Adaptive fuzzy Proportion Integration Differentiation control in hydraulic offshore wind turbine for optimal power extraction based on the estimated wind speed

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Abstract
In this paper, a novel fuzzy Proportion Integration Differentiation (PID) controller is proposed to extract the optimal energy from wind for a hydraulic offshore wind turbine. Firstly, in order to calculate the theoretical power, an adaptive neuro-fuzzy inference system (ANFIS) is designed for wind speed evaluation, in which the input parameters include rotor speed, rotor torque, and pitch angle, and the output parameter is the estimated wind speed. Then, the optimal power coefficient is achieved by controlling the hydraulic pump torque to tracking the optimal rotor speed, and a fuzzy PID is designed to adjust the pump displacement and to obtain the optimal hydraulic pump torque. Furthermore, aiming to meet the various output power demand, a hydraulic accumulator is utilized for storing the excess energy, and a PID controller is designed for distributing the hydraulic energy between the accumulator and the Pelton turbine. Finally, the performance of proposed controls system are confirmed by two case simulations on a 5 MW hydraulic offshore wind turbine. The simulation results show that, compared with the conventional control methods (fuzzy logical and PID controller) used in electro-hydraulic servo system, the fuzzy PID controller can provide the better tracking effect with a faster speed and a minimal steady-state oscillation. Moreover, with the use of a hydraulic accumulator, all the power fluctuations from the wind speed disturbances are damped out and the output power become controllable.

KEYWORDS
ANFIS, fuzzy PID control, hydraulic accumulator, hydraulic transmission, offshore wind turbine, wind speed estimation

1INTRODUCTION

As one of the most competitive and zero-carbon energy sources, wind energy has been developed and used widely in the past decades. The Global Wind Energy Council (GWEC) has reported that the global wind energy industry have installed 51.3 GW of new capacity in 2018, and the future outlook is strong with over 300 GW of capacity expected to be installed by 2024. The stimulation of increasing demand for electricity, offshore wind turbine has gradually attracted more attention for the plenty of
high-quality wind energy resources and the spacious sea area in comparison with the onshore wind turbine. The global offshore market has reached a total installed capacity of 23 GW, with new installations of 4.49 GW in 2018. Nowadays, multi-megawatt wind turbine has become the mainstream model, but the large mass and complex structure bring inconvenience to the operation and maintenance of offshore wind turbine. The hydraulic type offshore wind turbine is a very effective way to overcome those barriers, for the several obvious advantages: (a) The hydraulic transmission is capable to handle higher torque and nearly constant power, which is transferred by hydraulic fluid. (b) In hydraulic transmission system, energy storage and power generation equipments are placed to the floating platform; therefore, the weight of the nacelle and the cost of operation and maintenance can be saved remarkable. (c) Hydraulic offshore turbine can be easily integrated with other energy source and improve the total energy yield; for instance, wind energy and cold deep seawater resource are jointly exploited. (d) Hydraulic transmission allows the energy storage system such as Compressed Air Energy Storage (CAES), Pumped hydro storage (PHS) and hydraulic accumulator to be integrated with the offshore wind turbine to mitigate fluctuations of the output power.

There are two problems demanding prompt solution in the research of hydraulic offshore wind turbine. The first one is how to ensure the wind turbine achieve the optimum power coefficient under various wind speed conditions. In the conventional maximum power control strategies, the wind turbine is generally described as a two-mass mechanical model, and some advanced intelligent controllers such as adaptive neuro-fuzzy control, sliding mode, and adaptive robust control have been introduced extensively to regulate the electromagnetic torque, angular speed, or output power of generator and guarantee the power coefficient tracking the optimal value. However, in hydraulic wind turbine, the generator is driven by Pelton turbine rather than rotor through gear box, so the classical control approaches fails to fulfill the requirements. In Ref., aiming to achieve the maximum power coefficient, passive torque control is adopted to adjust the size of the nozzle. In Ref., the reaction torque of hydraulic pump connected with rotor in nacelle is controlled to extract maximum wind power. Unfortunately, above approaches rarely considered the intrinsic properties of hydraulic transmission system such as the uncertainty, time-variant and highly nonlinear characteristics because of the flow–pressure relationship. Therefore, the new control strategies for hydraulic offshore wind turbine is needed. In this paper, a self-adaptive fuzzy Proportion Integration Differentiation (PID) control which can adaptively adjust PID parameters online is designed to control the displacement of hydraulic pump connected with wind turbine rotor and realize the maximum wind energy capture.

