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Pitch Control of Offshore Floating Wind Turbine Based on Fast Integral-Type Terminal Sliding Mode Control Method

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ABSTRACT

China has a vast territory and abundant offshore wind resources, which provides an environmental basis for the development of offshore floating wind turbine. The typical characteristics of the development of floating wind turbine are far-reaching sea and large-scale structure. The traditional controller can not deal with the complex marine working conditions and the complexity of the wind turbine structure. For the floating wind turbine, the main control objectives are to stabilize the power output, reduce the load and stabilize the movement of the platform in six degrees of freedom.Therefore, this paper proposes a pitch controller based on the fast integral-type terminal sliding mode (FITS) method, and selects the 5 MW barge floating wind turbine of National Renewable Energy Laboratory (NREL) as the research object. Combined with OpenFAST /Matlab software, the simulation experiments are compared with the traditional baseline gain scheduling PI controller(GSPI) from three aspects: power stability, load shedding and platform motion performance. The simulation results show the effectiveness of the proposed scheme.

Keywords: Wind turbine, sliding model control, loading shedding, stable power, pitch control

NONMENCLATURE

Abbreviations	
FITS	Fast integral-type terminal sliding mode
GSPI	Gain scheduling PI controller
NREL	National Renewable Energy Laboratory

1. INTRODUCTION

As a kind of renewable energy, wind energy has experienced rapid development from onshore wind power to offshore wind power. According to the latest report of the Global Wind Energy Council (GWEC) in April 2022, by 2021, the new installed capacity of global wind power had reached 93.6GW, of which the new installed capacity of offshore wind power was about 21.1GW, increase of 346% compared with 2020 [1]. The development of wind energy in renewable energy has received special attention. Although offshore wind turbines are developing rapidly, the development of offshore floating wind power is still in the pre commercialization stage. Therefore, before the commercialization stage in 2026[2], the research on the control technology of floating wind power is particularly important.

As the main wind energy conversion system, one of the key control objectives of wind turbine is power control. When the wind speed is lower than the rated wind speed, the wind turbine needs to control the electromagnetic torque to track the optimal power coefficient. When it is higher than the rated wind speed and lower than the cut-out wind speed, it needs to control the pitch angle to ensure that the rotor speed remains at the rated value and realize the stable power output, that is, pitch control[3][4]. This paper considers the constant power control of the wind turbine in full compliance with the operation area. Taking the 5MW barge floating wind turbine of NERL as the research object, this paper designs the pitch controller to achieve the purpose of constant power control.

For the nonlinear, multivariable and strong coupling characteristics of the far-reaching sea wind power generation system, as well as the natural wind speed, irregular waves, the dynamic changes of power demand and system operating conditions, the conventional control methods can not stabilize the power output. As a special nonlinear control algorithm, sliding mode control algorithm has strong robustness and adaptability in dealing with system nonlinearity, uncertainty and strong interference[5][6]. The traditional linear sliding mode can not solve the singularity problem[7][8]. In this paper, a nonsingular fast terminal integral-type sliding mode controller is designed to control the barge wind turbine. The introduction of integral sliding surface not only solves the singularity problem of the traditional sliding controller, but also improves the stability of the system. The symbolic function is introduced to improve the convergence speed of the system. In this paper, OpenFAST and MATLAB software are used for joint simulation to prove the fast convergence and stability of the proposed controller.

2. SYSTEM MODEL

2.1 Hydraulic pitch control system model

The function of the pitch system of the motor unit is to adjust the pitch above the rated wind speed, and the adjustment of the pitch angle plays an important role in stabilizing the power output and reducing the load. In this paper, the hydraulic pitch system is adopted, and the actuator of each individual pitch system can be described as a linear second-order model, in which the transfer function expression is as follows:

$$\frac{\beta}{\beta_r}=\frac{\omega_n^2}{\omega_n^2+2\varepsilon\omega_n+s^2} \tag{1}$$

Where $\beta_r,\varepsilon,\omega_{\mathrm{n}}$ are the reference pitch angle, damping ratio and oscillation frequency respectively.

