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INVESTIGATING ROBUST PITCH ANGLE CONTROL TECHNIQUES OF THE NREL 1.5 MW HAWT

Abdelrahman Marzouk Elkattan *,1,2, **Mohamed Saber Sokar**2, **Osama Ezzat Abdellatif** 2
1 October University for Modern Sciences and Arts (MSA), Cairo, Egypt
2 Faculty of Engineering at Shoubra, Benha University, Cairo, Egypt
*Correspondence: eng.elkattan@gmail.com

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ABSTRACT

Wind energy is a promising renewable source, but optimizing power output while safeguarding turbine integrity necessitates advanced control systems.This research investigates robust control techniques for regulating the pitch angle of wind turbines. A computer simulation environment (FAST-MATLAB/Simulink) is used to analyze these techniques on the NREL 1.5 MW HAWT. It explores control methods for both operational regions, In low wind speeds (Region 2), and (Region 3) in high wind speeds. The generator torque control assisted the turbine in achieving its maximum power coefficient (Cp) at low wind speeds. Blade pitch control took over when wind speeds increased, ensuring that the generator torque remained steady at its rated value and that the rotor speed remained constant at 20 rpm. As a result, the power curve became smooth, gradually growing at low wind speeds and leveling off at the rated power at high wind speeds. The power curve produced by the simulation and the one derived from the FAST software's control model matched.

KEYWORDS: Wind turbine, Pitch Control, Simulation, FAST, Power.

دراسة تقنيات التحكم المتمكن في زاوية الميل لشفرة توربينة رياح أفقية المحور من المختبر الوطني للطاقة المتجددة بقدرة 1.5 ميجا وات

عبدالرحمن مرزوق القطان*1,2 , **محمد صابر سكر** 2 , **أسامة عزت عبداللطيف**2
1 جامعة أكتوبر للعلوم الحديثة والآداب , القاهرة, مصر
2 كلية الهندسة بشبرا, جامعة بنها, القاهرة, مصر
*** البريد االليكتروني للباحث الرئيسي :** eng.elkattan@gmail.com

الملخص

طاقة الرياح هي مصدر متجدد واعد، ولكن تحسين إنتاج الطاقة مع حماية سلامة التوربينات يتطلب أنظمة تحكم متقدمة .يبحث هذا البحث في تقنيات التحكم المتمكنة لتنظيم زاوية ميل شفرات توربينات الرياح. يتم استخدام بيئة محاكاة الكمبيوتر (FAST-MATLAB / Simulink) لتحليل هذه التقنيات على نموذج توربينات الرياح المحدد، NREL 1.5 MW . تستكشف الدراسة طرق التحكم لمنطقتين تشغيليتين رئيسيتين. في سرعات الرياح المنخفضة (المنطقة 2)، و (المنطقة 3) في سرعات الرياح العالية. حققت استراتيجية التحكم المشتركة العديد من الأهداف، كما يتضح من النتائج. ساعد التحكم في عزم دوران المولد التوربين في تحقيق معامل القدرة الأقصى (Cp) عند سرعات الرياح المنخفضة. تولى التحكم في ميل الشفرات المسؤولية عندما زادت سرعات الرياح، مما يضمن ثبات عزم دوران المولد عند قيمته المقدرة وبقاء سرعة الدوار ثابتة عند 20 دورة في الدقيقة. ونتيجة لذلك، أصبح منحنى القدرة سلسًا، حيث ينمو تدريجيًا عند سرعات الرياح المنخفضة ويستقر عند القدرة المقدرة عند سرعات الرياح العالية. وقد تطابق منحنى القدرة الناتج عن المحاكاة مع المنحنى الناتج عن نموذج التحكم ببرنامج FAST .

الكلمات المفتاحية : توربينات الرياح، التحكم في زاوية ميل شفرة التوربينة، المحاكاة، برنامج FAST، الطاقة.

1 INTRODUCTION

Wind energy has emerged as a vital source of clean electricity generation, playing a key role in the transition towards a sustainable future. Its advantages are undeniable. Unlike fossil fuels, wind is a renewable resource, replenished by the continuous movement of air masses [1]. Wind farms contribute to reduced greenhouse gas emissions, combating climate change, while also fostering energy independence and creating jobs in manufacturing, construction, and maintenance [2].

However, integrating wind energy into the power grid presents a significant challenge: the variability of wind speeds. Wind isn't constant, and its intensity can fluctuate significantly throughout the day and across seasons [3]. This variability makes it difficult to consistently produce a predictable amount of electricity. During periods of low wind, gaps can arise between supply and demand, potentially causing grid instability and challenges in meeting peak energy consumption needs [3].

Researchers are actively developing solutions to address wind's intermittency. Energy storage technologies, improved wind forecasting models, and advancements in grid management practices are all being explored to ensure wind energy remains a reliable and efficient contributor to the global energy mix [4].

Wind energy is a key renewable source, but optimizing turbine performance under varying conditions remains a challenge. This paper addresses the need for robust control systems to enhance turbine efficiency across different operational regions. Using FAST-MATLAB/Simulink simulations, we investigate pitch angle control strategies for the NREL 1.5 MW HAWT. These strategies improve power output while protecting the turbine from excessive loads, thus extending its lifespan. The main contribution is a control framework that balances energy capture and turbine durability, providing valuable insights for both research and industry.

1.1 Role of pitch angle control in wind turbine performance optimization

One crucial element in optimizing wind turbine performance is pitch angle control. Wind turbines capture wind energy through the rotation of their blades. The angle at which these blades meet the oncoming wind, known as the pitch angle, significantly impacts the captured power and mechanical loads on the turbine [5]. At wind speeds below the turbine's rated capacity, a pitch angle close to zero degrees maximizes energy capture by allowing the blades to fully interact with the wind. However, when wind speeds surpass the rated limit, uncontrolled operation can lead to excessive power generation and potentially damage the turbine [6].

This is where pitch angle control comes into play. By adjusting the blade pitch angles dynamically, the control system regulates the captured power and protects the turbine from excessive loads. During high winds, the controller increases the pitch angle, effectively "feathering" the blades and reducing the captured wind energy to maintain safe and optimal operation [6]. This precise control allows wind turbines to efficiently extract maximum power under varying wind conditions, ultimately leading to improved overall performance and grid integration.