Another problem is how to eliminate the effect on control precision from uncertainty in wind speed measurement. Because the speed is a main factor to the output power of wind turbine, the accurate estimation of wind speed is crucial to maximum power point tracking control. In Ref., an adaptive linear prediction method was utilized to estimate wind speed, which can be easily incorporated into maximum power control algorithm. But in this method the appropriate size of the step is necessary, and the prediction time step should be lower than the response time of the system, otherwise the optimal control will fail to work. In Ref., the wind speed is computed with the mechanical torque value through an online training neural network-based algorithm. The neural network can approximate the wind speed due to the nonlinear learning law, but which is realized at the expense of more memory space and time. Recently, the Takagi-Sugeno (T–S) fuzzy modeling with linear and nonlinear consequent parts are successfully used in many dynamical systems. Artificial neural network (ANN) has been used to estimate the wind speed fluctuation based on the fractal interpolation. The neuro-fuzzy approach was used in wind speed parameters sensitivity analysis. As a hybrid intelligent technique of ANN and T-S fuzzy inference system (FIS), adaptive neuro-fuzzy inference system (ANFIS) is able to realize the nonlinear relationships between input and output data, has been used to estimate wind turbine optimal power coefficient and farm efficiency improve the wind energy available. In this paper, ANFIS is applied in estimation of wind speed for its excellent learning capability and huge decision-making power.

The main purpose of the research conducted here is to optimize the wind energy from hydraulic wind turbine through proposed adaptive fuzzy PID control. In the control system, a new ANFIS is designed to estimate the effective wind speed, and improving the reliability of wind turbine in case of mechanical sensor failures. The effectiveness of the proposed control scheme is verified through two simulation studies. The major contributions of this paper are as follows:

1. An offshore wind turbine with an open-loop hydraulic transmission system is designed, in which the seawater is used to transfer the hydraulic power. The system consists of a hydraulic pump fixed in nacelle and other hydraulic components located at the root of tower.
2. An ANFIS method is used to accurately estimate the effective wind speed, in which the rotor torque, rotor angular speed and pitch angle are considered the inputs.
3. A standard torque control scheme is proposed to capture the maximum available power from wind. A self-adjusting hybrid fuzzy PID controller is designed to control the displacement of hydraulic pump connected with the rotor.
in nacelle, through which the real reaction torque of pump is close to the optimal expected value.

4. In order to mitigate the fluctuation of wind power and provide steady output power, a hydraulic accumulator is employed, through which the surplus energy can be effective stored and released. Additionally, the work pressure is stabilized due to the using of hydraulic accumulator, so the safety of hydraulic transmission system is well ensured.

The remaining parts of this paper are showed as follows: Firstly, the proposed system and the detailed mathematical models are described in Sections 2 and 3, respectively. Then, an ANFIS controller used to estimate wind speed and a self-adjusting hybrid fuzzy PID controller designed to realize the MPPT are developed in Section 4 and Section 5, respectively. The simulations are conducted on a 5 MW offshore wind turbine, and the results are discussed in Section 6. Finally, conclusions are drawn in Section 7.

2 | SYSTEM OVERVIEW

As shown in Figure 1, an offshore wind turbine including an open-loop hydraulic transmission system is developed. A variable displacement pump (B) is connected to the wind turbine rotor (A) in the nacelle, through which seawater is pressed and moves in the hydraulic circuit. A pressurization system (C) is attached to the spar body of the offshore wind turbine, which includes a directly coupled hydraulic booster pump and motor extracting some power from the high-pressure side of the pipeline to actuate the booster pump on the low-pressure side. The hydraulic circuit includes a hydraulic accumulator (D), a nozzle (E), and a Pelton turbine (F). Those are connected in tandem to an induction generator (G). The hydraulic transmission and power generation system located on the floating platform can lighten nacelle weight and lower installation and maintenance cost.

