Fuzzy Logic-based Digital Hydraulics Control of Blade Pitch Angle in Wind Turbines

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Abstract. The pitch control system is generally employed in a wind turbine to mitigate load and maintain uniform power generation at above-rated wind speed regions. The hydraulic system has more power to weight ratio and so it is incorporated in the pitch system of large scale wind turbines. Some of the issues related to the usage of conventional valves in the Hydraulic Pitch System (HPS) are: internal leakage, throttling losses, high power loss, less fault-tolerant, requires high manufacturing tolerance, and more sensitive to contamination. To overcome these issues, digital hydraulics technology should be introduced as Digital Hydraulics Pitch System (DHPS). Commercially, Proportional Integral Derivative (PID) controller is used as a pitch controller but these controller performances don’t hold good when excessive disturbance or change in operating point occurs in the system. So, heuristic-based Fuzzy Logic Controller (FLC) is preferred which can surpass the PID problems. In this paper, a heuristic FLC based control strategy is proposed for a novel DHPS configuration to control the pitching action. The simulation model of DHPS is developed and system simulations are conducted. The comparative study on the effectiveness of FLC for DHPS and conventional valve controlled HPS is conducted.

1. Introduction

The necessity for renewable energy has started increasing exponentially due to the harmful effects created by non-renewable energy sources over the environment. On comparing the renewable energy sources, wind energy seems to be the most promising source of electric energy [1-3]. Since, Wind Turbine (WT) is given more priority than a conventional power plant by many countries, the technology related to WT has started to increase. To generate optimal power and also to safeguard the WT during high wind speeds, Pitch Control System (PCS) and yaw control system are mostly preferred [4-6]. Generally, PCS is employed at above-rated wind speed condition to maintain the uniform power generation and to mitigate erratic blade loads [7, 8]. The two types of PCS used in WT are: electro-mechanical and Hydraulic Pitch System (HPS). Electric motors are used as pitch actuators in case of an electro-mechanical pitch system whereas hydraulic cylinder/motor are used in the case of HPS. Since HPS are more robust to disturbance and has more power to weight ratio than its counterpart, HPS is mostly preferred in large scale WT [9, 10]. The advantage of using the hydraulic motor as the end actuator in HPS over the hydraulic cylinder is that the final pitch angle is directly proportional to the displacement of the hydraulic motor [11, 12]. Conventionally, pump control, and valve control technique are preferred in HPS [13]. The reason for considering Valve Controlled (VC) HPS to be better because it has higher bandwidth than the pump control HPS [14]. Conventional
VCHPS uses proportional or servo valves to control flow rate and uses a directional valve to control the direction of the fluid [15] as shown in figure 1.

![Figure 1. Conventional valve controlled hydraulic pitch system](image1)

These valves have few drawbacks like internal leakage, throttling losses, high power loss, less fault-tolerant, requires high manufacturing tolerance, high cost, and more sensitive to contaminations [16-18]. The drawback of the conventional valve controlled HPS can be overcome by implementing Digital Hydraulics (DH) technology. The DH uses a 2/2 hydraulic valve arranged in parallel combination along with various sizes of orifice known as Digital Flow Control Unit (DFCU) as shown in figure 2. Based on positioning the DFCU in the hydraulic system, DH can be categorized into few types such as: digital displacement motor and pump, switching control, and parallel valve technology [19, 20]. Here the digital motor concept is implemented. While designing the DFCU, the sizing of the orifice plays a vital role. The different methods utilized for sizing the orifice are discussed in [19, 21].

![Figure 2. Digital Flow Control Unit](image2)

Though there are many advantages in the DH, the controllability of DH is still a tedious task [16, 23]. The different valve actuation methods that are implemented in the DH system are: Pulse Width Modulation (PWM), Pulse Frequency Control (PFC), Modified Pulse Width Modulation (MPWM), Pulse Number Modulation (PNM), and Pulse Code Modulation (PCM) [19, 21, 24]. P + PID controllers were incorporated in [24] to analyze the robustness in the stability of DH which is subjected to unknown load and results show that the controller has better performance. In [25] a novel fine positioning method was developed where four DFCU were used which resulted in the accurate positioning of the hydraulic system. Zero-Flowrate-Switching (ZFS) control method makes the valve to turn off when the flow rate through the valve is zero [26]. The output of ZFS was found to be effective. Though different control techniques have opted in DH, still DH control has a large scope to improve the controllability due to the extreme non-linearity of 2/2 valves. To improve the controllability by resolving the non-linearities in the system, heuristic-based Fuzzy Logic Controller (FLC) is implemented in this paper.

