FUZZY LOGIC BASED DIGITAL HYDRAULICS CONTROL OF BLADE PITCH ANGLE IN WIND TURBINES

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Abstract. Pitch control system is generally employed in wind turbine to mitigate load and maintain uniform power generation at above-rated wind speed regions. 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 Hydraulic Pitch System (HPS) are: internal leakage, throttling losses, high power loss, less fault-tolerant, requires high manufacturing tolerance and more sensitive to contamination. In order 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 pitch controller but these controller performance doesn’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 has the ability to surpass the PID problems. In this paper, heuristic FLC based control strategy is proposed for a novel DHPS configuration to control the pitching action. 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. Keywords: Wind turbine, Pitch control, Fuzzy logic controller, Digital hydraulics

1. INTRODUCTION
The need for renewable energy has started to exponentially increase due to the harmful effects created by the non-renewable energy sources (fossil fuel and coal) over the environment. Among the renewable energy sources, wind energy is the most promising source of electric energy [1, 2, 3]. Since, Wind Turbine (WT) is given more priority than conventional power plant by many countries, the technology related to WT has started to increase. In order to generate optimal power and also to safe guard the WT during high wind speeds, Pitch Control System (PCS) and yaw control system are mostly preferred [4, 5, 6]. Generally, PCS is employed at above rated wind speed condition to maintain uniform power generation and to mitigate erratic blade loads [7,8]. Basically the two types of PCS used in WT are: electro-mechanical and Hydraulic Pitch System (HPS). Electric motors are used as pitch actuator in case of electro-mechanical pitch system where as hydraulic cylinder/motor are used in 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 hydraulic motor as the end actuator in HPS over hydraulic cylinder is that the final pitch angle is directly proportional to 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 HPS to be better because, it has higher bandwidth than the pump control HPS [14]. Conventional valve controlled HPS uses proportional or servo valves to control flow rate and also uses directional valve to control the direction of the fluid as shown in

![Figure 1. Conventional valve controlled hydraulic pitch system [15]](image-url)
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 [16,17,18]. The drawback of the conventional valve controlled HPS can be overcome by implementing Digital Hydraulics (DH) technology in HPS. DH uses 2/2 hydraulic valve arranged in parallel combination along with various sizes of orifice known as Digital Flow Control Unit (DFCU) as shown in (2). Based on positioning the DFCU in the hydraulic system, DH can be categorised into few types such as: digital displacement motor and pump, switching control and parallel valve technology [19, 20]. Here digital motor concept is implemented. While designing the DFCU, sizing of orifice play a vital role. The different methods utilized for sizing the orifice are to attain the varying flow rates are discussed in [19, 21].

![2/2 hydraulic valve and Orifice](image)

**Figure 2** Digital Flow Control Unit

Though there are many advantages in DH, the controllability of DH is still a tedious task [16, 23]. The different valve actuation methods that are implemented in DH system are: Pulse Width Modulation (PWM), Pulse Number Modulation (PNM), Pulse Frequency Control (PFC), Modified Pulse Width Modulation (MPWM) and Pulse Code Modulation (PCM) [19, 21, 24]. P + PID controllers were incorporated in [24] to analyse the robust stability of DH under unknown load mass and the results indicated that the controller has better tracking 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 flowrate through the valve is zero [26]. The output of ZFS were found to be effective. Though different control techniques were opted in DH, still DH control has a large scope to improve the controllability due to extreme non-linearity of 2/2 valves. In order to improve the controllability by overcoming the nonlinearities, 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 the description of Digital Hydraulic Pitch Control System (DHPCS). Section 4 describes the modelling of DHPCS. Section 5 gives the simulation results and discussion. Finally, conclusion are discussed in section 6.