3 | MATHEMATICAL MODELS

3.1 | Wind turbine and hydraulic accumulator

The kinetic power $P$ and the torque $T$ captured by wind turbine are expressed as:

$$ P = \frac{1}{2} \rho_{air} \pi R^2 C_p(\lambda, \beta) v^3 $$

$$ T = \frac{1}{2} \rho_{air} \pi R^2 C_p(\lambda, \beta) v^3 / \omega $$

where $R$ is the radius of turbine blade, $\rho_{air}$ is the air density, $\omega$ is the wind turbine rotor angular speed, $v$ is the wind speed, $C_p(\lambda, \beta)$ is the power coefficient, $\beta$ is the pitch angle, $\lambda$ is the tip-speed ratio given by:

$$ \lambda = \frac{\omega R}{v} $$

$C_p(\lambda, \beta)$ is a function of $\beta$ and $\lambda$ expressed as following:

$$ C_p(\lambda, \beta) = 0.517 \left( \frac{116}{\lambda} - 0.4 \beta - 5 \right) e^{-\frac{2(\lambda + 0.08 \beta)}{\beta^3 + 1}} + 0.0068 \lambda $$

A hydraulic accumulator (D) with a fixed volume cylindrical vessel is applied to smooth out the power pulsation generated from wind speed fluctuation, which can be integrated in a floating offshore wind turbine spar supporting platform. In the accumulator (D), a piston is used to separate the seawater from the air as shown in Figure 2. In the process of hydraulic energy storage, the input flow $Q_i$ exceeds the output flow $Q_o$, the piston goes up, so the excessive hydraulic energy transforms into compressed air energy stored in accumulator. The pressure energy release process is contrary to the storage. As high energy demand comes, the input flow $Q_i$ is less than the output $Q_o$, the piston moves down, as a result, the stored energy is discharged. The compressed air volume is computed as:

$$ V_{air} = Q_i - Q_o $$
According to the ideal gas equation, the relation between temperature \( T \), pressure \( p \), and volume \( V \) of gas is given as:

\[
pV = nR_mT
\]  

(6)

where \( n \) and \( R_m \) are the number of moles and the universal gas constant, respectively.

Under a isothermal compression condition, the pressure \( p_{\text{acc}} \) of compressed air in the accumulator is calculated as:

\[
p_{\text{acc}} = \frac{p_1V_1}{V_1 - \int V_{\text{acc}}\,dt}
\]  

(7)

Furthermore, the energy \( E \) stored in accumulator is computed as:

\[
E = \int_{p_1}^{p_2} Vdp = p_1V_1 \ln \left( \frac{p_2}{p_1} \right) = p_2V_2 \ln \left( \frac{p_2}{p_1} \right)
\]  

(8)

where \( V_1, V_2 \) and \( p_1, p_2 \) present the volume and pressure of the initial and final state.

The mathematical models about other components have been described in author’s previous study.\(^{20}\)

### 3.2 Inertia dynamics

The dynamic equation between wind turbine rotor and hydraulic pump is expressed as:

\[
(J + J_p)\ddot{\omega} + B\dot{\omega} = T - T_p
\]  

(9)

where \( J \) and \( J_p \) represent the rotational inerias of the wind turbine rotor and the hydraulic pump, respectively; \( B \) is the damping of the wind turbine rotor.

The dynamic equation between Pelton turbine and the generator is expressed as:

\[
(J_{\text{pel}} + J_{\text{gen}})\dot{\omega}_{\text{pel}} + B_{\text{pel}}\omega_{\text{pel}} = T_{\text{pel}} - T_{\text{gen}}
\]  

(10)

where \( J_{\text{pel}} \) and \( J_{\text{gen}} \) represent the rotational inerias of the Pelton wheel and generator, respectively; \( B_{\text{pel}} \) is the damping of the Pelton turbine; \( T_{\text{gen}} \) represents the generator torque; \( T_{\text{pel}} \) and \( \omega_{\text{pel}} \) represent the torque and angular speed of Pelton turbine output shaft, respectively.