2.2 Transmission chain system model

The traditional chain of wind turbine is the actuator of the whole energy conversion system. The main structure includes low-speed shaft, gearbox and high-speed shaft. The overall mechanical structure is shown in Fig.1

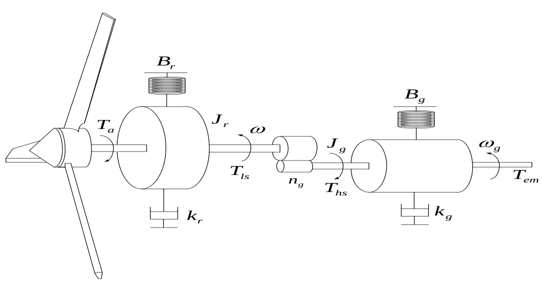


Fig.1 Wind turbine drive chain system model

According to Fig.1, the dynamic state equation of the wind turbine transmission system can be written as follows:

$$\begin{aligned}
\dot{\omega}&=\frac{1}{J_r}\left(\frac{P}{\omega}-\omega B_r+\frac{\omega_g B_r}{n_g}-\theta_r K_r\right)\\
\dot{\omega}_g&=\frac{1}{J_g}\left(\frac{\omega B_r}{n_g^2}+\frac{\theta_r k_r}{n_g^2}-T_g\right)\\
\dot{\theta}_r&=\omega-\frac{\omega_g}{n_g}
\end{aligned} \tag{2}$$

Where J_r and J_g are the moment of inertia ofwind turbine and generator rotor respectively; K_r and B_r are the stiffness coefficient and damping coefficient of the low-speed shaft of the wind turbine rotor respectively; T_g is the equivalent electromagnetic torque generated on the low-speed shaft of the wind turbine, $T_g=n_gT_{em}$; θ_r and θ_g is the rotor torsion angle of wind turbine side and generator side respectively; n_g is the transmission ratio of gearbox; P is the power captured by the wind turbine.

According to equations (1) and (2), the state vector is selected as $x=[\omega,\omega_g,\theta_r,\beta,\dot{\beta}]$,The control signal is u, then the nonlinear wind turbine model can be written in the following general form.

$$\dot{x}=f\left(x,\dot{x}\right)+gu \tag{3}$$

Where $f(x,\dot{x})$ is the nonlinear term of the wind turbine system, and g is the control input coefficient. According to equation (3), the second-order differential equation of rotor speed can be described as follows:

$$\frac{d^2x_1}{dt^2}=L_f(x)+L_g(x)u \tag{4}$$

Where

$$\begin{aligned}
L_f(x)&=\frac{\partial f_1}{\partial x_1}f_1+\frac{\partial f_1}{\partial x_2}f_2+\frac{\partial f_1}{\partial x_3}f_3+\\
&\quad\frac{\partial f_1}{\partial x_4}f_4+\frac{\partial f_1}{\partial x_5}f_5+\frac{\partial f_1}{\partial U}\dot{U}\\
L_g(x)&=\frac{\partial f_1}{\partial x_5}g_5
\end{aligned} \tag{5}$$

3. CONTROLLER DESIGN

3.1 Controller design

Define the error signal as

$$e=\omega-\omega_{r0} \tag{6}$$

Where ω_{r0} is the rated speed of rotor. Definition such as sliding model surface:

$$s=\dot{e}+c_1e+c_2\int_0^t(e+e^q+e^{l/r})dt \tag{7}$$

Where c_1 is the normal number. $0<l/r<1$, $q>l/r$ is a constant,The derivation of synovial variables is:

$$\dot{s}=\ddot{e}+c_1\dot{e}+c_2(e+e^q+e^{l/r}) \tag{8}$$

If considering the influence of disturbance d, the controller is designed as follows:

$$u=-\hat{L}_g^{-1}[\hat{L}_f+c_1\dot{e}+c_2(e+e^q+e^{l/r})+\hat{d}+r_1s+r_2\operatorname{sgn}(s)] \tag{9}$$

Where $\hat{L}_g,\hat{L}_f,\hat{d}$ represent the estimated values of L_g,L_f,d respectively, and r_1 and r_2 are normal numbers.

In order to estimate the size of external disturbance, the following form of disturbance observer is adopted.

$$\begin{aligned}\dot{z}&=-kz-k[k\dot{\omega}+L_f+L_gu]\\ \hat{d}&=z+k\dot{\omega}\end{aligned} \tag{10}$$

Where, z is the state of the observer, k is the gain of the stater, and $k>0$ is required. The proof of asymptotic stability of the observer is given. Firstly, the disturbance observation error is defined as follows:

$$\tilde{d}=d-\hat{d} \tag{11}$$

By deriving the observation error and combining (10) and (11), we can get:

$$\begin{aligned}\dot{\tilde{d}}&=\dot{d}-\dot{\hat{d}}\\ &=\text{-}\dot{z}-k\ddot{\omega}\\ &=k(d\text{ - }k\dot{\omega})+k(k\dot{\omega}+L_f+L_gu)\\ &\quad -k(L_f+L_gu+d)\\ &=\text{-}k\tilde{d}\end{aligned} \tag{12}$$

It can be seen from equation (12) that the disturbance observer is asymptotically stable.

