RESEARCH OF HYDRAULIC VARIABLE PITCH CONTROL OF THE WIND TURBINE BASEDON PID

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ABSTRACT: According to the requirement of pitch driving force, flow and load force of blade, the control system of hydraulic independent variable pitch and variable pitch actuator based on PID was designed. In the case of adding the PID controller and not adding the PID controller, the control strategy of the independent variable pitch is simulated in full load-case, and the stability of the system was analyzedto provide. The simulation results show that the PID controller can improve the control effect of the independent variable pitch of the wind turbine, improve the dynamic characteristics, and stabilize power output.

KEY WORDS: Wind Turbine, Hydraulic Variable Pitch, Dynamic Performance, PID Control.

1. INTRODUCTION

With the wind turbines towards the direction of large-scale development, MW wind turbine has become the mainstream products in the wind power market. At present, the variable pitch control technology is widely used in large wind turbines. And it can improve the efficiency of the wind turbine to capture wind energy and power generation quality. The variable propeller pitch control technology has the characteristics that it makes the wind turbine obtain good performance and reduce the impact of wind on the wind generator. The hydraulic variable pitch control technology has become one of the key technologies of wind power generation because of its high power, fast dynamic response, high precision, high torque and strong anti-interference ability[1-3]. The variable pitch system is usually placed in the engine room of the top of the wind turbine tower, which is greatly influenced by the vibration of the engine room. Therefore, under the outside interference, in order to ensure that the system can still maintain good performance when the parameters of medium and element gap are changed in a wide range, it is very necessary to study on the dynamic characteristics of the hydraulic variable pitch control technology and the variable pitch system.

2. HYDRAULIC VARIABLE PITCH CONTROL SYSTEM

Variable pitch control can be divided into two modes, unified control mode and independent control mode.

All blades of unified control mode are driven by an actuator, and the pitch angle is changed into the same for all blades. Each blade is controlled by an independent variable pitch actuator while the independent control mode. It ensure that the failure of an actuator and hydraulic system will not affect the control of the entire wind turbine. The distribution of natural wind on the swept surface on the whole wind wheel is not <u>unequal</u>. The independent blade control can be adjusted according to the wind speed on each blade. This can not only optimize the output power of the generator, but also reduce the dynamic load of the whole machine.

2.1. Structure of the Hydraulic Variable Pitch System

The independent hydraulic variable pitch mechanism is adopted in this paper. Three independent hydraulic systems are used, and the hydraulic cylinder is used as the prime mover. The crank connecting rod mechanism is connected with the piston rod of the hydraulic cylinder to drive three blades to carry out variable pitch[4-5].The pitch angle is proportional to displacement of the piston rod of the hydraulic cylinder. It can control displacement of the piston rod of the hydraulic cylinder to control the pitch angle. Schematic diagram of the hydraulic variable pitch system is shown in Fig 1. The power source of the hydraulic variable pitch system of the wind turbine unit is the hydraulic pump. The variable pitch control is realized by adjusting the electro-hydraulic proportional valve. According to the power or speed signal, the hydraulic variable pitch controller gives an electrical signal (voltage or current) to control

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the direction and size of the proportional valve output flow.

