Study on the variable pitch control of the wind power unit based on mamdani inference and conventional control algorithm

Asif Rashid¹ and Deng Ying²

¹,² School of Renewable energy and Clean Power, North China Electric Power University Beijing, China

Abstract. This paper firstly analysed the theory of the Wind Turbine (WT) pitch control algorithms to maximize energy yield, and then based on the analysis, 3 MW wind turbine model with a servo system and Doubly Fed Induction Generator (DFIG) is developed. The blade pitch angle is controlled to ensure that the variable speed WT system operate safely and the optimum power is achieved. Variation in rotor speed as a result of unsteady wind velocity is controlled using PI(D) method. Fuzzy technique is developed and implemented simultaneously. Control Algorithms reveal dynamic performance of the blade pitch angle, rotor speed and rated power characteristics. Within the wind turbine standard operating regimes, controllers have shown promising results. Proposed Fuzzy technique validates superior performance. Finally, MATLAB/SIMULINK tool box establishes the corresponding model to simulation test in order to verify the effectiveness and correctness of the analysed algorithms. Simulation result demonstrates that the developed pitch servo control system has good dynamic, steady state performance and robustness.

1. Introduction.

Wind energy is one of the oldest sustainable energy sources that mankind has started using to solve their different needs. The recent technological developments, the decline in costs and the huge impact of new financing structure have made the sector the driving force of economic growth all over the world. Above all, there is a global consensus on how to deal with the threat of climate change through the use of renewable energy technologies in the world [1]. For any production process, energy is the essence and it must be secured for the economic growth struggling economies Therefore, recently various experimental and numerical studies have been devoted to find ways of improving a WT output power [2]. For a sustainable innovation, sustainability is integrated into innovations, that means, the innovative technologies offer the promise that the demand to continue the economic growth can be balanced with the environmental, economic and social protection [3].

WT’s, both large and small, produce electricity for utilities, home owners and remote villages [4]. When WT’s are grouped together, they are referred to as “wind farms”. Wind farms comprise the turbines themselves along with roads for site access and the grid connection point. Infect over the last ten years’ wind energy is the world’s fastest growing energy source with an average annual growth rate of 31.1%. It is predicted that Wind Energy (WE) will provide 5% of the world’s energy in 2020. According to Pakistan’s Alternative Energy Development Board, wind power offers a technical potential...
of 360 GW which is supported by figures from Solar and Wind Energy Resource Assessment (SWERA) which estimates 349.3 GW potential [4]. For many developing countries, foreign direct investment (FDI) serves not only as an important source of capital but also as a valuable channel for transferring more productive and innovative technology and techniques. In the midst of the transition to cleaner energy systems that is occurring worldwide, enhancing the enabling environment for FDI in Renewable Energy (RE), in particular WE is attracting the majority of investment worldwide, could greatly facilitate competition in the electricity market, and advance the transition safely and efficiently [5].

The variable-speed turbines (VST’s) commonly employ active pitch systems to change the aerodynamic properties of rotor blades, reduce mechanical loads, and mitigate output power and torque fluctuations above rated Wind Speed (WS) incidents [6]. Energy Sphere in figure 1 shows various energy levels of standard VST’s based on different regions of operation. The presented control strategy specifically addresses the case of full load operation in the so-called Regime 3 (high WS’s), therefore it should be intended as a solution of this part of the WE conversion system control problem. Also, the pitch systems allow the turbines to operate in the partial load condition with relatively high efficiency, thereby enabling WT’s to work efficiently and extract the maximum amount of WE [7]. Therefore, the pitch systems have considerable effects on the aerodynamic and mechanical characteristics of WT’s and the development of more advanced pitch systems is of particular importance to the system reliability of modern VST’s.

