations (8), (9), and (10) and implements them in Simulink to get the electromechanical torque output of the WT at the given generator speed (pu), pitch angle (deg) and wind speed (m/s). The left f(u) function block in figure 9b represents equation (10), and the right one represents equation (9). This torque is negative purely due to MATLAB convention.

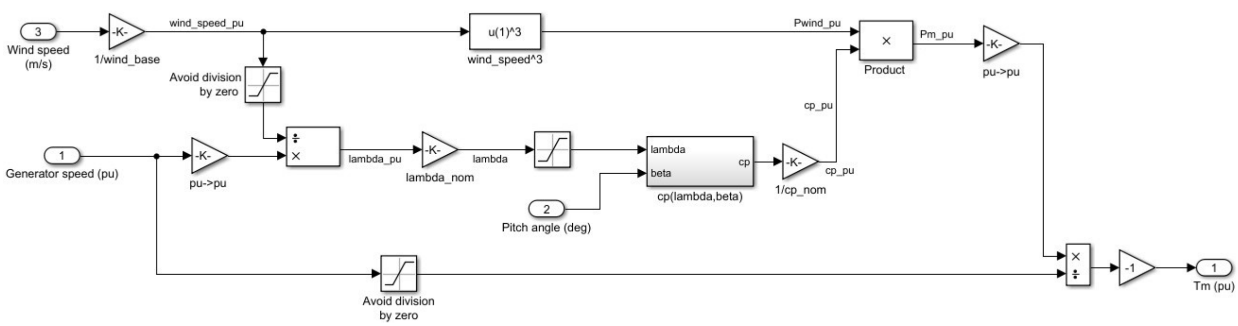

Figure 9a: WT subset interior modelling.

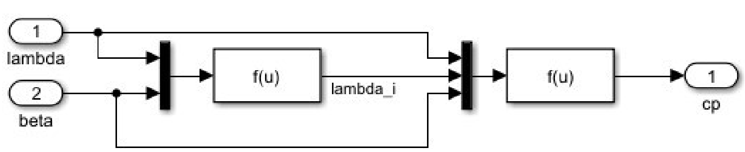

Figure 9b: cp (lambda, beta) subset interior modelling

Although this model does effectively control the output power, it has several shortcomings. The pitch angle must be manually altered every time as it is simply a constant block, and no safeguard is included or cut-in and cut-off wind speeds. It also does not show the coupling of the wind turbine with the generator. Furthermore, any noise that may be present in the output waveforms is not accounted for. The following model designed in this report attempts to mitigate these shortcomings as much as possible.

3.2 Improved model for WT control

The block diagram for the improved WT control model design is as follows:

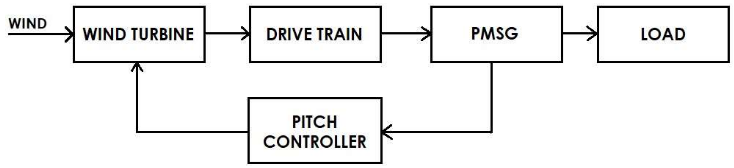

Figure 10: Block diagram for WT control

WTs are coupled with either doubly fed induction generators (DFIGs) used for geared operation, or permanent magnet synchronous generators (PMSGs) which operate gearless and are gaining popularity. Here, we have a WT coupled to a Permanent Magnet Synchronous Generator (PMSG) mechanically via a 2-Mass Drive train. The rotor speed output obtained from the PMSG block is fed as an input to the pitch controller block, which generates the required pitch angle automatically from this input. Finally, the PMSG is connected to a load which draws the power from it. This solves some of the apparent defects of the previous model.

The actual designed model is shown as follows. This design has been based, in part, on a novel control strategy proposed by Haque, Negnevitsky and Muttaqi in 2010 **[21]**. Here, a low pass filter has been used to get rid of any potential noise present in the electromagnetic torque (Te) waveform.