## 4 WIND SPEED ESTIMATION

In this paper, ANFIS is applied for the estimation of the wind velocity, due to its ability to accurately and effectively learn and decide. The basic structure of the ANFIS controller consists of four important parts, namely fuzzification, fuzzy rule base, inference engine and the defuzzification as shown in Figure 3.

In the fuzzification process, the input signal is converted into fuzzy inputs through the membership function; then, the fuzzy inputs are put into the neural network block. The neural network block is formed from fuzzy rule base and inference engine. The fuzzy rule base including a set of fuzzy IF-THEN rule is combined with fuzzy principles by fuzzy inference engine. Finally, defuzzification is used to convert the linguistic output from the neural network block into the numerical numbers. For designing ANFIS system, MATLAB Fuzzy toolbox is used.

According to Equation (2), wind speed can be acquired as a function of aerodynamic torque, rotor angular speed, and blade pitch angle. So, in the ANFIS controller, the rotor torque, rotor angular speed, and blade pitch angle are selected as the inputs and wind speed is the output. The collected data set is subdivided into data set A and data set B, which are used to train and test ANFIS controller, respectively. The membership functions (MFs) are choosing as triangular and the number of membership functions for each input is 3, and finally, the number of epochs for simulations is 50. Grid partition method and the hybrid method are utilized to generate the inference engine and optimize the fuzzy membership functions, respectively. Here, a 5 MW offshore horizontal axis wind turbine developed by NREL\(^{36}\) is considered, and the specifications of the wind turbine are shown in Table 1.

The collected data of the rotor torque and rotor angular speed as pitch angular is 0° as well as the simulation results of estimated wind speeds and the estimation errors between training are shown Figures 4-6. The statistical properties of the speed estimation errors for different mean wind speeds are summarized in Table 2.

Results in Figures 4-6 show that the values of wind speed estimated by ANFIS are well agree with the collected data. Hence, the proposed estimator has a ability to estimate the wind speed with high accuracy, and in the subsequent part, the estimated wind speed is used for designing the fuzzy PID control to achieve the MPPT. The final three-dimensional surface of ANFIS predicting the relationship between wind speed, the rotor torque and angular speed in constant pitch angle of 0°, is shown in Figure 7.
5 | CONTROL STRATEGIES

The two important control objects in this offshore wind turbine system are as follows: (a) Capturing the maximum wind energy through controlling the torques of hydraulic pumps in wind turbine. (b) Adjusting the output power to satisfy the consume demand through controlling the nozzle area. The general road map of the control system is illustrated in Figure 8. Firstly, an ANFIS is designed to estimate the wind speed, in which the rotor torque, rotor angular speed, and pitch angle are the inputs. Then, the fuzzy PID controller and PID controller are applied to capture the optimal wind energy and adjust the output power based on the estimated wind speed, respectively.

5.1 | Fuzzy PID control for capturing the maximum wind energy

5.1.1 | MPPT technique based on hydraulic pump torque control

In order to extract the maximal wind power as the wind turbine is working above the cut in value and below rated wind speed, the optimal power coefficient $C_{P,\text{opt}}$ should be maintained. The $C_{P,\text{opt}}$ is obtained by controlling the hydraulic pump torque at the optimal value $T_{p,\text{ref}}$ given as

$$ T_{p,\text{ref}} = \frac{1}{2\lambda_{\text{opt}}} \rho_{\text{air}} R^5 C_{P,\text{opt}} \omega^2 $$

(11)

The hydraulic pump torque $T_p$ is calculated by:

$$ T_p = \frac{p_p D_p}{2\pi \eta_{\text{mp}}} $$

(12)

where $D_p$ is displacement of the pump; $\eta_{\text{mp}}$ is mechanical efficiency; $p_p$ is the pressure loads of the pump, which equates to accumulator pressure.

From above equation, the torque control strategy can be realized by regulating the pump displacement $D_p$. An adaptive fuzzy PID controller is designed to adjust the pump displacement $D_p$. In the controller, an error signal $T_{p,\text{err}}$ is considered the input parameter, which can be got through subtracting the measured pump torque $T_{p,\text{meas}}$ from the optimal pump torque $T_{p,\text{ref}}$. The architecture of standard torque controller is depicted in Figure 9.