![Figure 1. Wind Energy Sphere](image)

Generally, the existing pitch systems can be typically categorized into two types: electro-mechanical and hydraulic types. The electro-mechanical pitch system normally employs an electric Servo Motor (SM) to pitch turbine blades. This system suffers various disadvantages however, this system appears to be relatively accurate and compact. The pitch angle control accuracy of the hydraulic system is relatively low due to the nonlinear transformation between the hydraulic piston displacement and pitch angle [8]. The variation in pitch angle is directly dependent on fluctuating nature of the wind. Generating the maximum amount of power from high penetration of wind is challenging. Various control mechanisms have been applied to operate VST’s economically. Power coefficient $C_p$ given in equation (1) represents the amount of electrical power converted by VST.

$$P_m(z) = C_p(z). P_{wind}(z)$$  \hspace{1cm} (1)

where $P_{wind}(z)$ is the power contained in the wind passing with speed $z$ (in m/s) through the VST, and $P_m(z)$ is the extracted electrical power. The power coefficient $C_p(z)$ represents the amount of power converted by VST system. Applying the momentum theory to improve the power performance,

$$P_{wind}(z) = (0.5). (\rho.A.z^3) $$  \hspace{1cm} (2)

where $\rho$ is the density of air (in $kg/m^3$) and $A$ being the area of VST blades. Joining equations (1) and (2), the theoretical power can be written as,
The power coefficients of modern commercial VST’s reach values of 0.45 and more. The functional behaviour of the power coefficient $C_p(z)$ is the result of certain control strategies as well as of Betz limit. Considering the conventional PI and PID control techniques, figure 2 represents the real time behaviours of $C_p$ in a simulated environment.

Single loop methods commonly known as PI and PID control regulates the WT pitch servo mechanism globally [9]. Due to the robustness and rule based inference, Fuzzy control method is widely preferred [10]. In this study Logical Fuzzy and standard PI/PID controllers based WT pitch servo model have been developed and analysis of output power has been done. Therefore, by extending previous studies on this topic, this study aims to clarify the relative significance of the advanced pitch control mechanisms.

The remainder of the paper is organized as follows: Section 2 describes the modelling of DFIG based WT pitch control system with correlation parameters. Section 3 discusses the background of conventional and logical control algorithms. Section 4 presents materials and methods used for analysis. Section 5 analyses the results. Section 6 extends the analysis of proposed fuzzy technique with other non-linear and robust controllers. Section 7 draws the main conclusions of this study followed by references.

Figure 2. Power Coefficient; Conventional PI and PID controllers (Base WS 12 m/s)

2. Pitch control Wind Energy servo system

Electromagnetic SM’ s are designed to meet the unique requirements of pitch control systems. Standards are achieved by adjusting the blades in VST’s by rotating them so that they use the right fraction of the available WE to get the most power at output, all the while ensuring the turbine does not exceed its safety limits. This maintains the maximum rotational speed of WT in the event of high winds, loss of electrical load, or other catastrophic events. Pitch Servo (PS) mechanism offers higher performance and additional safety [11]. Correlation Parameters of $C_p(z)$ provides the effectiveness of system depending on tip speed ratio $\lambda$ and blade pitch angle $\beta$. It can be expressed as,

$$C_p(\lambda, \beta) = 0.5176 \cdot \left[116 \cdot \frac{1}{\lambda_i} - 0.4 \cdot \beta - 5\right] e^{\frac{21}{\lambda_i}} + 0.0068\lambda$$

(4)

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.008 \beta} - \frac{0.035}{\beta^3 + 1}$$

(5)

$$\lambda = \frac{\Omega_r \cdot R}{z}$$

(6)
where $\lambda_i$ is a constant variable, $\Omega_r$ is the rotor angular speed, $R$ is the radius of VST rotor and $z$ in radian per seconds shows speed of the wind. Pitch control system uses $\lambda$ to be the intermediate control parameter, by adjusting the value of $\beta$ to achieve the desired $C_p(\lambda, \beta)$ [12].