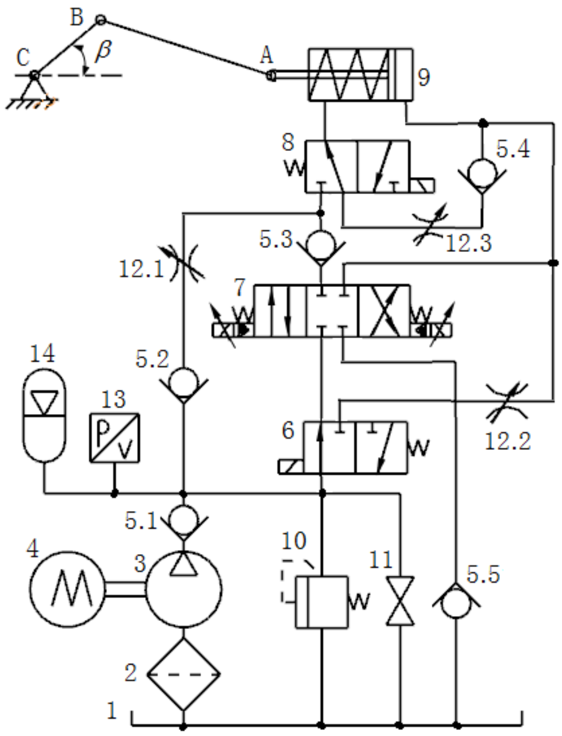

Fig 1. **Schematic of the hydraulic variable pitch system**

According to the output hydraulic oil direction and flow of electro-hydraulic proportional valve, hydraulic cylinder to control the direction and speed of the piston, and displacement of the piston of the hydraulic cylinder is controlled by the electro hydraulic proportional directional valve. The control voltage of the electro-hydraulic proportional valve is proportional to displacement of the piston of the hydraulic cylinder. By using the displacement sensor be installed in the hydraulic cylinder, the closed loop control of the position of the hydraulic cylinder is controlled by the PID adjustment. When No. 6 valve is in the left position, No. 7 electro-hydraulic proportional valve is in the left position and No. 8 valve is in the right position, the hydraulic oil flow into the rod cavity of the hydraulic cylinder, and the hydraulic oil flow out the without rod cavity of hydraulic cylinder, and the hydraulic oil flow back to the tank through the left position of No. 7 electro-hydraulic proportional valve. At the same time, the piston rod moves to the right, the blade pitch angle decreases. When the piston rod moves to the most right position, the pitch angle is 0 degrees. When No. 6 valve is in the left position, No. 7 electro-hydraulic proportional valve is in the right position and No. 8 valve is in the right position, and the hydraulic oil flow into the without rod cavity of the hydraulic cylinder, and the hydraulic oil of the without rod cavity flow into the without rod cavity of hydraulic cylinder, and this forms differential circuit. At the same time, the piston rod moves to the left, the blade pitch angle increases. When the piston rod moves to the most left position, the pitch angle is 90 degrees. In order to improve the pitch speed, the pitch control system not only introduces the differential circuit, but also uses the accumulator to protect the system. When the system is in trouble and power off, the hydraulic pumpis shut down in an emergency, and hydraulic pressure from accumulator make the blade reset.

2.2. Control of the Hydraulic Variable Pitch System Based on PID

The hydraulic variable pitch system of the wind turbine based on PID control is shown in Figure 2. The electro-hydraulic proportional valve controlled the piston of the hydraulic cylinder to drive the crank connecting rod mechanism to realize that the pitch angle is controlled. The detection system feedback displacement of the piston rodto the PID controller with the aid of displacement sensor. The pitch angle values be given were compared with the measured values of the actual response to form deviation. The PID pitch controller tunes PID parameter based on the deviation values of the pitch angle. The control voltage of the electro-hydraulic proportional valve of the hydraulic system is calculated. After the voltage signal is converted to the current signal through the D/A controller, the current signal control the electro-hydraulic proportional valve output flow size and direction to drive movement of the piston of the hydraulic cylinder, so as to realize to control and adjust the pitch angle. The displacement sensor measured the displacement signal of the piston of the hydraulic cylinder. The A/D controller calculates the actual pitch angle based on the displacement signal. The hydraulic variable pitch system is a typical position control system. The system realizes the control of displacement of the piston rod of the hydraulic cylinder by controlling the output pressure of the electro-hydraulic proportional valve. So the control performance of the system depends on the characteristics of the electro-hydraulic proportional valve, the hydraulic cylinder and other components and the design of the pitch controller.

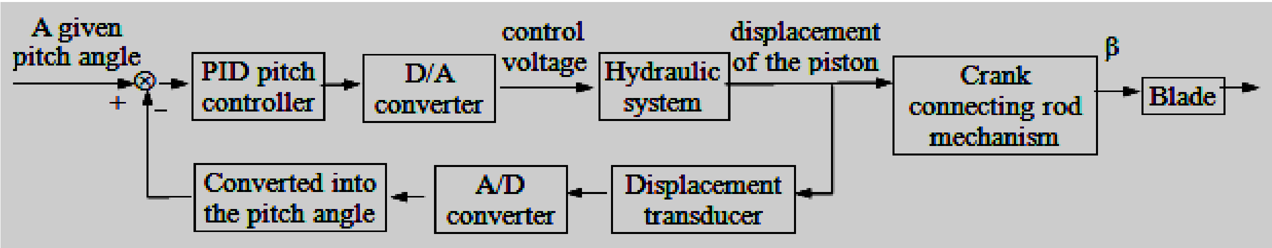

Fig 2. Control block diagram of the variable pitch control system

Hydraulic variable pitch system can be divided into three working process: One is to capture wind energy size and the rated number difference is positive, the proportional valve controls the piston of the hydraulic cylinder to extend out according to the input signal, and the pitch angle increases. This process is referred to as closing pitch. Two is to capture wind energy size and the rated number difference is negative, the proportional valve controls the piston of the hydraulic cylinder to retract according to the input signal, and the pitch angle decreases. This process is referred to as opening pitch. Three is that the wind turbine encounter to emergency situation, the hydraulic variable pitch system can quickly make the blade reset.