5.1.2 | Mathematic model of electro-hydraulic servo system

Figure 10 presents the schematic diagram of the electro-hydraulic servo control system proposed to implement the adjustment of hydraulic pump displacement. The system contains the following components: 1-wind turbine rotor; 2-torque sensor; 3-a variable displacement pump with axial pistons; 4-hydraulic transmission system; 5-hydraulic cylinder for modifying the displacement of the pump; 6-electro-hydraulic servo valve; 7-servo amplifier; and 8-seawater. The control objective of this electro-hydraulic servo control system is to accurately track the optimal expected pump torque $T_{p,\text{ref}}$. As shown in Figure 10, the error signal $T_{p,\text{err}}$ between the optimal pump torque $T_{p,\text{ref}}$ and the measured value $T_{p,\text{meas}}$ is converted into current signal to adjust the position of valve spool through the servo amplifier. When the spool moves, the direction and flow of liquid passing the electro-hydraulic servo valve are changing, as a result, the piston in hydraulic cylinder is moving accordingly. Consequently, hydraulic pump displacement is adjusted, and the hydraulic pump torque controller is achieved.
The electro-hydraulic servo control system includes the servo amplifier, torque sensor, and the servo valve.

1. The output current of the servo amplifier is approximately proportional to the input voltage, which is simplified to a proportional system. The transfer function is as follows:

\[ G_1(s) = \frac{\Delta I(s)}{U_e(s)} = K_a \]  \hspace{1cm} (13)

where \( \Delta I \) is the output current of the servo amplifier; \( U_e \) is the input voltage of the servo amplifier; \( K_a \) is the servo amplifier gain.

2. The transfer function of torque sensor is also simplified to proportional system:

\[ G_2(s) = \frac{R_f(s)}{T_{error}(s)} = K_{cv} \]  \hspace{1cm} (14)

FIGURE 4  The collected data as well as estimated results as mean wind speed is 5.5 m/s

FIGURE 5  The collected data as well as estimated results as mean wind speed is 7 m/s

FIGURE 6  The collected data as well as estimated results as mean wind speed is 9.5 m/s
where $R_f$ is the feedback voltage signal of torque sensor; $T_{error}$ is the torque error signal; $K_{sv}$ is the torque sensor gain.

3. The servo valve dynamics is represented as a second order response:

$$G_3(s) = \frac{Q_{sv}(s)}{\Delta I(s)} = \frac{K_{sv}}{\omega_n^2 + 2\zeta_{sv}\omega_n s + 1}$$

where $Q_{sv}$ is the output flow of servo valve; $\Delta I$ the current of the servo valve; $K_{sv}$ is the Servo valve flow gain; $\omega_n$ is the natural frequency of electro-hydraulic servo control system; $\zeta_{sv}$ is the damping ratio.

4. The transfer function of the electro-hydraulic servo control system can be expressed as follows based on Equations (13)-(15).

$$G_4(s) = \frac{K_u K_{sv} K_{sv}}{\omega_n^2 + 2\zeta_{sv}\omega_n s + 1}$$

The displacement of the pump $D_p$ is defined as follows:

$$D_p = D_{max} \tan \alpha = D_{max} \frac{X_p}{X_{p\max}}$$

where $D_{max}$ is hydraulic pump maximum displacement; $\alpha$ is the swash plate angle; $X_p$ is the piston displacement of hydraulic cylinder; and $X_{p\max}$ is maximum piston displacement of hydraulic cylinder.

Based on the Equations (12) and (17), the transfer function of hydraulic variable displacement pump can be obtained by Laplace transformation as follows:

$$G_5(s) = \frac{D_{max}p_p}{A_p X_{p\max} \eta_{mp} s}$$

where $A_p$ is hydraulic cylinder cross-sectional area; $p_p$ is the work pressure; and $\eta_{mp}$ is mechanical efficiencies of hydraulic pump. According to the above analysis, the block chart of the fuzzy PID controller transfer function can be obtained as shown in Figure 11.