1.2 Literature review on existing pitch angle control methods and their limitations

As wind energy deployment expands, the wind turbine size increase and the need for robust control that increases the power conversion efficiency while simultaneously reduces the attendant loads to decrease maintenance and increase the turbine's service life becomes more pressing. Variable speed, variable pitch has been proposed as alternative control schemes to the early fixed speed, fixed pitch turbine models. While controlling the blade pitch angle to adjust power at high wind speeds is used, also has a significant impact in reducing the loads on the turbine. With the continuous increase in the size of the turbine, there is a very interesting role in the turbine control to reduce loads by as much as possible. Torque control is used in the turbine often to get the maximum power at low wind speeds, as well as to adjust the torque at high wind speeds. It is worth noting that Individual Pitch Control (IPC) was suggested at the end of the seventies [7], and has ever since been discussed by many researchers.

IPC can performed through two types of actuators: hydraulic and electric (motor) actuators. With electric actuators, the pitch angle often changes between 10 to 20 degrees [8],which puts only a small gear segment under load, hence the need for replacing the whole gear due to wear. However, hydraulic pitch controllers evade this problem by using a hydraulic cylinder for each blade to change the pitch angle.

Early research into Individual Pitch Control (IPC) focused on establishing its potential benefits. Bossanyi's pioneering work in the early 2000s highlighted IPC's role in managing generator torque and reducing loads on multi-MW turbines [9]. Subsequent studies by Jelavić et al. [10] and Namik and Stol [11] further emphasized IPC's effectiveness in mitigating structural loads, such as tilt and yaw moments, particularly for larger and offshore wind turbines.

Researchers explored various IPC techniques, including linear quadratic Gaussian (LQG) control, adaptive control strategies, and hybrid approaches. These studies consistently demonstrated IPC's superiority over traditional collective pitch control (CPC) in terms of load reduction and power optimization [12]. Bossanyi and Wright's field tests provided valuable insights into the practical implementation of IPC, showcasing its potential for real-world applications [13].

Recent research has delved deeper into IPC, exploring advanced control algorithms and their impact on turbine performance. The integration of IPC with other control strategies, such as fuzzy logic and model predictive control, offers promising avenues for further optimization. Additionally, the development of high-fidelity simulation tools has facilitated the design and analysis of complex IPC systems.

Early research focused on the application of fuzzy logic control (FLC) to address the nonlinear challenges of wind turbine systems. Zhang et al. (2007) [14] demonstrated the effectiveness of a fuzzy-PD controller in enhancing wind turbine performance compared to traditional PI controllers. Subsequently, Zhang et al. (2008) [15] expanded on this work by comparing FLC with conventional proportional-control (PC) strategies, highlighting the superior performance of FLC in terms of fatigue loads, power peaks, and torque peaks.

Muyeen et al. (2009) [16] introduced an FLC-based strategy to maintain consistent power output at wind speeds exceeding the rated value. This controller exhibited robustness to wind fluctuations and improved transient stability. Fard et al. (2011) [17] further explored FLC for pitch angle control, achieving smoother power output and reduced mechanical fatigue compared to traditional controllers.

To enhance FLC performance, Chiang et al. (2011, 2012) [18] and [19], developed an adaptive fuzzy controller incorporating self-organizing rules. This approach demonstrated superior pitch control capabilities compared to standard fuzzy sliding mode control. Alberto et al. (2011) [20] conducted a comparative analysis of PI, FLC, and Fuzzy-PI controllers, highlighting the strengths of fuzzy logic in handling nonlinearities and achieving better overall performance.

Zhanga et al. (2013) proposed an improved proportional-integral-plus (PIP) controller for wind turbines, building upon traditional PID control [21]. Li et al. (2014) [22] introduced an L1 adaptive output feedback controller, emphasizing the importance of accurate wind speed estimation. Rajendran and Jena (2014) [23] explored the application of adaptive FLC to variable speed wind turbines, demonstrating its robustness to disturbances.

1.2.1 FAST

The integration of FAST, FAST code developed by NREL and is one of the most important and common wind turbine simulation tools, and MATLAB/Simulink has emerged as a powerful tool for advancing wind turbine research. Zhang et al. (2014) [24] pioneered this approach by developing a comprehensive wind turbine model within the FAST-MATLAB/Simulink environment. Subsequently, Vidal et al. (2012) [25] streamlined the control design process by creating a convenient block diagram representation of torque and pitch controllers within MATLAB/Simulink.

Furthermore, Li et al. (2014) [22] leveraged the CART-based simulation capabilities of FAST to validate the performance of their proposed control strategies. Boukhezzar (2007) [26] extended this approach by comparing controller performance using both FAST and the faster, albeit less accurate, SymDyn simulator. Wilson et al. (2009) [27] applied the FAST-Simulink interface to evaluate hybrid control systems under various wind conditions.

Based on this literature survey, it is evident that the choice of control method significantly influences wind turbine performance, energy extraction, and structural longevity. Existing studies have highlighted the need for accurate aerodynamic and load calculations to develop effective control strategies.

To address these challenges, this research aims to create a precise control model for wind turbines by utilizing the sophisticated modeling capabilities of FAST. By interfacing FAST with MATLAB/Simulink, we can leverage the strengths of both software packages to design and simulate advanced control strategies. This approach will enable us to optimize power output, reduce blade loads, and enhance overall turbine performance.

2 WIND TURBINE CONTROL

Wind turbines are sophisticated, nonlinear, dynamic systems subjected to random wind turbulences, and gravitational, centrifugal, and gyroscopic loads. Because of the nonlinearity, unsteadiness, and complexity of the wind turbines aerodynamics, their rotors experience fatigue loading. Some of the early models failed tragically because of blade issues, gearbox issues, mechanical breakdown, tower collapse, yaw motor events, etc, however, with improved designs, many of such failures have minimized in recent years. Additionally, using the latest technology trends, modern wind power systems can generate significantly larger amounts of power efficiently and cost effectively. Nonetheless, failures due to unexpected loads are still present.

With the expansion in deployment of wind energy, there is an urgent economic need for development of large wind turbines that can operate efficiently and reliably at minimum cost. Certainly wind turbine control strategies play a key part in dealing with the operational challenges and must therefore be robust given the complex environmental conditions they are subjected to.

Though early wind turbines operated as fixed speed machines, most modern utility-scale wind turbines operate in variable speed mode with the turbine speed changing continuously in response to the attendant wind condition. This has been aided by the technological advances and accompanying cost reduction in power electronics necessary to convert the generator frequency to that of the grid. Opposite to constant speed machines, variable speed wind turbines operate most of the time around their maximum conversion efficiency and are additionally capable of enduring small power fluctuations.

2.1 Fixed Speed, Pitch-Controlled WT

Generally, a fixed speed, pitch-controlled wind turbine operates at a closely fixed speed. Thus an induction generator is frequently used for this control technique which is connected directly to the grid. With changing wind speeds, the energy produced will inevitably change because the energy produced proportional to the cube of the wind speed. At high wind speeds blade pitch angle are adjusted in order to adjust the power produced to the desired value. This technique is based primarily on reducing aerodynamic power of the rotor.