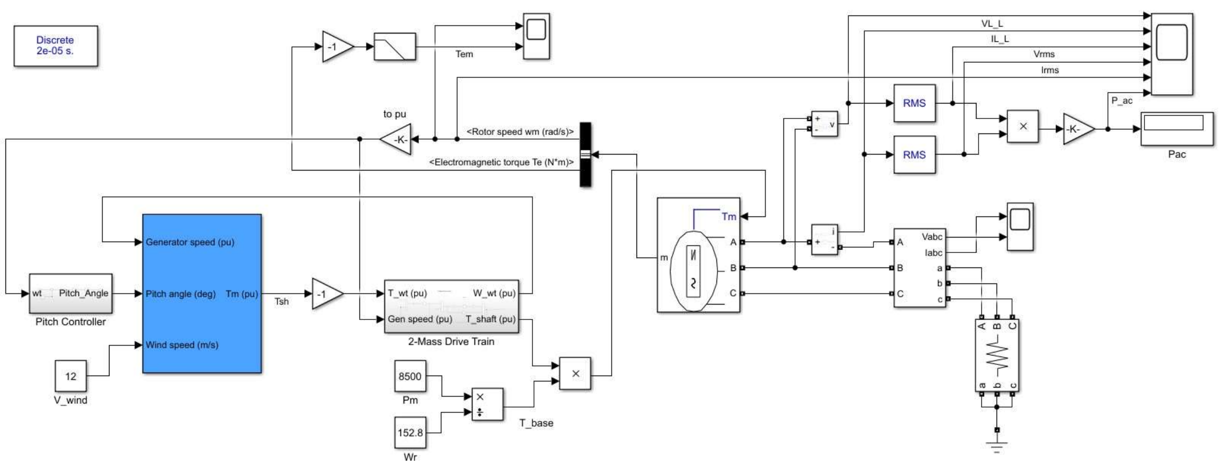

Figure 11: Improved WT control model

This model shows how the earlier WT block may be successfully integrated with a three phase system, and hence provides a more complete picture than the previous one. The WT block interior design has been modified slightly to accommodate cut-in and cut-off speed limits with the help of switches. This is of utmost importance, as the WT generator can be irreparably damaged mechanically without these safeguards in place. The modified design is shown in the following diagram (here, the cut-in and cut-off speeds were taken as 3m/s and 21m/s respectively).

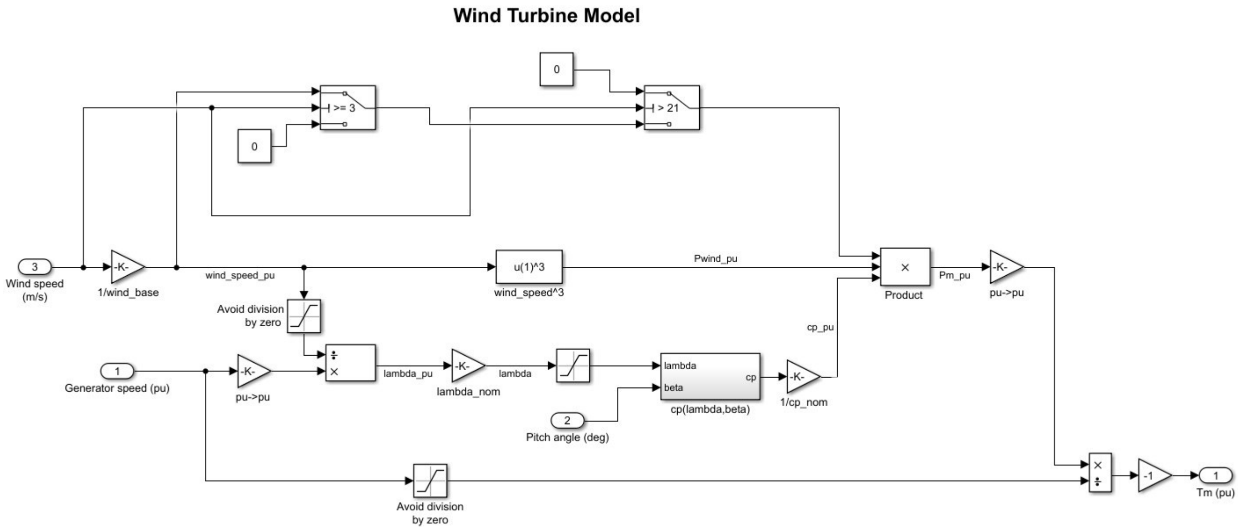

Figure 12: Modified and improved WT block interior

The interior design of the drive train subset is also shown as follows. The drive train in this report has been modelled (and simplified) from the design proposed by Liu, Gao, Geng and Wu in **[22]**. In my design, some of the constant values and mechanical parameters have been chosen for simplicity and ease of implementation. However, the relative accuracy of the model is not compromised greatly. The adjoining figure shows how the turbine of the wind energy system is connected to the shaft of the generator.