The majority of VST’s in wind farms are equipped with DFIG’s (as shown in figure 3) due to their advantages over other VST generators (VSTG’s). The power factor control can be implemented in this system because of their ability of decoupling the control of active power and reactive power by controlling the terminal voltages [13]. For noise free power at the output, direct-quadrature synchronous frame commonly known as d-q axis reference frame is utilized, where d-axis is aligned with the stator flux space vector. By using this space vector control technique, the output active and reactive power from the stator and rotor can be calculated.

\[
\begin{align*}
\begin{bmatrix}
\phi_{ds} \\
\phi_{qs}
\end{bmatrix} &= L_s \begin{bmatrix} i_{ds} \\
i_{qs}\end{bmatrix} + L_m \begin{bmatrix} i_{dr} \\
i_{qs}\end{bmatrix} \\
\begin{bmatrix}
\phi_{dr} \\
\phi_{qr}
\end{bmatrix} &= L_r \begin{bmatrix} i_{dr} \\
i_{qr}\end{bmatrix} + L_m \begin{bmatrix} i_{ds} \\
i_{qs}\end{bmatrix}
\end{align*}
\]

(7) \hspace{2cm} (8)

where, $(\phi_{ds}, \phi_{qs})$ are d-q axis components of stator flux in synchronous frame and $(\phi_{dr}, \phi_{qr})$ are d-q axis components of rotor flux in synchronous reference frame. $(i_{ds}, i_{qs})$ and $(i_{dr}, i_{qr})$ are current components for stator and rotor in d-q axis synchronous frame. Stator voltage $(V_{ds}, V_{qs})$ and rotor voltage $(V_{dr}, V_{qr})$ is given in (9) and (10).

\[
\begin{align*}
\begin{bmatrix}
V_{ds} \\
V_{qs}
\end{bmatrix} &= R_s \begin{bmatrix} i_{ds} \\
i_{qs}\end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \phi_{ds} \\
\phi_{qs}\end{bmatrix} + \Omega_e \begin{bmatrix} 0 \\
-\phi_{qs}\end{bmatrix} \\
\begin{bmatrix}
V_{dr} \\
V_{qr}
\end{bmatrix} &= R_r \begin{bmatrix} i_{dr} \\
i_{qr}\end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \phi_{dr} \\
\phi_{qr}\end{bmatrix} + \left[\Omega_e - \Omega_r\right] \begin{bmatrix} 0 \\
-\phi_{qr}\end{bmatrix}
\end{align*}
\]

(9) \hspace{2cm} (10)

$R_s$ and $R_r$ are the stator and rotor resistance where $\Omega_e$ is angular velocity of stator magnetizing flux.

\[
\begin{align*}
P_s &= \frac{3}{2} \left[ V_{ds} i_{ds} + V_{qs} i_{qs} \right] \\
Q_s &= \frac{3}{2} \left[ V_{qs} i_{ds} - V_{ds} i_{qs} \right]
\end{align*}
\]

(11) \hspace{2cm} (12)

Figure 3. Pitch Servo mechanism.
\[ P_r = \frac{3}{2} \left[ V_{dr}i_{dr} + V_{qr}i_{qr} \right] \]  
\[ Q_r = \frac{3}{2} \left[ V_{qr}i_{dr} - V_{dr}i_{qr} \right] \]

where, \( P_s \) represents active power and \( Q_s \), the reactive power of the stator. Similarly on the rotor side of the DFIG, active and reactive power is given by \( P_r \) and \( Q_r \) respectively [14]. In the same synchronous frame, the electromagnetic torque \( T_e \) developed by the DFIG is given by,

\[ T_e = \frac{3}{2} P \frac{L_m}{L_s} \left[ \Phi_{ds}i_{qr} - \Phi_{qs}i_{dr} \right] \]

where, \( L_m \) and \( L_s \) are magnetizing and stator self-inductance. Pairs of poles number is given by \( P \). The mechanical equation governing VST can be simply written as follows,

\[ J (\Omega_r) = -k\Omega_r + T_a - N_g - T_e \]

where \( \Omega_r \) is the rotor angular speed, \( k \) is the coefficients of viscous friction of the low-speed shaft, \( N_g \) is the gearbox ratio, \( T_e \) is the electric torque of the generator. Depending upon \( C_p(\lambda, \beta) \), the torque that the VST extracts from the wind is \( T_a \) [15].