However, pitch angle control depends basically on reducing the error in the power, the difference between the generated power and the rated or required power, and this is not the only goal of pitch angle control. At low wind speeds, for example, the goal is to adjust the angle of pitch at the optimal situation to produce the maximum power and get the highest aerodynamic efficiency. And the angle of optimal pitch depends mainly on the tip speed ratio (TSR).

2.2 Variable-Speed Pitch-Controlled Wind Turbine

Variable speed wind turbines offer significant advantages over their fixed-speed counterparts. By adjusting rotor speed, these turbines can extract maximum power from the wind while operating at optimal efficiency. However, controlling these complex systems requires sophisticated control strategies.

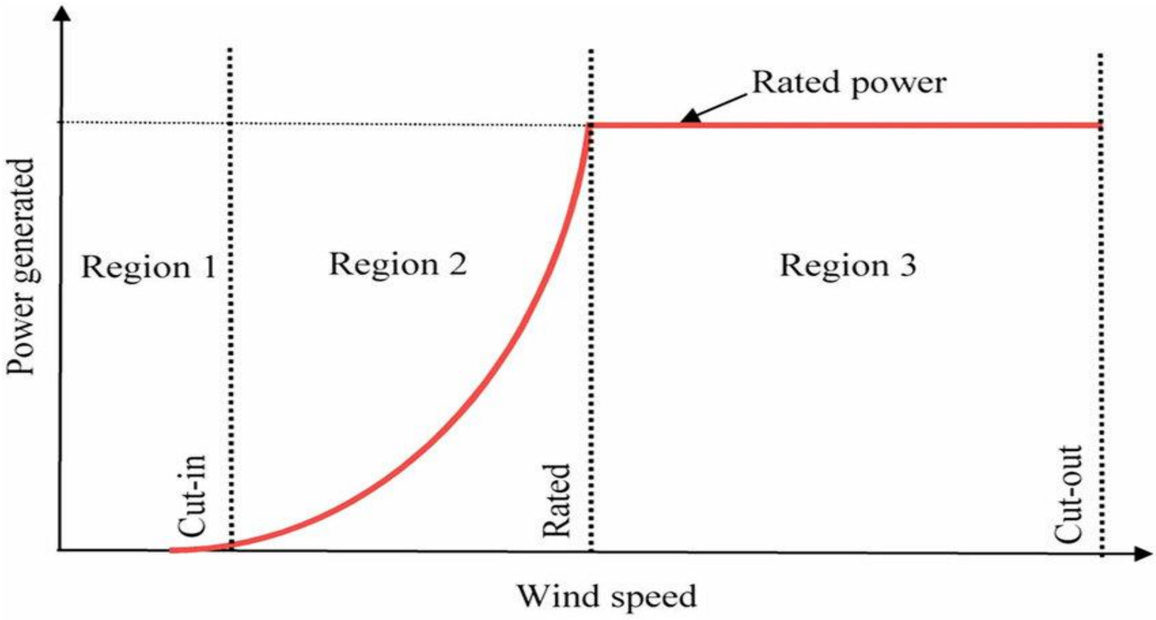

Figure 1 Wind Turbine Operation Regions.

As shown in figure 1, Variable speed wind turbines operate in three distinct wind speed regions. Below the cut-in speed, the turbine is inactive. Between the cut-in and rated speeds (Region 2), the goal is to maximize power output. Above the rated speed (Region 3), the focus shifts to regulating power to protect the turbine while maintaining grid stability. Understanding these operating regions is crucial for designing effective control strategies.

Furthermore, Pitch control is a key component of wind turbine regulation. By adjusting blade angles, operators can optimize power capture at low wind speeds and protect the turbine from excessive loads at high wind speeds. Additionally, generator torque control plays a crucial role in managing power output and maintaining turbine stability.

Early research focused on developing effective control strategies using traditional methods like PID control. However, the nonlinear nature of wind turbines highlighted the need for more advanced approaches. Fuzzy logic control emerged as a promising alternative, offering improved performance in terms of power quality, load reduction, and system stability.

Recent advancements have led to the development of hybrid control strategies combining the strengths of different control techniques. These approaches have shown promising results in enhancing wind turbine performance and reliability. As wind turbine sizes continue to increase, the importance of advanced control systems will grow, necessitating further research and development in this field.

2.3 Overview of Simulation Tools (FAST and Matlab/Simulink)

In 2005, Germanischer Lloyd evaluated FAST code and adopted it an appropriate program of the design and loads calculations for wind turbines [28]. FAST, Fatigue, Aerodynamics, Structures and Turbulence, code [29] that numerically simulates the kinematics based on assumed modes and BEM theory. FAST is a complete aeroelastic simulator capable of forecasting the ultimate and fatigue loads of two- and three-bladed HAWTs. FAST can simulate the turbine under constant or non-uniform wind conditions calculating the loads only as a function of rotor location and then assess the perturbations of the system based on a linearized model for a given set of input perturbations.

The interface between FAST and Simulink was established by Matlab, enabling users to control the turbine models in a way more easily by using block diagram technique. Which gives an amazing flexibility for the design of various control systems for WTs.

3 WIND TURBINE MODELING AND CONTROL SYSTEM DESIGN

3.1 Wind Turbine Mathematical modeling

This part focuses on the mathematical development of the turbine's aerodynamics and structural models. A presentation of the turbine's control algorithm subsequently follows.

Usually, variable-speed wind turbine contains of the subsequent components: aerodynamics, drive trains, and generator. The schematic of wind turbine is shown in Figure 2.

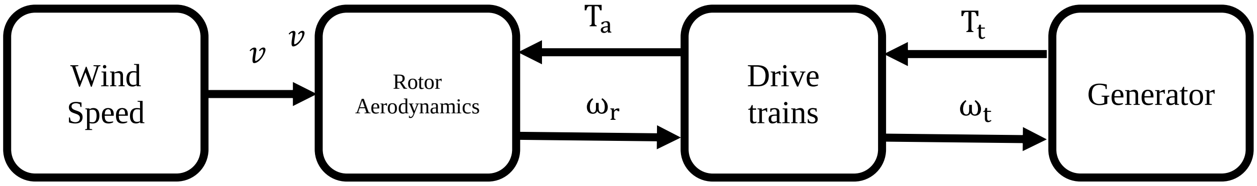

Figure 2 Schematic of Wind Turbine

Rotor aerodynamic power can be written as:

$$P_a = \frac{1}{2}\rho\pi R^2 C_p(\lambda,\beta)v^3 \tag{1}$$

The power produced from wind, P_a, proportional to the cubic wind velocity v. According to the relation between wind velocity and tip speed ratio (Equation 3.49) we can deduce , the value of blade pitch angle (β) and the value of tip speed ratio (λ) affect the calculation of the value of power coefficient (C_p),

$$\lambda = (\omega_r R)/v \tag{2}$$

Therefore, any variation in the wind velocity makes variation in the tip-speed ratio, resulting to power coefficient changing. Then, the extracted power is impacted. The power coefficient is necessarily related to the torque coefficient aerodynamic torque coefficient like below. By the relation:

$$P_a = \omega_r T_a \tag{3}$$

So the term of aerodynamic torque is;

$$T_a = \frac{1}{2}\rho\pi R^3 C_q(\lambda,\beta)v^2 \tag{4}$$

where;

$$C_q(\lambda,\beta) = (C_p(\lambda,\beta))/\lambda \tag{5}$$

A two-mass model of a wind turbine is displayed in Figure 3 (a).
With the aerodynamic torque T_a, the dynamic reaction of the rotor can be concluded at rotational velocity ω_r:

$$J_r\dot{\omega}_r = T_a - T_{ls} - K_r\omega_r \tag{6}$$

The difference between the ω_r and ω_{ls} cause torsion and friction effects, so the torque of low speed shaft is leading to brake rotor axis.

$$T_{ls} = B_{ls}(\theta_r - \theta_{ls}) + K_{ls}(\omega_r - \omega_{ls}) \tag{7}$$

Then the high speed shaft torque (T_{hs}) accelerate the generator, while the generator electromagnetic torque, T_{em} brake it;

$$J_g\dot{\omega}_g = T_{hs} - K_g\omega_g - T_{em} \tag{8}$$

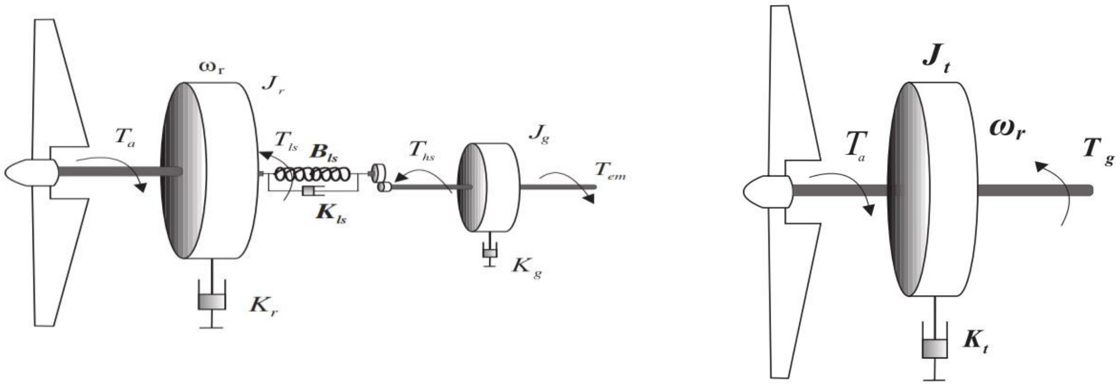

Figure 3 (a) Two-Mass Model of a Wind Turbine, (b) Single-Mass Model of a Wind Turbine [26]

Assuming a perfect gearbox with delivery percentage, N_gear,

$$N_{gear} = T_{ls}/T_{hs} = \omega_g/\omega_{ls} \tag{9}$$

By using Equations (3.55) and (3.56), the generator dynamics can be prescribed as

$$N_{gear}{}^2 J_g\dot{\omega}_g = T_{ls} - \left(N_{gear}{}^2 K_g\right)\omega_g - N_{gear}T_{em} \tag{10}$$

A single-mass model (Figure 3 (b)) of the turbine can be estimated, if a fully rigid low-speed shaft is supposed:

$$J_t \dot{\omega}_r = T_a - K_t \omega_r - T_g \qquad (11)$$

where;

$J_t = J_r + {N_{gear}}^2 J_g$
$K_t = K_r + {N_{gear}}^2 K_g$
$T_g = N_{gear} T_{em}$

3.2 Description of the control model (NREL 1.5 MW HAWTs) with relevant parameters.

The aim of this section is to develop a control algorithm for the NREL 1.5-MW HAWT, but this time the control model will be designed using FAST coupled to Matlab/Simulink. This control model will cover the two essential control regions (Region 2 and 3: torque controller and blade pitch controller respectively).

Subsequently we start by giving a detailed description of the machine. The 1.5 MW HAWT is a three bladed, upwind wind turbine, whose specifications are given in Table 1.

Table 1 Specifications of the NREL 1.5 MW HAWT

R	35	[m]
ρ	1.225	[kg/m^3]
k	0.002374	[N-m/rpm^2]
C_(p_max)	0.5	[-]
λ_opt	7.0	[-]
Rated Power	1.5	[MW]
Rated Torque	8376.56	[N.m.]
Rated Speed	1800	[rpm]
N_gear	87.965	[-]

3.2.1 Generator Torque Control (Region 2)

The control goal here is to custom generator torque to sustain best TSR, therefore sustaining ultimate Cp and maximizing power. In Region 2, pitch angle is kept constant.

To sustain best TSR in Region 2, the generator torque changes according to the next equation:

$$Q_{gen} = k\Omega^2 \qquad (12)$$

$$\text{Where,} \quad k = \frac{1}{2}\rho\pi R^5 \frac{C_{p_{max}}}{(\lambda_{opt})^3} \times \frac{1}{N_{gear}^3} \left(\frac{\pi}{30}\right)^2 \qquad (13)$$

where k is the generator torque constant in HSS side [N-m/rpm2] (defined in the FAST Manual [29] on pages 26-27 under the name of VS_Rgn2K).

Table 1 shows the factors desired for Region 2 of the 1.5 MW HAWT. Now we can put the value of k from and we get Q_gen=0.002374 Ω^2 [N.m].

Currently, Simulink is used to simulate this variable-speed torque control by interfacing with FAST. For this case, we put VSContrl to 3 in the FAST input file [29].