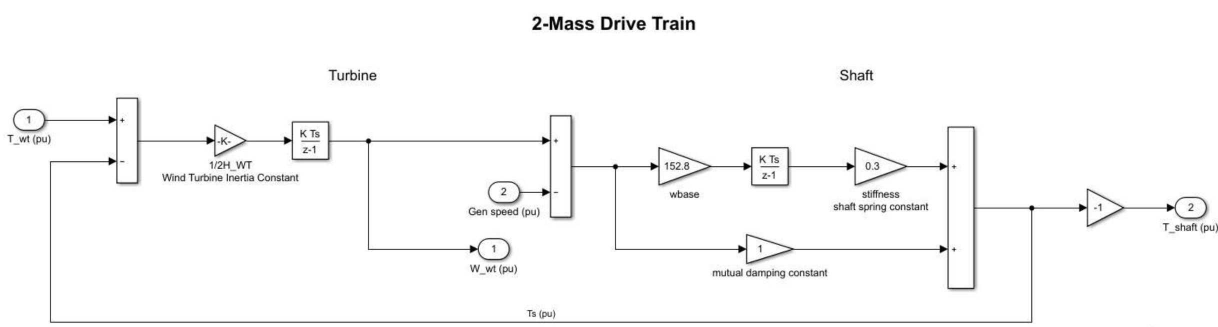

Figure 13: 2-Mass drive train subset design

The pitch angle controller design is also shown below. The gain, saturation and rate limiter block parameters chosen for the subset design are dependent on the WT design ratings. The design used in this report mostly follows the parameters chosen by Haque *et al* **[21]**. The design is shown in the following diagram.

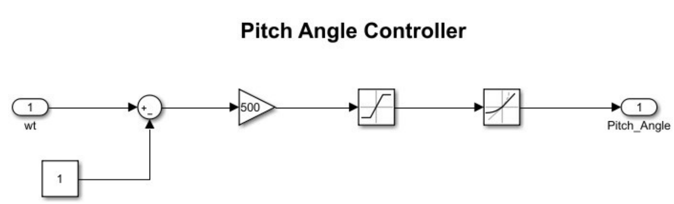

Figure 14: Pitch angle controller subset design

Finally, the output waveforms have been plotted and shown below. In the following figure, six different waveforms have been shown: line-to-line voltage (VL, kV), line-to-line current (IL, amps), root mean square (rms) voltage (kVrms), rms current (Irms), rotor speed (wm, rad/s), and AC output power (Pac, kW). From these waveforms, we can observe that the turbine output characteristics such as speed and power are being very nicely controlled at the desired values.