The contribution of this paper involves the development of a novel DHPS for wind turbine and also FLC. The output of FLC is DFCU pair valve state selection which results in varying the flow rate and also controlling the direction of the hydraulic fluid by using DFCU so that the required pitching action takes place at the pitch actuator to achieve the appropriate pitch angle. This paper is structured as follows: Section 2 presents a description of the system. Section 3 details the modeling of the
proposed system and FLC. Section 4 reveals the simulation results and discussion. Finally, section 5 discusses the conclusion.

2. System description

Figure 3 illustrates the proposed novel DHPCS which consists of FLC and DHPS. The DHPS consists of a fixed displacement pump driven by an electric motor. As discussed earlier the DFCU consist of 2/2 valves and orifice which is attached at the end of each valve.

![Diagram](image-url)

**Figure 3.** Proposed digital hydraulic pitch control system
The sizing of the orifice was carried out using the binary series method \([2^0, 2^1, 2^2, \ldots, 2^n]\). Since five valves are used in each DFCU, the DFCU is called 5-bit DFCU and it is possible to achieve \(2^n-1\) states. In this proposed configuration \(2^{-1}=31\) states with different flowrates for each state can be achieved as shown in table 1. DFCU AT and PA are connected at A port of the hydraulic motor and the DFCU PB and BT are connected at the B port of the hydraulic motor. Based on the required direction of rotation of the hydraulic motor either DFCU PA and BT pair or DFCU PB and AT pair is triggered so that clockwise/anticlockwise rotation is achieved. The pitch angle generated at the hydraulic motor is sensed by an angular sensor and the data are fed to the FLC.

| Table 1. DFCU pair valve states |
|---------------------------------|
| \(V_1\) | \(V_2\) | \(V_3\) | \(V_4\) | \(V_5\) | States | Flow |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 0 | 0 | 0 | 0 | 0 | 1 | 1 | Q1 |
| 0 | 0 | 0 | 1 | 0 | 0 | 2 | Q2 |
| 0 | 0 | 0 | 1 | 1 | 3 | 3 | Q3 |
| 0 | 0 | 1 | 0 | 0 | 0 | 4 | Q4 |
| . | . | . | . | . | . | . |
| . | . | . | . | . | . | . |
| 1 | 1 | 1 | 1 | 1 | 31 | Q31 |

3. System modeling
In this section, the blade load model and FLC are modeled for the proposed DHPCS. The closed-loop control strategy of DHPCS is shown in figure 4. FLC was chosen for the proposed configuration due to its advantage over the Proportional Integral (PI) and Proportional Integral Derivative (PID) [27]. The inputs to the FLC are blade load \(P_t\) and pitch angle error \(\beta_e\) where \(\beta_e\) is obtained from equation 1.

\[
\beta_e = \beta_{\text{ref}} - \beta_g
\]  

where \(\beta_{\text{ref}}\) is the pitch angle reference and \(\beta_g\) is the pitch angle generated. The output of the FLC is states.

![Figure 4. Block diagram of proposed digital hydraulic pitch control system](image)

3.1 Blade load model
The load that is developed over the blades due to varying wind speed is an important parameter to be considered while designing DHPS since the DHPS should overcome the blade load \(P_t\) and has to achieve the required pitch angle. The \(P_t\) is arrived from [28] as shown in equation 2.

\[
P_t = -390 + 170.9v - 92.96\beta - 0.39v^2 - 0.24v\beta - 3.73\beta^2
\]  

The different blade loads for varying pitch angle and wind speed are shown in table 2 which is obtained by substituting the wind speed and pitch angle values in equation 2. The blade load model is
developed by using equation 2 in Matlab/SIMULINK and the developed model will generate the loads which the DHPS should overcome.

### Table 2. Blade load under different pitch angle and wind speed [28]

| Wind speed (m/s) | Pitch angle (deg) |
|------------------|------------------|
|                  | 0°               | 5°               | 10°              |
| 11               | 1428 Nm          | 867 Nm           | 141 Nm           |
| 12               | 1600 Nm          | 1020 Nm          | 280 Nm           |
| 13               | 1765 Nm          | 1182 Nm          | 445 Nm           |
| 14               | 1929 Nm          | 1335 Nm          | 574 Nm           |
| 15               | 2114 Nm          | 1500 Nm          | 730 Nm           |
| 16               | 2266 Nm          | 1672 Nm          | 900 Nm           |
| 17               | 2420 Nm          | 1824 Nm          | 1035 Nm          |
| 18               | 2554 Nm          | 2000 Nm          | 1206 Nm          |
| 19               | 2707 Nm          | 2138 Nm          | 1355 Nm          |
| 20               | 2830 Nm          | 2307 Nm          | 1547 Nm          |