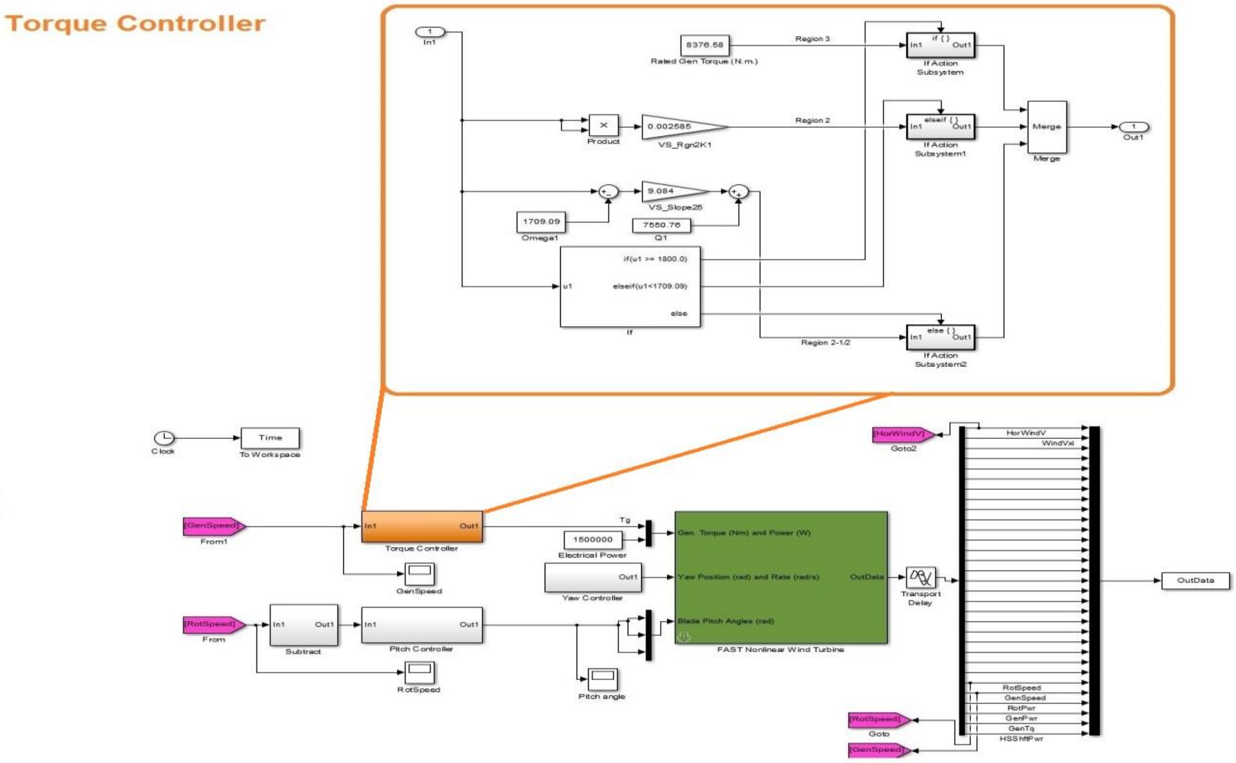

Figure 4 Simulink Model of the Overall Wind Turbine Control Showing the Generator Torque Controller

Figure 4 shows the overall Simulink control system for WTs in the upper part of the figure, connected to the FAST block (in green), with a focus on unit generator torque controller block in orange. This block shows in more detail in the lower part of the figure and takes input in the form of generator speed.

In the figure, there are three branches of the regions 2, 2½, and 3 respectively. The first branch (Region 3) has a single constant input in the form of generator torque equivalent to rated torque. The second branch (Region 2) takes its input in the form of multiplication of the squared generator speed by the VS_Rgn2K1 torque. The last branch is for Region 2½. The generator speed determines which branch to achieve at every moment, according to the conditional "if" statement.

The second branch is used to extract the maximum power at low wind speeds (below rated speed), while the first branch works on adjusting the generator torque at a certain value (rated torque), the third branch works as a transition between the first and second branches.

Now, the baseline generator torque controller for Region 2 have been presented. In the next section, the design of a baseline pitch controller for Region 3 will be conducted.

3.2.2 Blade Pitch Angle Control (Region 3)

Presently, the baseline PID collective blade pitch angle controller for Region 3 will be design for the 1.5 MW HAWT. Actually, we use a two ways to designate a simulation of Region 3 control; a FAST-Simulink scheme of the closed-loop system, and a user-written subroutine directly in FAST.

The aim of Region 3 is to adjust rotor velocity to a certain value (20 rpm for the 1.5 MW HAWT). Generator torque is kept at constant value in Region 3. A valuable linear scheme for this control design is designated in [47], p. 73, and has the procedure:

$$\Delta\dot{\Omega} = A\Delta\Omega + B\Delta\beta + B_d\Delta w \tag{14}$$

where $\mathrm{A} = \frac{\gamma}{I_{rot}}$, $\mathrm{B} = \frac{\zeta}{I_{rot}}$, $\mathrm{C} = \frac{\alpha}{I_{rot}}$. I_{rot} is the overall angular inertia (due to the rotor, gearbox, shafts, generator, etc.).