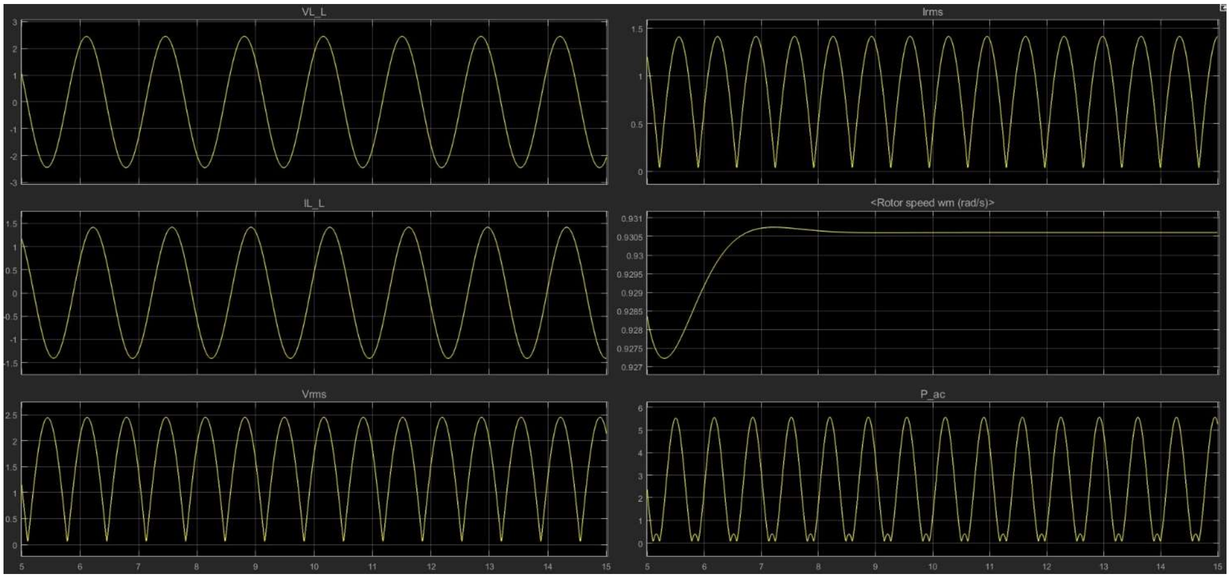

Figure 15: Output waveforms of the WT control model

3.3 Further possible improvements to this model

The previously discussed model, too, has areas that could be improved further. For instance, Maximum Power Point Tracking (MPPT) algorithms, discussed earlier in some detail, have not been implemented in either of these schematics. These algorithms are used to extract maximum possible power from available wind speeds. While implementing these algorithms has the possibility of further increasing the complexity of the model, it can also further improve the control abilities of the model. Isolation transformers can be implemented on the load side for safety purposes. And, we can also implement rectifiers and inverters for AC-to-DC and DC-to-AC conversion, respectively, as well as implementing choppers for DC-to-DC conversion as needed.

4. Operational Control of Wind Turbines and Recent Developments

4.1 Operational control of WTs

Advances in power electronic interfaces have contributed to various improvements in interfacing a WT system with the utility system. The grid side converter (GSC) and machine side converter (MSC) are the two major components in a power electronic system interface when considering the control of WT s. GSC focuses primarily on stable grid integration of the WT system by dc link voltage control and has implications for optimal power delivery into the power system with the objective to minimize losses. The GSC is classified into two groups, listed below. **[23]**.

Direct power control (DPC**)** aims for fast control of both active and reactive power of the WT system. It eliminates the need for pulse width modulation blocks or an inner current control loop. Setting the reactive power reference to zero achieves unity power factor operation. The major advantage is the reduction in computational time and system complexity. The DPC system has a fast dynamic and robustness towards uncertainties while its parameter variation is high. The simplicity of its algorithm and architecture is its major advantage, bearing in mind the high power factor. Its setback is the need for a filter inductance and a sampling frequency (due to variable switching) thereby increasing cost. Voltage oriented control (VOC**)** is similar to the field oriented control of the machine side converter as both use a dual loop control structure. However, VOC focuses on improving power quality with minimal power ripple. The control strategy is based on a PI control in the synchronous reference frame and a dc link voltage control loop with an inner current control loop. A focus of this control is fast response and high steady performance while directly measuring the DC link voltage. Its disadvantage is the poor total harmonic distortion in line voltage distortion.

The MSC controls the variable speed operation of the WT system by capturing maximum energy from wind. To enhance power output and system stability, the rotor speed of the wind generator is controlled to its maximal value. The two control strategies associated with the MSC, similar in characteristics and dynamic performance, are discussed below.

Field oriented control (FOC) ensures an increase in optimal efficiency by directly controlling the current and utilizing the total line current for producing torque. It operates on the basis of a dual loop strategy. The inner loop depends on the synchronous reference frame while the outer loop control depends on the speed and rotor position to generate the reference current of the three phases. In order to get peak electromagnetic torque with minimum stator current, the d-axis of the stator should be set to zero while the stator current q-axis controls the developed electromagnetic torque. In contrast, the direct torque control (DTC) strategy works with one outer loop control eliminating the need for transformation between reference frames. The switching pulse for the converter is directly obtained from the flux angle. This direct control of the torque and power ensures a faster response and less complexity of the system. Its advantages include eliminating rotor speed sensors, a faster response and the absence of a current regulation loop. But, the performance evaluation of the direct torque controller is limited by the torque and current ripples. The need for a varying switching frequency is another drawback.

