Maximum Power Extraction and Pitch Angle Control for Offshore Wind Turbine with Open-Loop Hydraulic Transmission

YaJun Fan
School of Mechatronic Engineering
Xi 'an Technological University
Xi'an, China
E-mail: fanyajunfan@sina.com

AnLe Mu
School of Mechanical and Precision Instrument Engineering
Xi'an University of Technology
Xi'an, China
E-mail: mu.andy08@gmail.com

Abstract—**This paper aims to extract optimal power from a hydraulic floating wind turbine using torque control and pitch control. When wind speed is below rated value, a nonlinear fuzzy controller is designed to capture maximum wind energy through regulating the displacement of hydraulic pump fixed in nacelle. When wind speed is above rated value, to achieve the pitch angle control and guarantee that the generation system safely works, an adaptive fuzzy controller is built and the stability of the control system has been analyzed through Lyapunov criterion. In order to validate the feasibility of the proposed controllers, the system has been simulated in Matlab/simulink under random wind speeds. The results show that as the wind speed is below the rated value the power coefficient has been kept to the optimal value. Furthermore, the maximum output power has been held near to rated value as the wind speed is above the rated value.**

Keywords-Offshore Wind Turbine; Hydraulic Transmission; Nonlinear Fuzzy Controller; Adaptive Fuzzy Controller; Optimal Power Extraction

I. INTRODUCTION

Nowadays, the increasingly serious environmental problems caused by fossil fuels have greatly influenced people's health condition and earth's safety. As one replacement of traditional fossil fuels, wind energy has been developed and used widely in the past decades. With the wind turbine technology maturing and increasing electricity demand, offshore wind turbine has been concentrated for the steadier wind speed and the spacious sea area[1]. But problems like the more mass and complexity caused by traditional mechanical transmission system hinder the development of the offshore wind turbine[2]. Recently, the investigation of hydraulic wind turbine have been conducted deeply[3-5] to overcome this problem. In[6], authors combined a closed oil circuit and an open seawater circuit as a energy transmission system. The results showed that the efficiencies of the energy transmission both were reduced slightly as the operating below and above rated wind speed, but the hydraulic transmission had excelled dynamic performance. In[7], authors used numerical models to estimate the annual energy production for three different drive train systems, and they concluded that there are little differences among the investigated configurations, while hydraulic transmission can improve system reliability as well as decrease the weight of the nacelle and diminish the cost of maintenance. In[8] authors used the seawater in the hydraulic transmission as a cooling medium in district cooling system by passing through heat exchange, Simulation results showed that 12.2 GWhr of cooling energy can be got from this novel system. Thus, in this paper an offshore wind turbine with open-loop hydraulic transmission is taken as the research object, as shown in Fig. 1.

Another crucial factor affecting the output power is the control system in the variable speed and pitch wind turbine[9,10]. Considering the strong nonlinear nature of the wind turbine dynamics, some advanced intelligent controllers have been designed in the conventional mechanical wind energy transmission[11,12]. In[13], authors have employed fuzzy logic controller to regulate the rotational speed of the wind turbine rotor through controlling the electromagnetic torque. In[14] a new intelligent controller based on adaptive Neuro-fuzzy algorithm is designed to capture the maximum output power of wind turbine. In[15], two control methods based on feedback linearization and quasi continuous sliding mode control were designed for tracking the optimal rotor speed and increasing the efficiency. Simulation results showed that feedback linearization control with observer has a better ability in performance and load reduction in various wind speeds. As mentioned above, the research related to the control system of wind turbine are focused on traditional mechanical transmission. Recently, some control systems based on a hydraulic wind turbine have been investigated. But, inherent characteristics of hydraulic transmission system such as the highly nonlinear characteristics have not been considered. In this paper, a fuzzy logic controller which can effectively solve control problems of nonlinear system is designed to control the displacement of hydraulic pump and maximize captured wind energy.

The other parts of this paper are shown as follows: Firstly the detailed mathematical model is presented in Section 2.The fuzzy control for optimal power exaction and an adaptive fuzzy control for pitch angle adjustment are developed in Section 3 and 4, respectively. Simulation results and discussion are shown in Section 5. Finally, conclusions are drawn in Section 6.