3. MATHEMATICAL MODEL OF HYDRAULIC PITCH CONTROL SYSTEM

Non symmetrical hydraulic cylinder differential circuit is controlled by electro-hydraulic proportional valve in the process of closing pitch. Non symmetricalhydraulic common circuit is controlled by electro-hydraulic proportional valve in the process of opening the pitch. So their hydraulic natural frequency, hydraulic damping ratio and other parameters are not the same, they need to be modeled separately. The mathematical model of the variable pitch hydraulic system requires the transfer function of the proportional electromagnet, the electro-hydraulic proportional valve port flow equation, the continuity equation of the flow of the hydraulic cylinder, the force balance equation of the hydraulic cylinder and the displacement equation of the crank connecting rod mechanism[6-8].

3.1. Close Pitch

3.1.1. The Relationship Equation Between the Pitch Angle β and the Displacement y of the Piston

$$y(s) = K_y \beta(s) \tag{1}$$

3.1.2 Force Balance Equation of the Electro-Hydraulic Proportional Pilot Valve

The electro-hydraulic proportional valve in the variable pitch hydraulic system is a pilot operated proportional valve. Through amplification effect of the pilot valve of the electro-hydraulic proportional valve, high pressure and large flow liquid flow control can be realized. The control principle of the electro-hydraulic proportional valve is the closed loop control of displacement force feedback. The position of the pilot valve core and the main valve core is connected with the feedback spring. When the electromagnet pushes the pilot valve core to overcome the spring force of the feedback spring and move down, the upper cavity pressure of the main valve core will drop. Under the action of pressure difference, the main valve core moves up to enable the proportional valve to open. Displacement of the main valve core is changed into a feedback force acting on the pilot valve core through a feedback spring. Finally the force and the electromagnetic force reach the balance.

$$F_i = K_i \cdot i = F_f = K_f \cdot x_V \tag{2}$$

In the formula (2), F_i is the electromagnetic force of the proportional valve; F_f is the pilot valve spring force; K_i is the magnification factor of the electromagnetic force and electric current of proportional valve; i is the input current of the electromagnet of proportional valve; K_f is the; x_V is the displacement of the Proportional valve spool.

3.1.3. Electro-Hydraulic Proportional Valve Port Flow Equation

$$Q_L = x_V C_q A_T \sqrt{\frac{2}{\rho}(P_P - P_C)} - \frac{x_V C_q A_T \sqrt{\frac{2}{\rho}(P_P - P_C)}}{2(P_P - P_C)} P_C = K_q x_V - K_C P_C \tag{3}$$

In the formula (3), Q_L is the Electro-hydraulic proportional valve port flow; K_q is the magnification factor of the flow; K_C is the magnification factor of the flow–pressure; P_C is the outlet pressure of the electro-hydraulic proportional valve; P_p is the supply pressure; A_T is the cross section area of the valve; C_q is the flow coefficient of the valve port.

3.1.4. Flow Continuity Equation of Hydraulic Cylinder

$$Q_L = A_1\frac{dy}{dt} + \frac{V_0}{\beta_e}\frac{dP_C}{dt} + C_{in}(P_P - P_C) \tag{4}$$

After Laplace transform, the formula is:

$$Q_L(s) = A_1 sy(s) + \frac{V_0}{\beta_e}sP_C(s) + C_{in}P_C(s) \tag{5}$$

In the formula (5), A_1 is the effective working area of the without rod cavity of the hydraulic cylinder; β_e is the volume elastic modulus of the hydraulic oil; V_0 is the working volume of the hydraulic oil; C_{in} is the internal leakage coefficient.

3.1.5. Force Balance Equation of Hydraulic Cylinder

$$P_C A_1 L = G\frac{d^2\beta}{dt^2} + T_L \tag{6}$$

After Laplace transform, the formula is:

$$A_1 LP_C(s) = Gs^2\beta(s) + T_L(s) \tag{7}$$

In the formula (7), G is the rotation inertia of the blade around the longitudinal axis; T_L is the load torque; L is the simplified equivalent arm length of four bar mechanism.