4.2 Discussions and recent WT control developments

Safety enhancement, reliability, reducing production cost and improvement in power quality has been the focus of wind energy research. To achieve these objectives, having appropriate control strategies that can deal with multiple objective problems is very important. Cost and turbine technology are underlying factors to consider in choosing the appropriate control method. The fixed speed WT, though old technology, still contributes to a large number of installed WTs globally. Passive stall control was originally designed to work with fixed speed WTs, but nowadays the active stall control of WTs is recommended in fixed speed WTs (although its slightly more expensive) as its more efficient than passive control and less expensive than pitch control. For variable speed wind systems, especially in high wind speed areas like coastal regions, pitch control is recommended for better performance and efficiency.

Pitch control is gaining traction especially with large variable speed WTs. Irrespective of the chosen pitch control technique, each control method can be implemented either by electrical or hydraulic controller. There has been wide debate on the suitability of one controller over the other. The proponents of electric pitch controllers hinge their arguments on environmental issues since this controller poses no risk of leaking hydraulic fluids under high pressure. The risk of energy waste is also lower while consumption of power is less than its hydraulic counterpart as the latter requires a pump running at all times to keep the system's oil at high pressure and to be always ready when the rotor blades have to be turned. However, a major concern of this controller is the failsafe of the batteries/capacitors. The battery life of an electric pitch controller system is between two to three years. Also, this controller is better suited for colder climates as the hydraulic oil tends to lose its viscosity as temperature plummets. This means the hydraulic controller is better suited to be implemented in warmer climates (though that is not to say that electric pitch controllers cannot be used in warmer climates). Another strength is the speed and reliability of the hydraulic system.

Despite the fluctuations and rising oil prices, hydraulic fluid price in pitch control is irrelevant as it's a closed system which recycles all of its oil needs. Also, since hydraulic systems use fewer technical components than electric control systems, its maintenance and diagnostics is much easier to implement.

However, recent developments in WT control shows that a hybrid controller for pitch control may be possible. With this control, the turbine blades are turned electrically while the failsafe features which prevent damage to the blades runs hydraulically. The risk of leaking oil would be mitigated here since the pitch control would rely mostly on electrical power with reduced energy costs as the control system would rely on a hydraulic system for failsafe power. This will be an excellent option for countries where governments are concerned about reduced costs and high efficiency.

There is a need to focus on mitigating structural loads on various WT subsystems. The IPC if properly researched can greatly contribute to mitigating rotor blade load. Using IPC, output power fluctuations of WTs can be reduced, stabilizing the output and improving the power quality of the grid, while CPC can be deployed for rotor speed regulation during high wind speed. It is also possible to achieve the simultaneous reduction in structural loads on the different subsystems of the WT by fusing more than one control technique. However it is important to ensure that each of these methods do not interfere with each other. Further research on the IPC could lead to improved performance in WT control by combining optimization and intelligent control methods in wind power systems.

The many available algorithms for tracking the WT's optimum power point makes choosing an appropriate MPPT technique difficult. Thus, analyzing these techniques with respect to their complexity, speed of convergence and performance requirements is vital. The IPC based algorithms such as the TSR and PSF are simpler to use and respond faster compared to the DPC algorithms. Their drawback, however, is that the captured mechanical wind power is maximized instead of output electrical power. The OTC algorithm, though simple and fast, is less efficient than the TSR algorithm as it doesn't measure wind speed directly, meaning variations in wind speed are not reflected instantly and on the reference torque. The TSR algorithm has a fast response to varying wind conditions making it highly efficient, however its implementation expensive thus adding extra cost to the WT system. The PSF algorithm is similar to the OTC in terms of its performance and complexity. The DPC algorithms on the other hand are more reliable, cost effective and require less memory. Without any prior measurement of wind speed, these algorithms can optimally calculate the available electrical power. But, their major setback is their unsatisfactory behavior during varying wind conditions thus limiting their application. Currently no methodologies or selection criteria are available to assist designers and developers of wind energy systems in choosing the best MPPT technique for a given WT installation. This is a potential research area which can be further developed to assist in determining the best MPPT technique for a specific application.