3. Control Strategies

Well-developed control methods ideally suit the operation of variable speed variable pitch turbine (VSVPT) system, especially when it comes to blade pitch \( \beta \) control enhancing the efficiency power generating system. \( \beta \) angle adjustment of the turbine servo architecture is made with precision, otherwise uncontrollable forces occur and the architecture gets damaged [16]. To accomplish this task many conventional, logical and modified versions of servo \( \beta \) angle motion control methods have been proposed.

In this study, the pitch control strategies are used to maximize wind power capture in Regime 3 of the VST system. Regime 3 is encountered when the WS’s are high enough that the VSVPT must limit the fraction of the wind power captured so that safe electrical and mechanical loads are not exceeded. It is achieved by effectively controlling the \( \beta \) angle of the WT blades. The conventional Proportional (P) and Derivative (D) based servo pitch controllers are firstly applied to regulate the rotor speed of VSVPT by adjusting the \( \beta \) angle and then Logical Fuzzy technique is applied for further analysis. Optimum variable speed control can enhance the quality of WT captured power by effectively operating the servo motion.

3.1. Conventional Proportional Integral (PI) and Derivative (D) Gain Control

PI and PID controllers are popular and powerful tools used in speed and power regulation because of their robust performance and simplicity [17, 18]. The PI(D) controller has a control loop which has feedback mechanism, commonly used in VSVPT control operations. Moreover, PI is a particular form of PID, which is widely used since D-action is not used very often [19]. A PI(D) controller corrects the error \( e(t) \) between the output and the desired input and it produces a control signal \( x(t) \) which reaches the plant output to the desired input. Proportional \( (P) \), Integral \( (I) \) and \( D \) modes are used in PI(D) operation The \( P \) term in the control algorithm applies appropriate proportional changes for error to the control output. The second \( I \) term examines the process variable over time and offset of set point and then corrects the output if necessary. D control monitors the rate of change of process variable and accordingly changes the output when there are unusual changes. The differential equation of PI(D) controller is described as in (17) where \( K_p \), \( K_i \) and \( K_d \) are \( P \), \( I \) and \( D \) gains, respectively [20-22].

\[ x(t) = K_p e(t) + K_i \int_0^t e(t) \, dt + K_d \frac{de(t)}{dt} \]  

The structure of PI(D) controller is shown in figure 4. In order to control \( \beta \) angle of VSVPT system, \( K_p \), \( K_i \) and \( K_d \) are tuned using Auto Tuning (AT) method as there is no absolute tuning methodology
[23, 24]. Figure 5 and figure 6 shows the closed loop stability of the system with precise values of P, I and D Gains. AT routines for PI(D) controllers are highly desirable characteristic for VSVPT operation. Such applications reduce the amount of time required to adjust the controller gain parameters for a given energy conversion process, as well as the expertise required for such objective [25, 26]. Depending upon the applied WS and automatically tuning robust PI(D) controller in MATLAB, the ideal response gain values show $K_P = 0$, $K_I = 1$ and $K_D = 0$ for overshoot = 0% which is less than 20 % with amplitude 1 and, in case of considered VSVPT system, tuned gains for P, I and D equals for $K_P = 5101373152.6025$, $K_I = 1.038607968293523 e^{+17}$ and $K_D = -1.0371$ with overshoot value = 5.71% with amplitude peak value of 1.06 much closer to 1 are achieved. These Gain coefficient values are further considered to analyse the effects of $\beta$ angle on output power ($P_m(z)$) and rotor speed ($\Omega_r$) of WE generation system.

![Figure 4. PI(D) controller structure](image)

![Figure 5. Ideal PID Tuned Responses](image)
3.2. Logical Fuzzy Control Inference (FCI)