3.1.6. Transfer Function of the Pitch Angle β and the Displacement x_V of the Piston

By formula (1), (3), (5)and (7), the relationship can be get between β and x_V:

$$\beta(s) = \frac{\frac{K_q}{A_1K_y}x_V - \frac{T_L}{A_1^2K_yL}(\frac{V_0}{\beta_e}s + C_{in} + K_C)}{\frac{V_0G}{\beta_eA_1^2K_yL}s^3 + \frac{(C_{in}+K_C)G}{A_1^2K_yL}s^2 + s} = \tag{8}$$

$$= \frac{K_Vx_V - \frac{T_L}{A_1^2K_yL}(\frac{V_0}{\beta_e}s + C_{in} + K_C)}{s(\frac{s^2}{\omega_h^2} + \frac{2\xi_h}{\omega_h} + 1)}$$

In the formula (8), K_V is the velocity coefficient of the hydraulic cylinder piston, $K_V = \frac{K_q}{A_1K_y}$; ω_h is the natural frequency of hydraulic of closing pitch, $\omega_h = \sqrt{\frac{\beta_eA_1^2K_yL}{V_0G}}$; ξ_h is the damping ratio of the hydraulic system of closing pitch, $\xi_h = \frac{C_{in}+K_C}{2A_1}\sqrt{\frac{\beta_eG}{V_0K_yL}}$.

By formula (8), the blade pitch angle β is affected by the working pressure of the hydraulic pump and variable load torque. Without taking into account the load torque, there is a formula (9).

$$\beta(s) = \frac{K_Vx_V}{s(\frac{s^2}{\omega_h^2} + \frac{2\xi_h}{\omega_h} + 1)} \tag{9}$$

By formula (2) and (9), there is formula (10).

$$\beta(s) = \frac{K_d i}{s(\frac{s^2}{\omega_h{}^2} + \frac{2\xi_h}{\omega_h}s + 1)} \tag{10}$$

In the formula (10), K_d is the proportional amplification factor of the electro-hydraulic system, $K_d = \frac{K_VK_i}{K_f}$.

The closed-loop transfer function of the variable pitch system is the formula (11).

$$G(s) = \frac{\beta(s)}{I(s)} = \frac{\frac{K_d}{s(\frac{s^2}{\omega^2} + \frac{2\xi_h}{\omega_h}s + 1)}}{1 + \frac{K_dK_s}{s(\frac{s^2}{\omega_h{}^2} + \frac{2\xi_h}{\omega_h}s + 1)}} = \tag{11}$$

$$= \frac{K_d}{s(\frac{s^2}{\omega_h^2} + \frac{2\xi_h}{\omega_h} + 1) + K_dK_s}$$

Because the inherent frequency of the variable pitch system is much greater than the natural frequency of the wind turbine, the formula (11) can be simplified as a first-order link. That is the formula (12).

$$G(s)=\frac{K_d}{s+K_dK_s} \tag{12}$$

3.2. Open Pitch

3.2.1. Flow Continuity Equation of Hydraulic Cylinder

$$Q_L=A_1\frac{dy}{dt}+\frac{V_0}{(1+\lambda^2)\beta_e}\frac{dP_L}{dt}+(\frac{1+\lambda}{1+\lambda^3}C_{in}+\frac{1}{1+\lambda^2}C_{out})P_L \tag{13}$$

After Laplace transform, the formula is:

$$Q_L(s)=A_1sy(s)+\frac{V_0}{(1+\lambda^2)\beta_e}sP_L(s)+C_TP_L(s) \tag{14}$$

In the formula (14), λ is the area ratio, $\lambda=\frac{A_2}{A_1}$; A_2 is the effective working area of the rod cavity of hydraulic cylinder; P_L is the load pressure, $P_L=P_1-\lambda P_2$; $C_T=\frac{1+\lambda}{1+\lambda^3}C_{in}+\frac{1}{1+\lambda^2}C_{out}$; C_{out} is the external leakage coefficient.