Light Detection and Ranging (LIDAR) for WT control is an old technology which has existed for over forty years, but is rarely discussed in research papers since its control application has been limited due to high costs. LIDAR-based feedforward control has been proposed as complementary to the baseline control system to enhance the above rated pitch control performance. The initial attempts focus on designing independent feedforward controllers enabling wind information as a controller input, thus compensating the wind disturbances in the control system **[24]**. It works by measuring wind speed via sensors before it interacts with the WT, giving the WT time to react to the control output signals. This can be very useful in large WTs with massive blades making it possible to activate pitch actuation ahead of time for minimizing the effect of asymmetrical loads on the rotor blades. This technology, though old, is still very well researched and very important for controlling WTs in the future. Model predictive control (MPC) is the main control method for LIDAR. It considers future states as inputs for the control law optimization. These future states can be provided by LIDAR by measuring wind speed ahead of the rotor. LIDAR allows the deployment of feedforward control. LIDAR-assisted control has limited improvements in energy capture and yaw control performances in below rated operation, but requires more control actions. Therefore, applying LIDAR measurements for above rated pitch control could be more beneficial. The concept of LIDAR needs to be properly investigated since it is not currently implemented commercially in WTs.

Another recent WT control development is smart rotor application. This is an intensive research area dealing with reduction of loads for future WTs. This concept employs sensors and actuators distributed along the blades of the WT with embedded intelligence. Unlike the pitch angle control which turns the entire blade by a pitch motor, the relative wind flow is controlled by the smart rotor by using the specific actuators located along the blade making the WT rotor a smart device which can react faster and more precisely to load events. A lot of proposals such as trailing edge flaps, micro tabs active blade twist, and boundary layer control have been made for installing various active load control devices in WTs **[25]**. It has been suggested that smart rotors be used as auxiliary devices instead of load control systems, making the smart rotor act as a compliment to pitch control systems **[26]**.

5. Conclusion

The various available concepts of WT control has been discussed here, although most literatures only discuss the pitch control of WTs. The active and passive stall control, pitch control of WTs and the MPPT methods available have been discussed. The electric and hydraulic controllers for pitch control have also been discussed, with the hydraulic converter having a tendency to lose oil viscosity in regions with lower temperatures, so it is believed that it may be better suited in warmer climates. Two different models demonstrating the pitch control of WTs have been implemented successfully with controlled output plots attached herewith, with detailed explanations of the underlying governing equations, model parameters, as well as potential improvements and future scope of work to further develop and improve on these schematics. Finally, an overview of power electronic interfaces for grid integration of WTs have also been discussed, followed by an overview of, and discussion on, recent developments in the control of wind turbines.

6. References

[1] Apata, O., and D. T. O. Oyedokun. "An overview of control techniques for wind turbine systems." Scientific African 10 (2020): e00566.

[2] J.G. Njiri, D. Soeffker, State-of-the-art in wind turbine control: trends and challenges, Renewable Sustainable Energy Rev. 60 (2016) 377–393.

[3] S.A. Frost, M.J. Balas, A.D. Wright, Direct adaptive control of a utility-scale wind turbine for speed regulation, Int. J. Robust Nonlinear Control: IFAC-Affiliated Journal 19 (1) (2009) 59–71.

[4] M. Geyler, P. Caselitz, Individual blade pitch control design for load reduction on large wind turbines, in: Proceedings of the European Wind Energy Conference (EWEC 2007), Milano, Italy, 2007, pp. 7–10. May.

[5] H. Moradi, G. Vossoughi, Robust control of the variable speed wind turbines in the presence of uncertainties: a comparison between H∞ and PID controllers, Energy 90 (2015) 1508–1521.

[6] R.M. Kamel, A. Chaouachi, K. Nagasaka, Enhancement of micro-grid performance during islanding mode using storage batteries and new fuzzy logic pitch angle controller, Energy Convers. Manag. 52 (5) (2011) 2204–2216.