II. Mathematical models

A. Wind turbine

In this paper an open-loop hydraulic transmission system is presented. It mainly includes a variable displacement pump coupled to the wind turbine rotor and a hydraulic motor connected with generator. The schematic of the proposed wind turbine system block diagram are shown in Fig. 1.

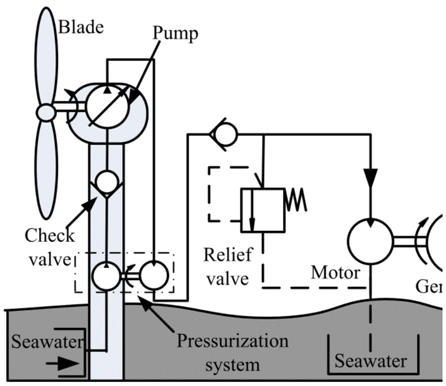

Figure 1. Schematic of the proposed wind turbine.

Wind turbine converts the wind energy captured by blades into mechanical energy. The aerodynamic torque T and the captured power P are calculated as, respectively,

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

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

where R is the radius of turbine blade, ρ_{air} is the air density, ω is the wind turbine rotor angular speed, v is the wind speed, $C_P(\lambda,\beta)$ is the power coefficient of the wind turbine, expressed as ,

$$\begin{aligned} C_P(\lambda,\beta) &= 0.517(\frac{116}{\lambda_i} - 0.4\beta - 5)e^{-\frac{21}{\lambda_i}} + 0.0068\lambda \\ \frac{1}{\lambda_i} &= \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \end{aligned} \tag{3}$$

where β is the pitch angle, λ is the tip speed ratio of wind turbine, calculated by.

$$\lambda = \frac{\omega R}{v} \tag{4}$$

B. Hydraulic components (pump, motor)

The variable displacement pump installed in nacelle is used to convert the mechanical torque from rotor into hydraulic energy. Then the hydraulic energy is transmitted to motor connected with a generator. Accordingly, the hydraulic flow rate Q and torque T of the pump and motor in wind turbine are described as,

$$Q_{pump} = \frac{\omega_{pump} D_{pump}}{2\pi\eta_{Vp}} \tag{5}$$

$$T_{pump} = \frac{pD_{pump}}{2\pi}\eta_{mp} \tag{6}$$

$$Q_{motor} = \frac{\omega_{motor} D_{motor}}{2\pi\eta_{Vm}} \tag{7}$$

$$T_{motor} = \frac{pD_{motor}}{2\pi}\eta_{mm} \tag{8}$$

where D, ω and p are displacement ,angular speed and work pressure, respectively. The subscript "pump" and "motor" refer to the hydraulic pump and motor, respectively. $\eta_{Vp/Vm}$ are volumetric efficiencies of pump and motor, $\eta_{mp/mm}$ are mechanical efficiencies of pump and motor.

C. Inertia dynamics

The dynamic equation for the low speed shaft of wind turbine rotor and hydraulic pump is,

$$\left(J + J_{pump}\right)\dot{\omega}_{pump} = T - T_{pump} \tag{9}$$

where J and J_{pump} are the rotational inertias of the wind turbine rotor and the hydraulic pumps, respectively.

The dynamic equation for the high speed shaft of the hydraulic motor and the generator is,

$$\left(J_{motor} + J_{gen}\right)\dot{\omega}_{motor} = T_{motor} + T_{gen} \tag{10}$$

where J_{motor} and J_{gen} are the rotational inertias of the hydraulic motor and generator, respectively. T_{gen} is the generator torque.

III. Fuzzy control for optimal power exaction

When wind turbine works under rated wind speed, the control objective is to optimize the captured energy through tracking the desired rotor angular speed. In this control stage the pitch angle of the blades is kept constant.

From (6), the pump torque is proportional to displacement as the work pressure p is constant. In order to keep the measured pump torque $T_{pump,meas}$ in accordance with the optimal expected value $T_{pump,dem}$, a fuzzy controller is built to adjust the pump displacement D_{pump} , and the control architecture of the pump torque is shown in Fig. 2.

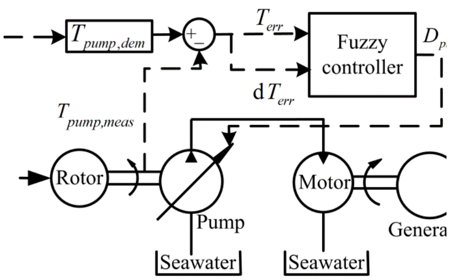

Figure 2. Control architecture of fuzzy controller.