Now

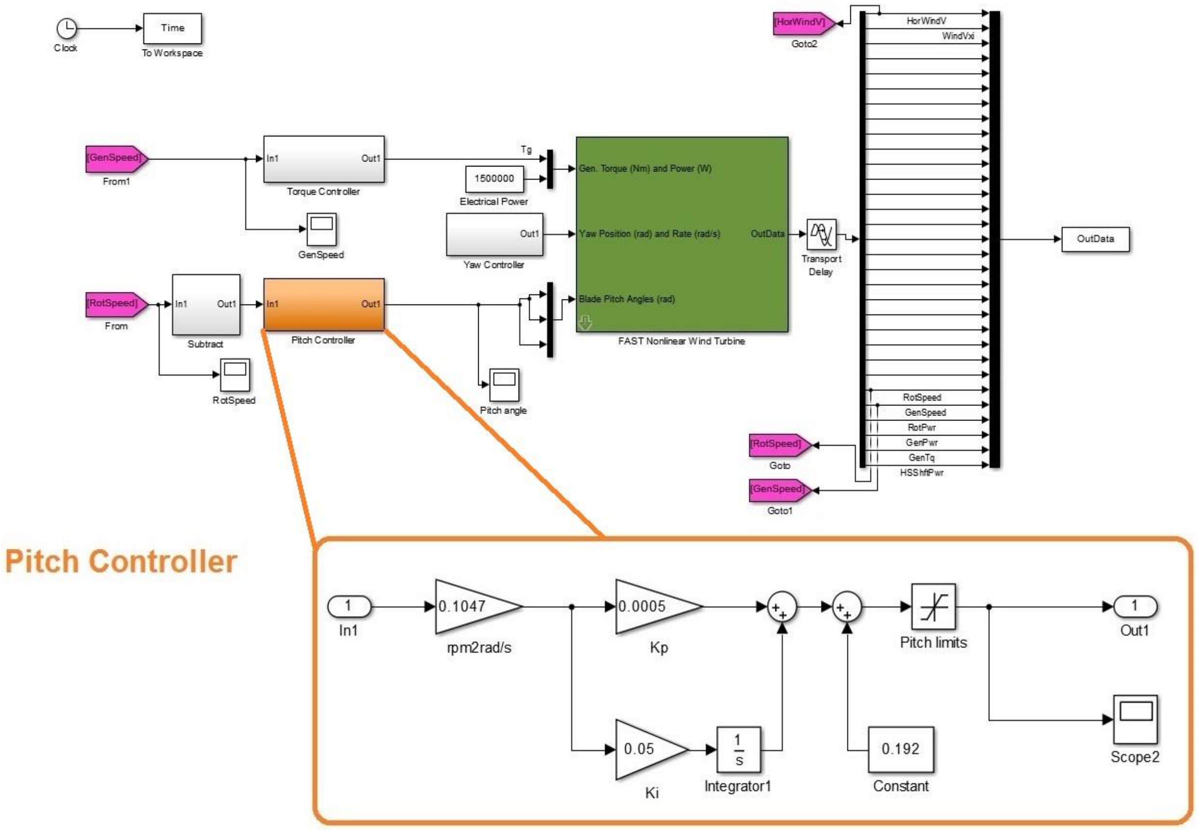

Figure 5 Simulink Model of the Overall Wind Turbine Control Showing the Blade Pitch Controller

$$\gamma = \frac{\partial Q_{aero}}{\partial \Omega}, \zeta = \frac{\partial Q_{aero}}{\partial \beta}, \alpha = \frac{\partial Q_{aero}}{\partial \mathrm{w}}$$

The aim is to use PID control to adjust turbine velocity. The control can be defining by stating the pitch deviation $\Delta\beta$ in Equation (14) as a collecting of a rotor velocity term, a term relative to the integral of rotor velocity, and a term relative to the derivative of rotor velocity.

Thus, the typical PID control equation:

$$\Delta\beta(s) = K_p\Delta\Omega(t) + K_I\int \Delta\Omega(t)dt + K_D s\Delta\dot{\Omega}(t) \tag{15}$$

Currently, the aim is selecting a suitable values for the gains K_p ,K_I ,K_D to sustain a stable closed-loop system and accomplish perfect response. In the next, a technique for selecting these gains is submitted to provide wanted closed-loop response. Initially, we require a system in the Laplace domain as follows:

$$\Delta\beta(s) = K_p\Delta\Omega(s) + K_I\frac{1}{s}\Delta\Omega(s) + K_D s\Delta\Omega(s) \tag{16}$$

By solving the equations 15 and 16, the following equation results:

$$\Delta\Omega(s)[s-A] = \mathrm{B}\Delta\beta(s) + \mathrm{B_d}\Delta w(s) = \mathrm{B}\left(K_p\Delta\Omega(s) + K_I\frac{1}{s}\Delta\Omega(s) + K_D s\Delta\Omega(s)\right) + \mathrm{B_d}\Delta w(s)$$

Now, the relation between the output $\Delta\Omega(s)$ and the input $\Delta w(s)$ can be written in the form of closed-loop transfer function:

$$T_C(s) = \frac{\Delta\Omega(s)}{\Delta w(s)} = \frac{B_d s}{(1-BK_D)s^2 + \left(-A-BK_p\right)s + (-BK_I)} \tag{17}$$

To check stability of the model, the characteristics equation (the denominator of transfer function) must be used. However, the roots of the characteristics equation must have negative real parts (locate in the left-half of the s-plane). This is corresponding to needing that the factors of "s" in the previous equation essential all be positive [48] page 284, i.e.

$$(1-BK_D) > 0, \left(-A-BK_p\right)s > 0, (-BK_I) > 0$$

Now, the turbine parameters A and B must be evaluated by selecting an appropriate Region 3 operating point. For example, we select the wind speed, rotor speed, and blade pitch angle to be: w_0=18 m/s ,Ω_0=20 rpm ,and β_0=11 degrees. Currently, we can set these turbine parameters by implementing a linearization analysis with FAST. At this moment, the results of this linearization can become:

$A = -0.716, B = -7.2$

The output characteristic equation develops:

$$(1+7.2K_D)s^2 + \left(0.716+7.2K_p\right)s + (7.2K_I) = 0 \tag{18}$$

This provides the conditions for stability as:

$$(K_D) > -0.1389, \left(K_p\right) > -0.0994, (K_I) > 0$$

Positive values of K_p, K_I, K_D enhance the efficient inertia, damping, and stiffness of the model defined by equation 18. This displays the effects of feedback in the equation 15 on this closed-loop model.

Thus it is frequently beneficial to convert the characteristic equation to the custom:

$$s^2 + 2\delta\omega s + \omega^2 = 0 \tag{19}$$

where: $2\delta\omega = \frac{-A-BK_p}{1-BK_D}, \omega^2 = \frac{K_I}{1-BK_D}$

Solving for K_I *and* K_p we get:

$$K_I = \frac{-\omega^2(1-BK_D)}{B}, and\ K_p = -\frac{A}{B} - \frac{2\delta\omega(1-BK_D)}{B} \tag{20}$$

The roots of Equation (19) are $s = -\delta\omega \mp \omega\sqrt{\delta^2-1}$. For the underdamped case, when <1 , we have two complex conjugate roots: $s = -\delta\omega \mp j\omega_d$, where $\omega_d = \omega\sqrt{\delta^2-1}$. Here, ω is named the undamped natural frequency, ω_d the damped natural frequency, and δ the damping ratio.

For the critically damped situation, when $\delta = 1$, we have the two repeated roots $s = -\omega \mp j0$.

For the overdamped situation, when $\delta > 1$, we have the two real roots: $s = -\delta\omega \mp \omega\sqrt{\delta^2 - 1}$.

Several control performance can be accomplished by choosing various values for the parameters δ and ω.

The technique of selecting the values of ω and δ was concluded by Risoe [30]. He recommends selecting δ to be from 0.6 to 0.7; ω may be set to 0.6 for respectable response. For design purposes, assume we need to accomplish good performance by choosing $\delta = 0.6$. Put $\omega = 0.6\, r/s$. To simplify the computations, we set $K_D = 0$, and the other two gains can be computed from Equation (20) as:

$K_I = 0.05, K_D = 0.0005\ s.$

Currently, the closed-loop system can be simulated to confirm control response with these gains.

Figure 5 shows the overall Simulink control system for wind turbines in the upper part of the figure, connected to the FAST block (in green), with a focus on unit blade pitch controller block in orange. This block shows in more detail in the lower part of the figure and takes input in the form of rotor speed (the difference between rotor speed and the set point at 20 rpm).