#### 3.2 Fuzzy logic controller

FLC is based on the rules which are helpful when the dynamics of the system and also the complete nonlinearities of the system are not known. Similar to human beings making decisions, FLC applies reasoning and so the rules possess the knowledge of an expert of the system. The main advantage of FLC is that a mathematical description of the system which is to be controlled is not required. Fuzzy Logic Toolbox™ which is available in Matlab/SIMULINK. Generally, there are three stages in the FLC and they are fuzzification, fuzzy rules, and defuzzification. In the fuzzification process, the inputs are converted into fuzzy sets using linguistic terms and membership functions. Inputs and output use Triangular Membership Functions (TMF) which is shown in figure 5. TMF is highly sensitive when variables arrive at zero value [29]. Fuzzy rules are assigned as shown in table 2, where if and then statements are used to coin the rules like $IF \ x_1=A_1 \ and \ x_2=A_2 \ THEN \ y=B$. The last process in the FLC is defuzzification where the fuzzy sets are converted into precise action with real values.

![Figure 5 Triangular membership function for inputs and output](image-url)
Table 3. Fuzzy rules

| Blade load | Pitch angle error |
|------------|-------------------|
| NH         | NH               | NM | NS | ZO | PS | PM | PH |
| NH         | NH               | NM | NM | ZO | PM | PH | PH |
| NM         | NH               | NM | NM | ZO | PM | PM | PH |
| NS         | NM               | NM | NS | ZO | PS | PM | PM |
| ZO         | NM               | NS | NS | ZO | PS | PS | PM |
| PS         | NM               | NM | NS | ZO | PS | PM | PM |
| PM         | NH               | NM | NM | ZO | PM | PM | PH |
| PH         | NH               | NM | NM | ZO | PM | PH | PH |

4. Simulations results and discussion
The FLC performance is tested by implementing it in the DHPS. Simulations were conducted from 3 sec to 10 sec (since it took 0-3 sec for the DHPCS to initiate). Reference pitch angle data of a 2MW wind turbine was obtained from [30]. These data reveal the exact pitch angle the blade should set in the wind turbine to extract optimal power and also to mitigate blade load. Here we are not going to discuss the optimal power generated and also load mitigated. Here we are going to discuss the performance of controller tracking the reference pitch angle. A random wind profile as shown in figure 6(a) was given as an input to the reference pitch angle model to generate the required $\beta_{ref}$. Further, the states generated by the FLC is shown in figure 6(b).

The reference pitch angle generated is shown in figure 6(c) which was obtained by giving figure 6(a) wind profile as input. Figure 6(c) shows the comparison of $\beta_g$ to $\beta_{ref}$. The $\beta_g$ follows the same trend as $\beta_{ref}$. At the same time, there is a lag in terms of magnitude between $\beta_{ref}$ and $\beta_g$ which is due to the nonlinearities exist in the DHPS. The pitch angle error has more influence over the states, if the error is more, then higher states are assigned to DFCU so that the high flow rate is attained by DFCU to compensate the error. For more pitch error, higher states values are assigned which can be observed in figure 6(d). The maximum pitch error observed was $1.009^\circ$ as indicated in figure 6(d). The minimum error shows that the FLC has a better tracking ability which was developed for DHPS. Since the wind speed is drastically changing, FLC plays a vital role in tracking the pitch angle at all conditions. Future work involves reducing the lag so that the tracking performance can be improved and also to reduce the hydraulic system initiation lag.
Figure 6. DHPCS response
5. Conclusion
The hydraulic pitch system delivers high power to weight ratio to mitigate load and maintain uniform power generation. In this paper, Digital hydraulics technology is implemented in a hydraulic pitch system to achieve the same performance of proportional or servo valve controlled system. The output of the fuzzy logic controller selects the DFCU pair and also the states to achieve the required pitch angle. The results show the controller has better tracking ability and the maximum pitch error observed was 1.009°. The model was tested for various wind patterns and the output was found to be effective. So by implementing the proposed DHPCS, cost-effective, highly robust, fault-tolerant, and high response pitch systems can be established in wind turbines.