Firstly, aiming to get the demand displacement of pump D_{pump}, in addition to computing the error T_{err} between the demand torque and real value, the torque change rate $\mathrm{d}T_{err}$ is also be input. The two inputs are fuzzified by fuzzy controller, and the fields of the two inputs are [-1, 1] and [-0.1, 0.1], respectively. The torque error T_{err} and error change $\mathrm{d}T_{err}$ are divide into 7 and 5 subsets,

T_{err} = [NB, NM,NS, ZO, PS,PM, PB]

$\mathrm{d}T_{err}$ = [NB, NM, ZO, PM, PB]

where NB, NM,NS, ZO, PS,PM, PB mean negative big, negative middle, negative small, zero, positive small, positive middle and positive big, respectively.

Then, fuzzy inferences are conducted according to the established fuzzy control rules to get the fuzzy output. Finally, the displacement of pump D_{pump} is obtained by defuzzification, which is limited in a range [0, 1] and separated into 7 semantic variables as.

D_{pump} = [NB, NM,NS, ZO, PS,PM, PB]

The membership functions is generalized by Gauss membership functions (MF), and the MF are expressed as follows,

$$\begin{cases} f_j\left(x_i, \sigma_{ij}, c_{ij}\right) = e^{-\frac{\left(x_i - c_{ij}\right)^2}{2\sigma_{ij}^2}} \\ i = 1, 2, 3;\ j = 1, 2, \ldots n. \end{cases} \tag{11}$$

where i =1, 2 are input value, i =3 is output value, $\left\{\sigma_{ij}, c_{ij}\right\}$ is a set of parameters set, n is the MF number of the ith input. The fuzzy inference rules between inputs T_{err}, $\mathrm{d}T_{err}$ and output D_{pump} are summarized in Table 1.

TABLE I. THE FUZZY RULE TABLE.

$\mathrm{d}T_{err}$	T_{err}						
	NB	NM	NS	ZO	PS	PM	PB
	D_{pump}						
NB	NB	NM	NS	PB	PB	PB	PB
NM	NB	NM	NS	ZO	PB	PB	PB
ZO	NB	NB	NS	ZO	PS	PB	PB
PM	NB	NB	NB	ZO	PS	PM	PB
PB	NB	NB	NB	NB	PS	PM	PB

In the process of defuzzification, a Centroid method is used to obtain the output D_{pump} as follows,

$$D_{pump} = \frac{\sum_{j=1}^{n} u_j A\left(u_j\right)}{\sum_{j=1}^{n} A\left(u_j\right)} \tag{12}$$

where $A\left(u_j\right)$ means the fuzzy output function, and u_j means the weight of the output D_{pump}.

IV. ADAPTIVE FUZZY CONTROLLER

When wind turbine works above rated wind speed, the output power is limited by control the blade pitch angle to keep the generating system safely running. Here, an adaptive fuzzy controller is designed to achieve the pitch angle control, and Lyapunov stability approach is adopted to keep the nonlinear system under control.

According to the sensitivity of aerodynamic power to blade pitch for a 5MW offshore wind turbine [16]. A second order optimistic curve fitting is chosen to approximate the optimal pitch angle $\beta^*(v)$, the relevant expression is given as follows.

$$\beta^*(v) \approx -0.06629v^2 + 3.949v - 34.48 \tag{13}$$

Aiming to find a control law that can make the pitch control system track the reference $\beta^*(v)$, the tracking error $e(t)$ and its derivative $\dot{e}(t)$ are defined as,

$$\begin{cases} e(t) = \beta(t) - \beta^*(t) \\ \dot{e}(t) = \dot{\beta}(t) - \dot{\beta}^*(t) \end{cases} \tag{14}$$

where $\beta(t)$ is the control output.

The error function is defined as.

$$s(t) = ce(t) + \dot{e}(t), c > 0 \tag{15}$$

The dynamic control model of blade pitch angel actuator is expressed as,

$$\ddot{\beta}(t) = f(\boldsymbol{\beta}) + u(t) \tag{16}$$

where $u(t)$ is the control input, $\boldsymbol{\beta} = [\beta, \dot{\beta}]$, $f(\boldsymbol{\beta}) = f(\beta, \dot{\beta})$.