The Fuzzy Control Inference (FCI) is a non-linear method that uses fuzzy rules to model the aspects of human knowledge without employing precise analysis [27]. The imprecise knowledge is effectively modelled through the use of linguistic values and Membership Functions (MF’s) [28]. A fuzzy rule base contains a set of fuzzy If–Then rules along with connectors “OR” or “AND” for drawing essential decision rules, MF’s and fuzzy logical operations [29, 30]. The servo operation in VSVPT- β angle control system can effectively be controlled by this methodology where the use of fuzzy rules ensures that the operating status of the WE generation system remains within the desired range of operation. Proposed fuzzy control model as shown in figure 7 automatically adjusts the β angle to measure the rotor speed so as to increase power production. Fuzzy control system as shown in figure 8 is based on the change in rotor angular speed (ΔΩr) from its reference value in relation with varying WS (m/s). Ωm is the measured speed of DFIG and Ωreff is the desired or reference rotor speed. In the proposed logical fuzzy system, seven fuzzy sets have been considered for variables: Positive Large (PL), Positive Medium (PM), Positive Small (PS) and Zero (ZO), Negative Large (NL), Negative Medium (NM), and Negative Small (NS). Here, Table I lists the control rules for the input Ωr and output variable (β angle). The interpretation for fuzzy β angle control is straightforward, because if the wind wheel speed is below the nominal value, the angle decreases and if it is above, the β angle increases. Ωr and ΔΩr has a degree of membership represented by their MF’s µ(Ωr) and µ(ΔΩr) respectively. Each membership value is closed in a unit interval [0, 1]. Based on Table I, Table II reflects variation in output β pitch angle related to the MF’s of wind wheel speed Ωr and change in the wind wheel speed ΔΩr respectively. Interpreting the combinations of µ(Ωr) and µ(ΔΩr) where, if the membership of rotor speed is high and also the membership of change in rotor speed is high then as a result, the output operation would be negative large which indicates that the pitch control servo system will stop the WT operation thereby pushing it to the safe state. Likewise, the fuzzy If-then rule as given in Table II, characterizes other operational stages of WT system. The results of the proposed FCI shows superiority over the conventional PI(D) methods to generate optimized power under full load conditions by maintaining relative β angle.

![Logical Fuzzy Control Inference](image)

3.2. Logical Fuzzy Control Inference (FCI)

![Fuzzy control model](image)
\[ \Omega_r = \Omega_{ref} - \Omega_m \]  
\[ \Delta \Omega_r = \Omega_{r_n} - \Omega_{r_{n-1}} \]  

Figure 8. Fuzzy control system

Table I. If-Then rule for \( \beta \) angle in response to \( \Omega_r \) and \( \Delta \Omega_r \).

| \( \Omega_r \) | \( \beta \) angle | \( \Delta \Omega_r \) | \( \beta \) angle |
|-------------|----------------|----------------|----------------|
| NL          | NL             | NL             | NL             |
| PL          | PL             | PL             | PL             |
| ZO          | ZO             | ZO             | ZO             |

Table II. \( \beta \) pitch angle based servo output

| \( \mu(\Omega_r) \) | \( \mu(\Delta \Omega_r) \) | NL | NM | NS | ZO | PS | PM | PL |
|-----------------|-----------------|----|----|----|----|----|----|----|
| NL              | PL              | PL | PL | PL | PM | PM | PS | ZO |
| NM              | PL              | PM | PM | PM | PS | ZO | NS | NM |
| NS              | PL              | PM | PS | PS | ZO | NS | NM | NM |
| ZO              | PM              | PM | PS | ZO | NS | NS | NM | NL |
| PS              | PM              | ZO | NS | NS | NM | NL | NL | NL |
| PM              | PS              | ZO | NS | NM | NM | NL | NL | NL |
| PL              | ZO              | NS | NM | NM | NL | NL | NL | NL |

4. Materials and Methods

The WT pitch servo system with DFIG was modelled. The rated power of the WE conversion system was chosen to be 3 MW. The PI, PID and fuzzy control techniques were developed and implemented to analyse the performance of VSVPT system. The control was incorporated into 40 seconds dynamic simulations with base WS of 14 m/s with some rough turbulence. The impact of variation in pitch angle as a result of control algorithms showed promising results. The whole VSVPT control system was developed and simulated in MATLAB/SIMULINK environment where FCI delivered power efficient results.