### 5.1.3 Design of fuzzy PID controller

The PID controller is generally used in industrial control fields for some merits such as simple structure, less computation, and easy implementation. However, the conventional PID controllers are poor in adapting to operation environments and adjusting parameters. So, in this paper, a fuzzy logic PID control which can automatically tune the PID parameters by fuzzy controller based on pump torque $e_T$ error and its derivative $e_{T\epsilon}$ is developed to control the displacement of the hydraulic pump. Figure 12 demonstrates the structure of designed adaptive fuzzy PID controller, which contains two modules: one is the conventional PID controller; another is the fuzzy inference mechanism. The fuzzy controller is composed of two inputs (pump torque $e_T$ error and its derivative $e_{T\epsilon}$) and three output components (proportional $\Delta K_p$, integral $\Delta K_i$ and differential $\Delta K_d$), which can build the fuzzy relationship between PID parameters with “$e_T$” and “$e_{T\epsilon}$” by using the experience of experts and fuzzy set theory. The PID controller parameters are tuned on the basis of the following equations:

$$\begin{cases} K_p = K_p' + \Delta K_p \\ K_i = K_i' + \Delta K_i \\ K_d = K_d' + \Delta K_d \end{cases}$$

where $K_p'$, $K_i'$, and $K_d'$ are the initial values of the PID controller’s parameters; $\Delta K_p$, $\Delta K_i$, and $\Delta K_d$ are the variation values; then, the PID controller’s parameters $K_p$, $K_i$, and $K_d$ will be adaptively tuned online by the fuzzy controller.

On the base of fuzzy set theory, the input and output data should are transformed into proper linguistic variables. In this paper, the two inputs (pump torque $|e_T|$ error and its derivative $|e_{T\epsilon}|$) are transformed into uniform fuzzy range [0,
2] and [0, 200], respectively, and the three outputs (proportional $\Delta K_p$, integral $\Delta K_i$, and differential $\Delta K_d$) are limited in range [0, 12], [0, 96] and [0, 0.06], respectively. Then, the fuzzy ranges of two inputs and three outputs are separated into 4 linguistic variables, respectively, and the corresponding fuzzy subsets are expressed as:

$$|e_T|, |ec_T| = [ZO, S, M, L],$$

$$\Delta K_p, \Delta K_i, \Delta K_d = [ZO, S, M, L],$$

where ZO, S, M, and L mean zero, small, middle, and positive large, respectively. Triangular membership functions (MF) are chosen to create the input and output partitions. The input MFs are shown in Figure 13A,B. The output MFs are shown in Figure 14A-C.

The effects of PID controller parameters $K_p$, $K_i$, and $K_d$ on the stability, response speed, overshoot, and steady-state performance of the electro-hydraulic servo system are very crucial. To establish exact fuzzy inference rules, some fundamental principles to adaptive tune the parameters of fuzzy PID controller on the basis of pump torque $|e_T|$ and its derivative $|ec_T|$ are adopted as follows:

1. When $|e_T|$ is large, bigger $K_p$ should be taken to speed up the system’s response speed, and smaller $K_d$ should be chosen to avoid the differential over saturation, and $K_i$ should be set to be zero to prevent large overshoot, simultaneously.
2. When $|e_T|$ and $|ec_T|$ are in the middle size, $K_p$ should be taken smaller, $K_i$ and $K_d$ should be selected to sure the system has a smaller overshoot and fast response speed.
3. When $|e_T|$ is small, bigger $K_p$ and $K_i$ should be chosen to make the system have good steady-state performance, and $K_d$ should be small to avoid the system’s oscillation. When $|ec_T|$ is small, $K_d$ should be set large to improve the system's anti-jamming performance.

According to the adaptive parameter tuning rules of PID controller shown before, the fuzzy inference rules between inputs $|e_T|$, $|ec_T|$ and outputs $\Delta K_p$, $\Delta K_i$, $\Delta K_d$ are summarized in Table 3. And the three-dimensional surfaces of the relationship between inputs and output are shown in Figure 15A,B,C, respectively.

Finally, a Centroid is applied to implement defuzzification, so the output $\Delta K_p$ ($\Delta K_i$ and $\Delta K_d$ are similar) can be obtained as follows:

$$\Delta K_p = \frac{\sum_{j=1}^{n} u_{pj} A(u_{pj})}{\sum_{j=1}^{n} A(u_{pj})}$$

(20)

where $A(u_{pj})$ means the fuzzy output function, and $u_{pj}$ means the weight of the output $\Delta K_p$. 