Taking time derivative of $s(t)$, and using (16) and (18) lead to.

$$\dot{s}(t) = c\dot{e}(t) + f(\boldsymbol{\beta}) + u(t) - \ddot{\beta}^*(t) \tag{17}$$

We define an optimal parameter $\mathbf{w}^*$ as,

$$\mathbf{w}^* = \arg\min_{\mathbf{w}\in\Omega}\left\{\sup_{\beta\in R^2}\left|\hat{f}(\boldsymbol{\beta}) - f(\boldsymbol{\beta})\right|\right\} \quad (18)$$

where $\hat{f}(\boldsymbol{\beta}) = \hat{\mathbf{w}}^{\mathrm{T}}\xi(\boldsymbol{\beta})$ is output of fuzzy system, $\xi(\boldsymbol{\beta})$ is fuzzy basis vector.
Thus, $f(\boldsymbol{\beta})$ is expressed as,

$$f(\boldsymbol{\beta}) = \mathbf{w}^{*\mathrm{T}}\xi(\boldsymbol{\beta}) + \varepsilon \quad (19)$$

where ε is the approximation error of fuzzy system.

Here, a Lyapunov function is designed to satisfy Lyapunov's Second Stability criteria, which is defined as.

$$\begin{cases} \mathrm{V} = \dfrac{1}{2}s^2 + \dfrac{1}{2\gamma}\tilde{\mathbf{w}}^{\mathrm{T}}\tilde{\mathbf{w}} \\ \gamma > 0, \tilde{\mathbf{w}} = \hat{\mathbf{w}} - \mathbf{w}^* \end{cases} \quad (20)$$

The time derivative of V leads to.

$$\dot{\mathrm{V}} = s(c\dot{e}(t) + f(\boldsymbol{\beta}) + u(t) - \ddot{\beta}^*(t)) + \frac{1}{\gamma}\tilde{\mathbf{w}}^T\dot{\hat{\mathbf{w}}} \quad (21)$$

Design the control law as.

$$u(t) = -c\dot{e}(t) - \hat{f}(\boldsymbol{\beta}) + \ddot{\beta}^* - \eta\,\mathrm{sgn}(s) \quad (22)$$

By substituting (22) into (21), the following expressing can be obtained.

$$\begin{aligned} \dot{\mathrm{V}} &= s(f(\boldsymbol{\beta}) - \hat{f}(\boldsymbol{\beta}) - \eta\,\mathrm{sgn}(s)) + \frac{1}{\gamma}\tilde{\mathbf{w}}^{\mathrm{T}}\dot{\hat{\mathbf{w}}} \\ &= s(-\tilde{\mathbf{w}}^{\mathrm{T}}\xi(\boldsymbol{\beta}) + \varepsilon - \eta\,\mathrm{sgn}(s)) + \frac{1}{\gamma}\tilde{\mathbf{w}}^T\dot{\hat{\mathbf{w}}} \\ &= \varepsilon s - \eta|s| + \tilde{\mathbf{w}}^{\mathrm{T}}\left(\frac{1}{\gamma}\dot{\hat{\mathbf{w}}} - s\xi(\boldsymbol{\beta})\right) \end{aligned} \quad (23)$$

Design the adaptive law as.

$$\dot{\hat{\mathbf{w}}} = \gamma s\xi(\boldsymbol{\beta}) \quad (24)$$

By substituting (24) into (23), the following expression can be obtained.

$$\dot{\mathrm{V}} = \varepsilon s - \eta|s| \le 0, \quad as \quad \eta \ge |\varepsilon|_{\max} \quad (25)$$

In (25), when the value of η is greater than or equal to $|\varepsilon|_{\max}$, Lyapunov's second method for stability can be realized.

V. SIMULATIONS AND DISCUSSIONS

The efficiency of the proposed control method was verified in simulation on a 5 MW offshore horizontal axis wind turbine [16] with an open-loop wind energy hydraulic conversion systems. In the above section, an open-loop hydraulic wind turbine and its control strategies have been described in detail. In order to investigate the performance of the proposed system and controllers, The system has been simulated in Matlab/simulink. Performance of the optimal power control is shown in Fig. 3.