4 SIMULATION RESULTS

4.1 Control Model of a 1.5MW HAWT

In the following, the simulation results of the generator torque control, the pitch control, each one separately, and the overall control of the two operation regions of a 1.5 MW HAWT by using these two control models together are presented.

4.1.1 Baseline Generator Torque Control Design (Region 2)

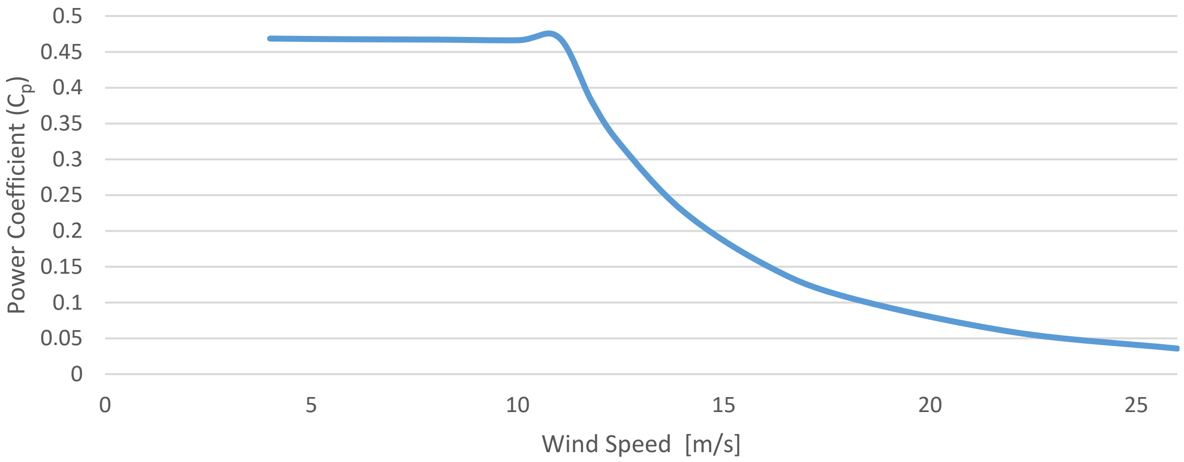

Figure 6 Power Coefficient with Wind Speed

Stimulation of the FAST turbine system have been done at step winds. These step winds allow the operation of the turbine pass initially through a region 2, then pass through the region 2½ and finally pass through the region 3. Figure 5 displays the output generator torque with generator velocity for this simulation.

Also in Figure 6, we can notice the values of power coefficient (C_p) in Region 2 near to $C_{p_{max}}$ and C_p is decreasing gradually with the increasing of wind speeds (In Region 3).

4.1.2 Baseline Pitch Angle Control Model (Region 3)

The simulation of this controller happens with time of 40 s at step wind input (at the wind speed is 18 m/s).

Figure 7 displays the expected rotor velocity reaction to this step wind input. We hold at different situations in which the damping ratio was selected at different values ($\delta = 0.6, 1\ and\ 2$), additionally natural frequency was selected 0.6 rad/s with all values of damping ratio. Damped oscillation is occurred at $\delta = 0.6$, where the damping ratio is less than 1, and the result includes two complex conjugate roots. Critically damped response is occurred at $\delta = 1$, that characterizes the best time which can be accomplished. When δ to 2, the control response effects with the duration of time greater than the critical damping.

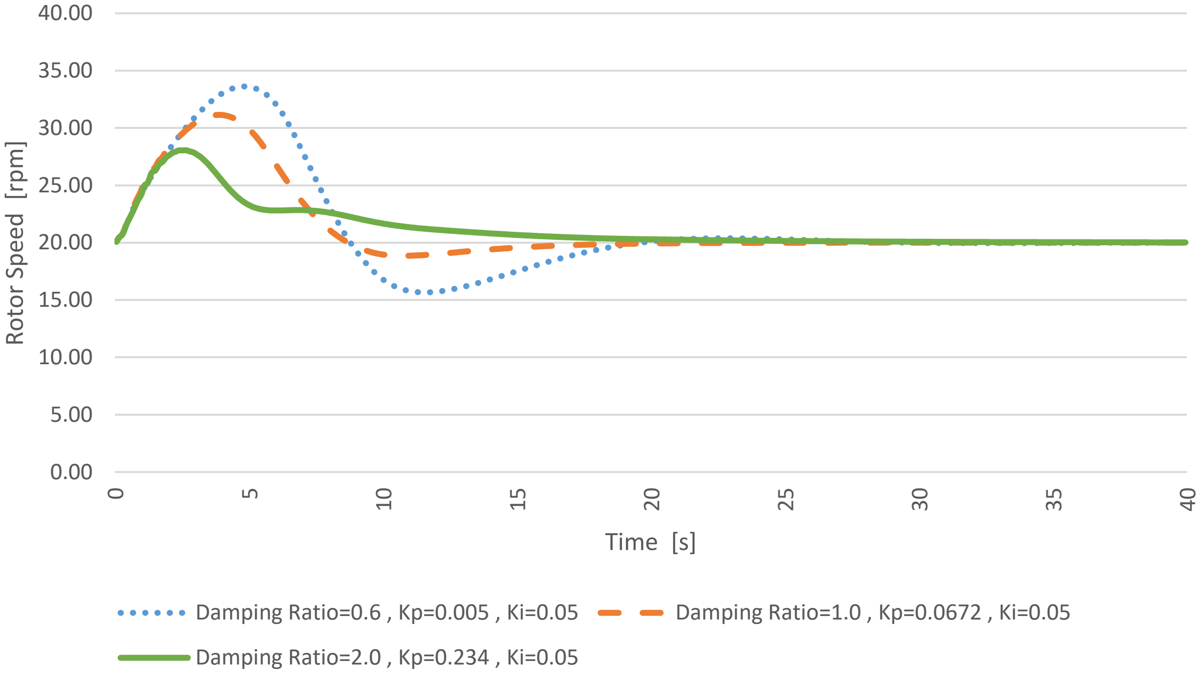

Figure 7 Response to a Step Wind Input for Different Damping Ratios (δ)

4.2 Overall Control of a 1.5 MW HAWT

We focus in our control model of the 1.5 MW HAWT on regions 2 and 3 only. To test and simulate the previous two control models together, torque and pitch control models, we run FAST/Simulink models at different step wind speeds increase progressively from cut in wind velocity to cut out wind velocity. At each step wind velocity, we run the control model with a certain time until the fluctuations in the rotor speed disappear and stabilize at a certain value. Subsequently, we take an average values of the steady rotor speed and other important corresponding parameters for example generator velocity, generator torque, pitch angle and High Speed Shaft (HSS) power. After that, we can draw these steady state values with the step wind speeds to get the wind turbine characteristics curves like the power curve.