**FIGURE 8** The block diagram of the overall system

**FIGURE 9** The architecture of standard torque controller
5.2 Output power of Pelton turbine control

In order to keep the output power of Pelton turbine meeting the demand, a PID controller is designed to control the nozzle area $A_{noz}$ by regulating the spear valve. The PID controller equation is expressed by20:

$$
\begin{align*}
A_{noz} &= K_p P_{Pel, err} + K_I \int P_{Pel, err} dt + K_D \frac{dP_{Pel, err}}{dt} \\
P_{Pel, err} &= P_{Pel, dem} - P_{Pel, meas}
\end{align*}
$$

The control structure of the output power is illustrated in Figure 16.

6 SIMULATIONS AND DISCUSSIONS

To evaluate the performances of Fuzzy PID control methods in hydraulic wind turbines, two simulation studies have been carried out by means of MATLAB/Simulink software.

6.1 The selections of the components

The efficiency of the proposed control method was verified in simulation on a 5 MW offshore horizontal axis wind turbine36 with an open-loop wind energy hydraulic conversion systems. The more details about the wind turbine can be found in Table 1. The key parameters of hydraulic pump, hydraulic accumulator, Pelton turbine, and generator are shown in Tables 4-6, respectively.

6.2 Case 1: transient performance simulations for a wind speed with step changes

In this section, transient performance of electro-hydraulic servo control system by using PID, fuzzy logical, and adaptive fuzzy PID control are investigated in Figure 17. Figure 17A shows the change curve of wind speed with 3 step changes, which is used to assess the transient performance of control strategies. Time response of the rotor angular speed is portrayed in Figure 17B, in which both the Fuzzy and PID have long adjustment time, while the Fuzzy PID has faster response speed. The power coefficient is a vital indicator to evaluate the conversion efficiency of the wind turbine, and the simulation results is shown in Figure 17C, which is should be kept at 0.48. In Figure 17C, it should be noticed that the Fuzzy PID reaches the optimal value at a settling time of 0.51 second, which is more fast than other controllers. Furthermore, the Fuzzy PID can maintain the optimal tip-speed ratio (8.1) as shown in Figure 17D. The changes of rotor torque and captured mechanical power are depicted in Figure 17E,F, respectively. When the wind speed changes, the Fuzzy PID reaches the optimal torque value and captures the maximum mechanical efficiency with a zero steady-state oscillation. According to the simulation results, the fuzzy and PID control need relatively long adjustment time, in addition, vibration and overshoot phenomenon simultaneously occur. While fuzzy PID controller has a better performance in tracking the maximum wind energy, which has quick response and small oscillations.

6.3 Case 2: steady-state performance for a variable wind speed

To validate the effectiveness of the proposed fuzzy PID controller on power coefficient as well as tip-speed ratio, the system performance is investigated at a random wind speed, and a output power with 3 step changes is required. The wind speed profile changes between 3 m/s and 12 m/s, and the real and estimated wind speed are shown in Figure 18A. In the Figure 18B, under the control of fuzzy PID, the rotor angular
FIGURE 12  Structure of adaptive fuzzy PID controller

FIGURE 13  The input membership functions

FIGURE 14  The output membership functions

TABLE 3  The fuzzy rule table

| $|e_1|$ | $|e_{ct}|$ | $\Delta K_p/\Delta K_i/\Delta K_d$ |
|---|---|---|
| ZO | ZO/ZO/ZO | L/L/S | M/ZO/L | L/ZO/L |
| S  | L/L/S  | L/L/S | M/ZO/L | L/ZO/L |
| M  | L/L/ZO | L/L/S | M/S/M  | L/ZO/M |
| L  | M/L/ZO | M/M/ZO | S/S/M  | M/ZO/S |
The response curve of the angular speed follows the same trend as which in wind speed, simultaneously. The fuzzy PID reaches the optimal power coefficient (0.48) quickly than fuzzy and PID controller as depicted in Figure 18C. In addition, it is observed that the fuzzy PID maintains the optimal value unless the rapid fluctuations occur, while the other controllers lose the tracking as the wind speed has small variations. Furthermore, the change of the tip-speed ratio is shown in Figure 18D, which confirms the good performance of the fuzzy PID controller. It is noticed that proposed fuzzy PID can solve the speed convergence and vibration problem, so the maximal wind energy is captured. In order to visually present the control effect of fuzzy PID, the variation of the PID parameters and the wind turbine rotor torque error are shown in Figures 19 and 20, respectively.