Fig. 3(a) shows the curve of wind speed. The operation regions of the turbine were between 3 and 25 m/s. The rated wind speed was about 11.4 m/s. Fig. 3(b) shows the power coefficient of wind turbine. As the wind speed is above 3m/s and below 11.4m/s, the values is near the optimal value 0.482. It is remarkable that through controlling the pump displacements, the pump torques are well adjusted to track the maximal power point. For above rated conditions, the target of the pitch angle control is not to achieve the maximum power efficiency but to guarantee the wind rotor speed does not exceed its rated value. So the fluctuation of power coefficient is contrary to the wind speed.

From Fig. 3(c), as the wind speed is above 3m/s and below 11.4m/s, the tip speed ratio of wind turbine is always close to the optimal value 8.1. Only a small decline in the tip speed ratio with a relatively rapid recovery is shown due to the sharp decrease in wind speed below rated conditions (t=37s). For above rated conditions, the trend the tip speed ratio is similar with the power coefficient.

Fig. 3(d) shows the generator output power. When the wind speed is above 3m/s and below 11.4m/s, thanks to the fuzzy controller for optimal power exaction, the output power follows the wind speed; when the wind speed is above 11.4m/s and below 25m/s, the adaptive fuzzy controller for pitch angle adjustment basically stabilizes the output power around rated power (5MW).

Fig. 4 shows performance of pitch angle control. In Fig. 4(a), when the wind speed is lower than the rated value (11.4m/s), the pitch angle is keep 0°, torque control is used to achieve the maximum power. When the wind speed is higher than the rated value, the pitch control is adopted to hold the maximum power output near rated value. Fig. 4(b) shows the control error of the pitch angle, which is kept within ±0.4°. Thus, according to the simulation results, the feasibility of adaptive fuzzy controller under stochastic wind speed can be confirmed.

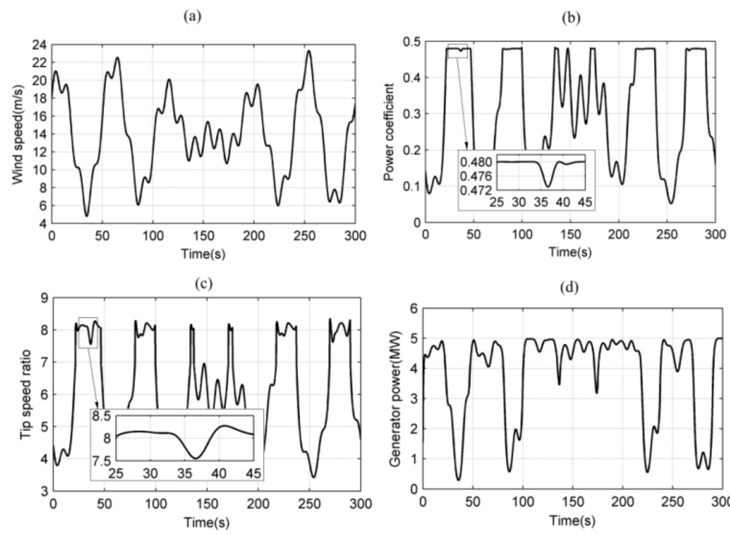

Figure 3. Performance of the optimal power control:(a)Wind speed, (b)Power coefficient, (c)Tip speed ratio, (d)Generator power.

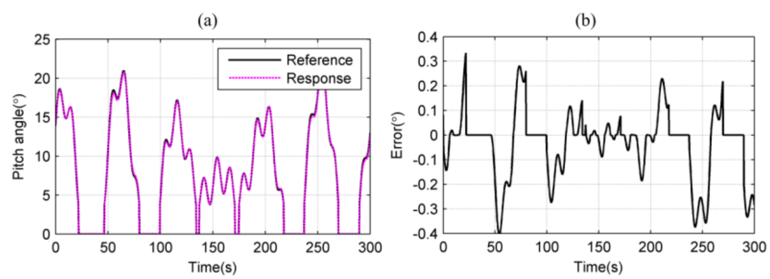

Figure 4. Performance of pitch angle control:(a)Pitch angle, (b)The error between reference and response value.