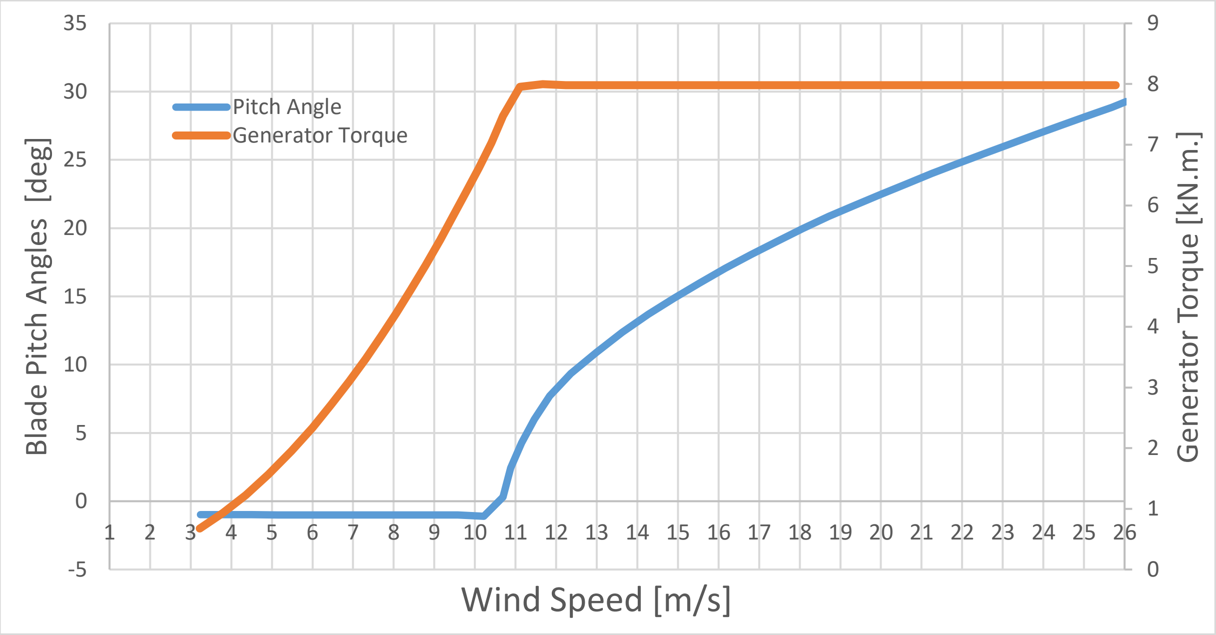

Figure 8 Blade Pitch Angles and Generator Torque at Different Wind Speeds for NREL 1.5 MW HAWT

After applying the overall control of the 1.5 MW, we can firstly notice changing the generator torque in the region 2 (below rated speed 11 [m/s]) to can get maximum generator speed. As well, we can notice generator torque stability close to the rated torque (8376.58 [N.m.]) of this machine (as shown in Figure 8).

On the other side, Figure 8 shows the effect of changing the blade pitch angle above the rated wind speed (Region 3) to adjust the rotor velocity to a specific set point (20 rpm for the 1.5 MW HAWT) while simultaneously maintaining a constant generator torque.

However, the most important curve of wind turbine operation, power curve, has been generated from this overall control of 1.5 MW turbine. In Region 2, the power increases gradually until it reaches and settles at the rated power in Region 3 (Figure 10). Also we generate the power curve by using control model in FAST (blue dash line) and compare it with the power curve by using the interface between FAST and MATLAB/Simulink (green solid line).

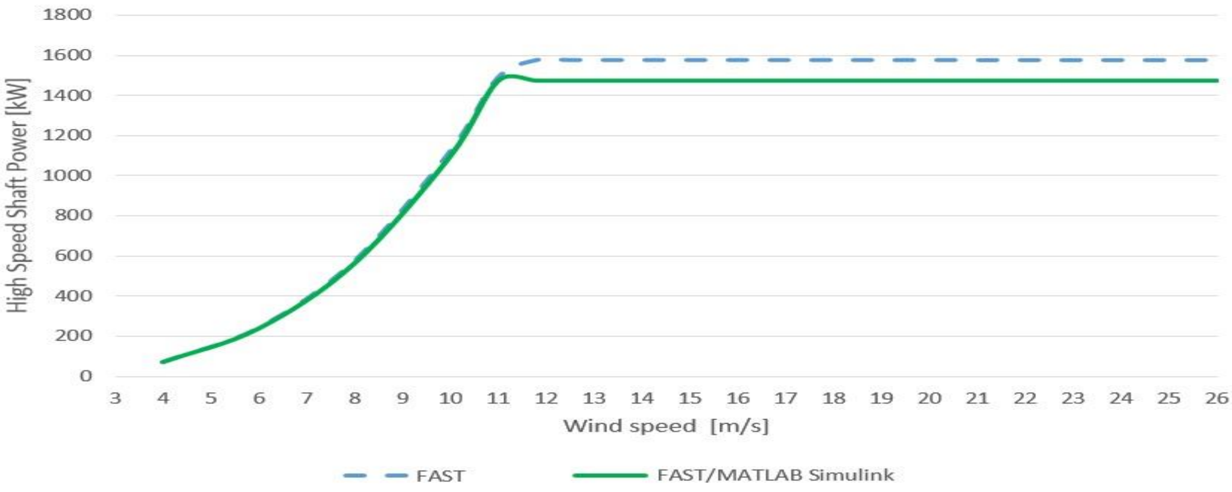

Figure 9 Power Curve with Wind Speeds for NREL 1.5 MW HAWT

CONCLUSION

Our study investigated two control methods for a wind turbine: generator torque control for low wind speeds and blade pitch control for high wind speeds. We built a simulation model using a combination of FAST software and Matlab/Simulink to control a 1.5 MW wind turbine from the National Renewable Energy Laboratory (NREL).

We focused on controlling the turbine's operation in specific wind speed zones. The model was then tested by simulating both control methods together across a range of wind speeds, from the point where the turbine starts generating power (cut-in) to the point where it needs to shut down (cut-out).

The results showed that the combined control strategy achieved several goals. In low wind speeds, the generator torque control helped the turbine reach its maximum power coefficient (Cp). As wind speeds increased, the blade pitch control took over, maintaining a constant rotor speed (20 rpm) and keeping the generator torque stable at its rated value. This resulted in a smooth power curve, with power increasing gradually in low wind speeds and then leveling off at the rated power in high wind speeds. The power curve generated by the simulation matched the one obtained from the control model within FAST software.

In simpler terms, we developed a system that efficiently controls a wind turbine across different wind speeds, maximizing power output and maintaining stable operation.

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