5. Results and Analysis

Commonly, the best way to extract the maximum power from the wind is through the VSVPT’s with pitch angle \( \beta \) control. Variation in blade angle \( \beta \) in response to the varying wind profile operates the servo motor in order to achieve the maximum efficiency of the WT system. The developed VSVPT system accepts wind velocity regulating the speed of rotor as inputs and outputs the output pitch angle generating optimum power. The results in the figure 9 (a-d) shows the wind wheel speed, extracted power and blade pitch angle in response to the applied wind profile.
Figure 9. Schemes showing the results: (a) The WS condition. (b) Wind wheel speed (c) The Rated Power (d) The Pitch angle variation.

In response to the base wind condition that is 14 m/s with a rough turbulence case, the responses of the WT system for 40 seconds simulation period are explained. The changing characteristics in the speed of wind wheel produces corresponding level of achieved power and changes in the pitch angle. In acknowledgement to the high level of applied wind during the first few instances of time, the FCI based controller has produced the maximum efficiency in terms of power as compared to the PI and PID controllers. Likewise, the pitch change up to 9° in case of Fuzzy algorithm can be observed in figure 9(d). Generally, the increase and decrease in WS, maximize and lessen the rotor speed, power and pitch correspondingly. As can be observed from the figure 9 (c), the power levels achieved in case of Fuzzy Algorithm shows superiority. Regarding the PI and PID innovations, the responses are much more identical but not as ideal as in matter of proposed FCI. Although, the results are in operational limits of 3 MW WT but the proposed fuzzy technique delivers promising results for regime 3 of the WT operation. For the systems behaviour to be more clearly observed, results of designed PI, PID and Fuzzy algorithms are presented accordingly. All the three rules show different behaviour in VSVPT operation. The blade angle ß as shown in figure 9 (d) varies to operate the system so as to extract maximum power from the available wind. During the range of operation, FCI has achieved optimum power level effectively between per unit rotor speed of 1.2 to 1.35, whereas PI(D) controller couldn’t operate at that level during that specific time interval as shown in figure 9 (b). It is also obvious from figure 9 (c) that FCI starts operating at optimum power within the first 10 seconds of simulation period where the conventional PI(D) controller is still not has achieved the desired maximum level of power. promising results.

6. Analysis of proposed FCI with conventional PI and PID robust controllers
The overall behaviour of the system can be recognized when the modelled turbine system operates under full load conditions thus generating the maximum and stable power under applied turbulent wind conditions. The results depict that proposed FCI technique is much more robust and efficient than as compared to the conventional PI(D) control methods. Under the regime 3 operating conditions PI and PID controllers delivered identical results however during the last 10 seconds simulation time period, PID controller showed superiority because of additional D-operation. In the achieved results, FCI has shown dominating results. Achieved results explains the difference between proposed FCI and conventional control methods. In connection with conventional controllers, FCI shows robustness in terms of its performance. It is seen that the pitch angle has an effect on the turbine performance, and for a given WS and rotor speed, there is an optimum pitch angle which gives maximum power. As shown in figure 9 (d), the optimum angle is 8.8° for which the turbine has achieved the optimum power. However, in case of conventional controllers the maximum pitch angle is 6.9°. In regime 3 when wind conditions are risky, flexibility in pitch servo control operation provides the system sustainable endurance in order to operate at optimum power levels. The proposed FCI technique as a solution to region 3 operating conditions where the system is facing large disturbances, delivers safety to the system by achieving optimum pitch and power levels efficiently when compared with the PI(D) methods hence showing robustness of the VSVPT control system.

7. Conclusion
Pitch angles (measured from the theoretical 0° position) can have a significant impact on the power production of the VSVPT unit. This paper has presented comparison of proposed FCI technique with various pitch control methods based on conventional PI and PID algorithms. Comparative results have validated the higher performance nature of the robust FCI pitch angle algorithms. The model considered with a varying wind profile shows the FCI technique as compared to the PI and PID controllers is better for the durability of WT dynamic system. The performance of the Fuzzy system shows that applied load on the system is economical. For every WT unit, generation of great amount of power from the available wind is the main objective. In this case the FCI algorithm has shown economical and energy efficient performance then as in matter of PI and PID control techniques. The superiority of FCI has been proven by its performance. With better control of the β pitch angle, VSVPT system will be protected from damaging WS’s in a better manner. This will eventually increase the life time of VSVPT system and reduce the costs of energy production.

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