3.2.2. Force Balance Equation of Hydraulic Cylinder

Because the viscous damping coefficient is very small, and the load spring coefficient is not considered, then that is the formula (15).

$$P_LA_1L=G\frac{d^2\beta}{dt^2}+T_L \tag{15}$$

After Laplace transform, the formula is:

$$A_1LP_L(s)=Gs^2\beta(s)+T_L(s) \tag{16}$$

3.2.3. The Transfer Function about the Blade Pitch Angle β and Displacement x_V of Proportional Valve

According to the process of the close pitch, the relationship between β and x_V can be get by formula (1), (3), (14) and (16). That is the formula (17).

$$\beta(s)=\frac{K_Vx_V-\frac{T_L}{A_1^2K_yL}(\frac{V_0}{(1+\lambda^2)\beta_e}s+C_T+K_C)}{s(\frac{s^2}{\omega_h'^2}+\frac{2\xi_h'}{\omega_h'}+1)} \tag{17}$$

In the formula (17), ω_h' is the natural frequency of hydraulic in the process of closing pitch, $\omega_h'=\sqrt{\frac{(1+\lambda^2)\beta_eA_1^2K_yL}{V_0G}}$; ξ_h' is the damping ratio of the hydraulic system in the process of opening pitch, $\xi_h'=\frac{C_T+K_C}{2A_1}\sqrt{\frac{(1+\lambda^2)\beta_eG}{V_0K_yL}}$.

Without taking into account the load torque, there is a formula (18) by formula (2) and (16).

$$\beta(s)=\frac{K_di}{s(\frac{s^2}{\omega_h'^2}+\frac{2\xi_h'}{\omega_h'}s+1)} \tag{18}$$

The closed-loop transfer function of the variable pitch system is the formula (19).

$$G(s)=\frac{K_d}{s(\frac{s^2}{\omega_h'^2}+\frac{2\xi_h'}{\omega_h'}+1)+K_dK_s} \tag{19}$$

Because the inherent frequency of the variable pitch system is much greater than the natural frequency of the wind turbine, the formula (19) can be simplified as a first-order link. That is the same the formula (12).

4. SIMULATION AND DYNAMIC CHARACTERISTIC ANALYSIS OF THE VARIABLE PITCH SYSTEM

The parameter has been tuned by PID controller. Simulation and analysis of the variable pitch hydraulic system of the large wind turbine (1.5MW) in Matlab/Simulink simulation environment [9].

In the process of closing pitch, the PID parameters are set as follows: $K_{PC}=9.5$, $K_{IC}=19.5$, $K_{DC}=0.1$. The comparison chart is shown in Fig 3 before and after the addition of the PID parameter tuning. The rise time of the step response and the steady state value of the system after the PID parameter tuning are significantly less than that of the PID parameter tuning. The system is without overshoot before the PID parameter tuning. The overshoot of the system is about 19% after the PID parameter tuning. In the case of the loss of a small amount of overshoot, through the PID parameter tuning, the system obtained a faster response time, and the dynamic performance of the system has been greatly improved.

In the process of opening pitch, the PID parameters are set as follows: $K_{PO} = 7.8$, $K_{IO} = 18.2$, $K_{DO} = 0.05$. The comparison chart is shown in Fig 4 before and after the addition of the PID parameter tuning. The response time of the system is greatly accelerated, the dynamic performance of the system is greatly improved, and they can meet the requirements of system stability and rapidity.

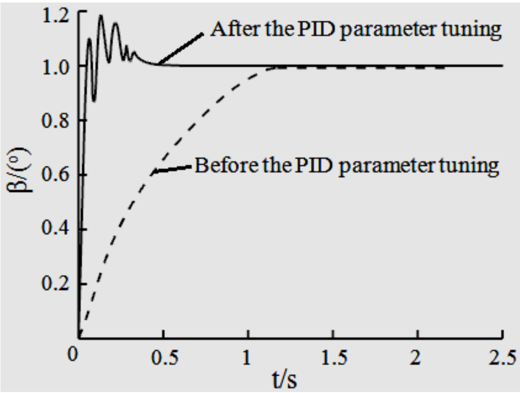

Fig 3. The system step response of closing pitch

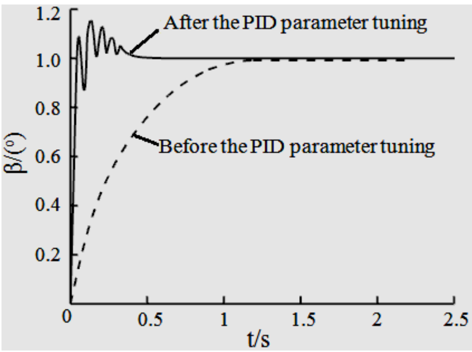

Fig 4. The system step response of opening pitch

5. CONCLUSION

The mathematical model of the independent hydraulic variable pitch mechanism of the wind turbine is established. On the basis of analyzing the open loop transfer function of the hydraulic system, the parameters of the PID controller are determined. In the Matlab/Simulink simulation environment, the mathematical model is simulated and analyzed, and the stability and dynamic characteristics of the system are verified.

6. ACKNOWLEDGEMENTS

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