### 2. System Description

The Figure 2 illustrate the proposed novel DHPCS which consist of FLC and DHPS. The DHPS consist of 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 valves. The sizing of orifice were carried out using the binary series method $[2^0, 2^1, 2^2, 2^3, ... 2^n]$. 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 $2^5-1=31$ states with different flowrates for each states 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 hydraulic motor either DFCU PA and BT pair or DFCU PB and AT pair is triggered so that clockwise/anticlockwise rotation are achieved. The pitch angle generated at the hydraulic motor sensed by an angular sensor and the data’s are fed to the FLC.

| V1   | V2   | V3   | V4   | V5   | States | Flow |
|------|------|------|------|------|--------|------|
| 0    | 0    | 0    | 0    | 1    | 1      | Q_1  |
| 0    | 0    | 0    | 1    | 0    | 2      | Q_2  |
| 0    | 0    | 0    | 0    | 1    | 3      | Q_3  |
| 0    | 0    | 1    | 0    | 0    | 4      | Q_4  |
|      |      |      |      |      | 5      | Q_5  |
|      |      |      |      |      | 6      | Q_6  |
|      |      |      |      |      | 7      | Q_7  |
| 1    | 1    | 1    | 1    | 1    | 31     | Q_31 |
3. SYSTEM MODELLING

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 (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 $P_l$ and pitch angle error $\beta_e$ where $\beta_e$ is obtained from

\begin{equation}
\beta_e = \beta_{\text{ref}} - \beta_g
\end{equation}

Here $\beta_{\text{ref}}$ is pitch angle reference and $\beta_g$ is pitch angle generated. The output of the FLC is states...
The load that is developed over the blades of the wind turbine due to varying wind speed play an important role in the pitch system since the DHPS should overcome the blade load $P_l$ and has to achieve the required pitch angle. The $P_l$ is arrived from [28] as shown in (2).

$$P_l = 390 + 170.9 \beta_e + 92.96 \beta_g + 0.39 \beta_g^2 - 0.24 \beta_e - 3.73 \beta_e^2$$

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

| Pitch Angle (°) | Wind speed (m/s) | 0°  | 5°  | 10° |
|----------------|-----------------|-----|-----|-----|
| 11             | 1428 Nm         | 867 | 141 |
| 12             | 1600 Nm         | 1020 Nm | 280 |
| 13             | 1765 Nm         | 1182 Nm | 445 |
| 14             | 1929 Nm         | 1335 Nm | 574 |
| 15             | 2114 Nm         | 1500 Nm | 730 |
| 16             | 2266 Nm         | 1672 Nm | 900 |
| 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 non lineairities of the system are not known. Similar to human beings making decision, FLC applies reasoning and so the controller rules possess expert knowledge of the system. The main advantage of FLC is that 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 fuzzification process the inputs are converted into fuzzy sets using linguistic terms and membership functions. Both the inputs and output uses Triangular Membership Functions (TMF) which is shown in (5). TMF are highly sensitive when variables arrives at zero value [29]. Fuzzy rules are assigned as shown in the table 2, where if and then statements are used to coin the rules like $\beta_g < 1 \Rightarrow 1 \Rightarrow \beta_g = 1$ $\Rightarrow 1$. 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

Table 3. Fuzzy rules

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

4. SIMULATION RESULTS AND DISCUSSION

The performance of the FLC is tested by implementing it in DHPS. Simulations were conducted from 3 sec to 10 sec (since it took 0-3 sec for the hydraulic system to initiate). Reference pitch angle data’s of a 2MW wind turbine was obtained from [30]. A random wind profile (6a) was given as an input to the reference pitch angle model to generate the required $\beta_{ref}$ which the DHPS should track.

Figure 6b 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 $\beta_g$ is due to the nonlinearities exist in the DHPS. The magnitude of error is shown in (6d) and the maximum error observed was $1.009^\circ$ which is indicated in (6d). The minimum error indicates 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 in reducing the lag so that the tracking performance can be improved and also to reduce the hydraulic system initiation lag.
5. CONCLUSION

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 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 states to achieve the required pitch angle. The results shows that the fuzzy logic controller has better tracking ability and the maximum error percentage that was observed to be 3.89%. The results were tested for various wind pattern and the output was found to be effective. So by implementing proposed DHPCS, cost effective, highly robust, fault tolerant and high response pitch system can be established in wind turbines.

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