References
[1] Connor B, Iyer S N, Leithead W E, and Grimble M J 1992 Control of a horizontal axis wind turbine using H infinity control. In Proceedings of the First IEEE Conference on Control Applications, 117-122
[2] Sholapurkar R B and Mahajan Y S 2015 Review of wind energy development and policy in India. Energy Technology & Policy. 2 122-132
[3] Petersen E L 2017 In search of the wind energy potential. Journal of Renewable and Sustainable Energy. 9 052301
[4] Yuan Y and Tang J 2017 On advanced control methods toward power capture and load mitigation in wind turbines. Engineering. 3 494-503
[5] Tong W 2010 Wind power generation and wind turbine design. WIT press United kingdom
[6] Njiri J G and Soeffker D 2016 State-of-the-art in wind turbine control: Trends and challenges. Renewable and Sustainable Energy Reviews. 60 377-393
[7] Fernando D B, Hernán D B and Ricardo J M 2006 Wind turbine control systems: principles, modelling and gain scheduling design
[8] Menezes E J N, Araújo A M and da Silva N S B 2018 A review on wind turbine control and its associated methods. Journal of cleaner production. 174 945-953.
[9] Tong W 2010 Fundamentals of wind energy. WIT Press United kingdom.
[10] Yin X X, Lin Y G, Li W, Gu Y J, Lei P F and Liu H W 2015 Adaptive back-stepping pitch angle control for wind turbine based on a new electro-hydraulic pitch system. International Journal of Control. 88 2316-26.
[11] Yin X X, Lin Y G, Li W, Gu Y J, Wang X J, and Lei P F 2015 Design, modeling and implementation of a novel pitch angle control system for wind turbine. Renewable Energy. 81 599-608.
[12] Yin X X, Lin Y G, Li W, Liu H W and Gu Y J 2015 Adaptive sliding mode back-stepping pitch angle control of a variable-displacement pump controlled pitch system for wind turbines. ISA transactions. 58 629-634.
[13] Lei X, Ni M, Li D, and Ma Y 2011 Study on simulation of digital pump-control cylinder position control system. Procedia Engineering. 16 729-736.
[14] Turner C W, Babbitt G R, Balton C S, Raimao M A and Giordano D D 2004 Design and control of a two-stage electro-hydraulic valve actuation system. SAE transactions. 833-846.
[15] Yin X X, Lin Y G, Li W and Gu Y J 2014 Integrated pitch control for wind turbine based on a novel pitch control system. Journal of Renewable and Sustainable Energy. 6 043106.
[16] Laamanen M S A and Vilenius M 2003 Is it time for digital hydraulics. In eighth Scandinavian international conference on fluid power.
[17] Scheidl R, Linjama M and Schmidt S 2012 Is the future of fluid power digital?. Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering. 226 721-723.
[18] Laamanen A, Siivonen L, Linjama M and Vilenius M 2004 Digital flow control unit—an alternative for a proportional valve?. In Bath Workshop on Power Transmission and Motion Control, Professional Engineering Publishing. 297
[19] Linjama M 2011 Digital fluid power: State of the art. *In 12th Scandinavian International Conference on Fluid Power*. 18-20.

[20] Merrill K, Holland M, Batdorff M and Lumkes Jr J 2010 Comparative study of digital hydraulics and digital electronics. *International journal of fluid power*. **11** 45-51.

[21] Kalaiarassan G and Krishnamurthy K 2019 Digital hydraulic single-link trajectory tracking control through flow-based control. *Measurement and Control*.

[22] Paloniitty M, and Linjama M 2018 High-linear digital hydraulic valve control by an equal coded valve system and novel switching schemes. *Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering*. **232** 258-269.

[23] Pedersen N H, Johansen P and Andersen T O 2018 Challenges with respect to control of digital displacement hydraulic units

[24] Linjama M, Huova M and Huhtala K 2016 Model-based force and position tracking control of an asymmetric cylinder with a digital hydraulic valve. *International Journal of Fluid Power*. **17** 163-172.

[25] Huova M, Linjama M, Siivonen L, Deubel T, Försterling H, and Stamm E 2018 Novel Fine Positioning Method for Hydraulic Drives Utilizing On/Off-Valves. *In BATH/ASME Symposium on Fluid Power and Motion Control*. 46

[26] Peng S 2017 An Zero-Flowrate-Switching (ZFS) Control Method Applied in a Digital Hydraulic System. *In Proceedings of 15th Scandinavian International Conference on Fluid Power*. 172-177.

[27] Eker I and Torun Y 2006 Fuzzy logic control to be conventional method. *Energy conversion and management*. **47** 377-394.

[28] Wang C S and Chiang M H 2016 A novel pitch control system of a large wind turbine using two-degree-of-freedom motion control with feedback linearization control. *Energies*. **9** 791.

[29] Eltamaly A M and Farh H M 2013 Maximum power extraction from wind energy system based on fuzzy logic control. *Electric Power Systems Research*. **97** 144-150.

[30] Zhou F and Liu J 2018 Pitch controller design of wind turbine based on nonlinear PI/PD control. *Shock and Vibration*.