[7] R.M. Kamel, A. Chaouachi, K. Nagasaka, Three control strategies to improve the microgrid transient dynamic response during isolated mode: a comparative study, IEEE Trans. Ind. Electron. 60 (4) (2013) 1314–1322.

[8] M. Chowdhury, N. Hosseinzadeh, W. Shen, Smoothing wind power fluctuations by fuzzy logic pitch angle controller, Renew. Energy 38 (1) (2012) 224–233.

[9] R. Ata, Artificial neural networks applications in wind energy systems: a review, Renew. Sustain. Energy Rev. 49 (2015) 534–562.

[10] A.M.S. Hwas, R. Katebi, Wind turbine control using PI pitch angle controller, in: Proceedings of the IFAC Conference on Advances in PID Control PID'12, 2012.

[11] J. Wang, N. Tse, Z. Gao, Synthesis on PI-based pitch controller of large wind turbines generator, Energy Convers. Manag. 52 (2) (2011) 1288–1294.

[12] X. Yang, et al., Petri net model and reliability evaluation for wind turbine hydraulic variable pitch systems, Energies 4 (6) (2011) 978–997.

[13] Y. Kong, Z. Wang, Modelling and analysing the hydraulic variable-pitch mechanism for a variable-speed wind turbine, Wind Eng. 31 (5) (2007) 341–352.

[14] L. Chen, F. Shi, R. Patton, Active FTC for hydraulic pitch system for an off-shore wind turbine, in: Proceedings of the Conference On Control and Fault-Tolerant Systems, 2013, pp.510-515.

[15] M.A. Abdullah, et al., A review of maximum power point tracking algorithms for wind energy systems, Renew. Sustain. Energy Rev. 16 (5) (2012) 3220–3227.
[16] D. Kumar, K. Chatterjee, A review of conventional and advanced MPPT algorithms for wind energy systems, Renew. Sustain. Energy Rev. 55 (2016) 957–970.
[17] N. Fermia, et al., Predictive & adaptive MPPT perturb and observe method, IEEE Trans. Aerosp. Electron. Syst. 43 (3) (2007).
[18] M. Abdullah, A. Yatim, C. Tan, An online optimum-relation-based maximum power point tracking algorithm for wind energy conversion system, in: Proceedings of the Power Engineering Conference (AUPEC), 2014 Australasian Universities, 2014, pp. 1–6.
[19] K.N. Yu, C.K. Liao, Applying novel fractional order incremental conductance algorithm to design and study the maximum power tracking of small wind power systems, J. Appl. Res. Technol. 13 (2) (2015) 238–244.
[20] Siegfried Heier, "Grid Integration of Wind Energy Conversion Systems," John Wiley & Sons Ltd, 1998, ISBN 0-471-97143-X
[21] M. E. Haque, M. Negnevitsky and K. M. Muttaqi, "A Novel Control Strategy for a Variable-Speed Wind Turbine With a Permanent-Magnet Synchronous Generator," in *IEEE Transactions on Industry Applications*, vol. 46, no. 1, pp. 331-339, Jan.-feb. 2010
[22] Liu, Jianxing & Gao, Yabin & Geng, Sijia & Wu, Ligang. (2016). Nonlinear Control of Variable Speed Wind Turbines Via Fuzzy Techniques. IEEE Access. 5. 1-1. 10.1109/ACCESS.2016.2599542.
[23] S. Li, et al., Optimal and direct-current vector control of direct-driven PMSG wind turbines, IEEE Trans. Power Electron. 27 (5) (2012) 2325–2337.
[24] J. Bao, et al., Feedforward control for wind turbine load reduction with pseudo-lidar measurement, Int. J. Autom. Comput. 15 (2) (2018) 142–155.
[25] L. Bergami, M. Gaunaa, Stability investigation of an airfoil section with active flap control, Wind Energy Int. J. Prog. Appl. Wind Power Convers. Technol. 13 (2-3) (2010) 151–166.
[26] C.E. Plumley et al., "Supplementing Wind Turbine Pitch Control With a Trailing Edge Flap Smart Rotor," 2014.