VI. CONCLUSION

In this paper a nonlinear fuzzy controller for maximum power exaction and an adaptive fuzzy controller for pitch angle adjustment have been proposed. Firstly, as wind turbine works below rated wind speed, a standard torque controller was used to capture the optimal power coefficient, which was realized by controlling pump displacement. The optimal expected pump torque can be calculated and compared with the measured pump torque to achieve the control signal error. Aiming to address the nonlinear problem between the required pump displacement and the control signal error, a two inputs and one output fuzzy controller system has been built adjust the pump displacement. Secondly, as the wind speed is above the rated wind speed, the output power is limited by controlling the blade pitch angle to keep the generation system safely working. An adaptive fuzzy controller has been designed to achieve the pitch angle control, and the stability of the control system has been analyzed through Lyapunov criterion. Finally, in order to validate the feasibility of the proposed controllers, the system has been simulated in Matlab/simulink under random wind speeds. Under low wind speed condition, the results show that thanks to the fuzzy controller, the power coefficient and the tip speed ratio of wind turbine have kept to the optimal value (0.482 and 8.1), respectively. Under high wind speed condition, adaptive fuzzy controller has successfully adjusted the pitch angle, and the maximum output power has been held near to rated value (5MW).

ACKNOWLEDGMENT

This work was supported by Scientific Research Plan Projects of Shaanxi Education Department (17JK0365) and Natural Science Foundation of Shaanxi Province (2018JM5166).

REFERENCES

[1] Global wind energy council. Global wind report(2018). www.gwec.Net/global-wind-report-2018.

[2] Ghassempour M , Failla G , Arena F . Vibration mitigation in offshore wind turbines via tuned mass damper. Engineering Structures, 2019; 183:610-636.

[3] Yin X, Zhang W, Zhao X. Current status and future prospects of continuously variable speed wind turbines: A systematic review. Mechanical Systems and Signal Processing 2019; 120:326-340.

[4] Fan YJ, Mu AL, Ma T. Study on the application of energy storage system in offshore wind turbine with hydraulic transmission. Energy Convers Manage 2016; 110:338-46.

[5] Fan YJ, Mu AL, Ma T. Modeling and control of a hybrid wind-tidal turbine with hydraulic accumulator. Energy 2016, 112:188-199.

[6] Laguna AJ. Modeling and analysis of an offshore wind turbine with fluid power transmission for centralized electricity generation. Journal of Computational and Nonlinear Dynamics 2015; 14.

[7] Silva P, Giuffrida A, Fergnani N, etc. Performance prediction of a multi-MW wind turbine adopting an advanced hydrostatic transmission. Energy 2014; 64:450-461.

[8] Buhagiar D, Sant T, Micallef C, etc. Improving the energy yield from an open loop hydraulic offshore turbine through deep sea water extraction and alternative control schemes. Energy 2015; 84:344-356.

[9] Njiri J G , Söffker D . State-of-the-art in wind turbine control: Trends and challenges. Renewable and Sustainable Energy Reviews, 2016, 60:377-393.

[10] Asghar A B , Liu X . Adaptive neuro-fuzzy algorithm to estimate effective wind speed and optimal rotor speed for variable-speed wind turbine. Neurocomputing 2018; 272: 495–504.

[11] P SM, A V, K Kottayil S. Development of a comprehensive MPPT for grid‐connected wind turbine driven PMSG.Wind Energy. 2019;22:732–744. https://doi.org/10.1002/we.2318

[12] Ammous S, Jebali M, Halima N B, etc. Development of a genetic algorithm for maximizing wind power integration rate into the electric grid. J. Renewable Sustainable Energy 11, 023303 (2019).

[13] Saravanakumar R, Jena D. Validation of an integral sliding mode control for optimal control of a three blade variable speed variable pitch wind turbine. International Journal of Electrical Power & Energy Systems 2015, 69:421-429.

[14] Golnary F , Moradi H . Design and comparison of quasi continuous sliding mode control with feedback linearization for a large scale wind turbine with wind speed estimation. Renewable Energy 2018, 127:495-508.

[15] Song D, Yang J, Su M, et al. A novel wind speed estimator-integrated pitch control method for wind turbines with global-power regulation. Energy 2017,138:816-830.

[16] Jonkman J, Butterfield S, Musial W, Scott G. Definition of a 5-MW reference wind turbine for offshore system development. Colorado: U.S. Department of Energy, National Renewable Energy Laboratory; 2009.