To verify the effect of the hydraulic accumulator on the output power, the performances of the Pelton turbine, accumulator, and generator output power is studied, as the

### Table 4 Parameters of the selected hydraulic pumps

| Parameter                  | Symbol | Value | Unit |
|----------------------------|--------|-------|------|
| Max pressure               | $p_{\text{max}}$ | 34    | MPa  |
| Working pressure           | $p_{\text{w}}$  | 15    | MPa  |
| Mechanical efficiency      | $\eta_{\text{me}}$ | 0.98  | /    |
| Volumetric efficiency      | $\eta_{\text{vp}}$ | 0.95  | /    |
| Maximum volumetric displacement | $D_{\text{p, max}}$ | 2500 | L/rev |
| Minimum volumetric displacement | $D_{\text{p, min}}$ | 30   | L/rev |

### Table 5 Main parameters of the hydraulic accumulator

| Parameter                  | Symbol | Value | Unit |
|----------------------------|--------|-------|------|
| Accumulator volume         | $V$    | 1000  | m$^3$|
| Air precharge pressure     | $p_0$  | 10    | MPa  |
| Accumulator rated pressure | $p_r$  | 20    | MPa  |
| Accumulator working pressure | $p_{\text{acc}}$ | 15   | MPa  |

FIGURE 15 The relationship between inputs and outputs

![Figure 15](image)

FIGURE 16 The architecture of Pelton turbine output power controller
maximum wind energy is captured by the proposed fuzzy PID controller. Figure 21 shows the change curves of the nozzle area and the Pelton turbine power. As shown, the system has the ability to regulate the output power of Pelton turbine as the nozzle area is controlled by a PID controller. As shown in Figure 22, the pressure in accumulator changes as the seawater in accumulator increases or decreases, the excess energy is simultaneously stored in or released from the hydraulic accumulator. The wind turbine captured mechanical power, the demand power, and generator output power are shown in Figure 23. From Figures 22 and 23, in the time duration of $t=0$ to $t=300$ seconds, captured total
power are less than the demand power, so the accumulator continually releases stored energy in this stage. In other stage, the captured total power from wind is surplus, and the accumulator stores the excess energy. Under the role of the accumulator, the generator power is changed coincidently with demand power.

7 | CONCLUSIONS

In this paper, an open-loop hydraulic wind turbine capable of storing energy is proposed. In order to capture the maximum wind energy when the wind speed is above the cut in value and below the rated value, a fuzzy PID controllers
is achieved to regulate the hydraulic pump torque based on the estimated wind speed which is implemented by an ANFIS approach. A hydraulic accumulator is applied to balance the demand and output power through storing and releasing the excess energy, and a PID control strategy is utilized to regulate the nozzle area and control the output power. Aiming to illustrate the performance of the proposed control system, a case study based on a 5 MW offshore wind turbine is undertaken, and the following conclusions are extracted:

1. In Figures 4-6, as the rotor speed, pitch angle, and pump torque are the inputs, ANFIS approach has a very good ability of estimating the wind speed and the estimation errors are less than 0.005 m/s in various mean wind speeds and different turbulence intensities.

2. The main advantage of fuzzy PID control approach in comparison with the fuzzy and PID control is that it has a faster response and zero steady-state oscillations as shown in Figures 17 and 18. When the wind speed randomly changes, the controller can maintain the optimal power coefficient and tip-speed ratio as shown in Figure 18.

3. Hydraulic accumulator has a very good performance in balancing the output and demand power as shown in Figures 22 and 23, which acts as a damper for the wind turbine system by absorbing power fluctuations coming from the wind speed, and made the output power meet the various need of users.
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