Since $\hat{L}_g^{-1}$ and $\hat{L}_f$ are not good at designing their own adaptive update law separately, two intermediate variables are defined as follows:

$$\begin{aligned}\hat{\Gamma}&=\hat{L}_f/\hat{L}_g\\ \hat{\chi}&=\hat{L}_g^{-1}\end{aligned} \tag{13}$$

According to (13), equation (9) can be rewritten as:

$$\begin{aligned}u=&-\hat{\chi}[c_1\dot{e}+c_2(e+e^q+e^{l/r})+\hat{d}\\ &+r_1S_m+r_2\operatorname{sgn}(S_m)]-\hat{\Gamma}\end{aligned} \tag{14}$$

The adaptive updating laws of $\hat{\chi}$ and $\hat{\Gamma}$ can be designed as follows:

$$\begin{aligned}\dot{\hat{\Gamma}}&=S_m=s-asat(s)\\ \dot{\hat{\chi}}&=[c_1\dot{e}++c_2(e+e^q+e^{l/r})\\ &\quad+\hat{d}+r_1S_m+r_2\operatorname{sgn}(S_m)]S_m\end{aligned} \tag{15}$$

Where a is a small positive value and satisfies the following relationship:

$$sat(s)=\begin{cases}\operatorname{sgn}(s), & |s|>a\\ s/a, & |s|\le a\end{cases} \tag{16}$$

3.2 Proof of stability

Select the following Lyapunov function:

$$\begin{aligned}V&=\frac{1}{2}(S_m^TS_m+\chi^{-1}\tilde{\chi}^2+\chi^{-1}\tilde{\Gamma}^2+\tilde{d}^2)\\ &=\frac{1}{2}(S_m^TS_m+\chi^{-1}(\hat{\chi}-\chi)^2\\ &\quad+\chi^{-1}(\tilde{\Gamma}-\Gamma)^2+\tilde{d}^2)\end{aligned} \tag{17}$$

By deriving equation (17), we can get:

$$\begin{aligned}\dot{V}=&S_m^T\{\chi^{-1}\Gamma-\chi^{-1}\hat{\Gamma}-\chi^{-1}\hat{\chi}(c_1\dot{e}+c_2(e+e^q+e^{l/r})\\ &-\hat{d}-\chi^{-1}\hat{\chi}\gamma_1S_m)-\chi^{-1}\hat{\chi}\gamma_2\operatorname{sgn}(S_m)+d+c_1\\ &+c_2(e+e^q+e^{l/r})\}+\chi^{-1}(\hat{\chi}-\chi)\dot{\hat{\chi}}+\chi^{-1}(\hat{\Gamma}-\Gamma)\dot{\hat{\Gamma}}\\ &-k\tilde{d}^2=\chi^{-1}(\hat{\Gamma}-\Gamma)(\dot{\hat{\Gamma}}-S_m)+S_m^T(\chi^{-1}\hat{\chi}-1)\\ &\quad\left(c_1\dot{e}+c_2(e+e^q+e^{l/r})-\hat{d}\right)+(\chi^{-1}\hat{\chi}-1)\dot{\hat{\chi}}\\ &+S_m^T\tilde{d}-S_m^T\chi^{-1}\hat{\chi}(\gamma_1S_m+\gamma_2\operatorname{sgn}(S_m))-k\tilde{d}^2\end{aligned} \tag{18}$$

The adaptive rate equation can be obtained by substituting (18)

$$\dot{V}=-S_m^T\gamma_1S_m-S_m^T\gamma_2\operatorname{sgn}(S_m)+S_m^T\tilde{d}-k\tilde{d}^2 \tag{19}$$

Adopt[9] $S_mS_m=|S_m|^2, S_m\ \operatorname{sgn}(S_m)=|S_m|, \gamma_2\ge(\eta+\varepsilon)$, we can get

$$\begin{aligned}\dot{V}&\le-\gamma_1|S_m|^2-\eta|S_m|-k\tilde{d}^2\\ &\le-\gamma_1|S_m|^2-|S_m|(\eta+\frac{k\tilde{d}^2}{|S_m|})\end{aligned} \tag{20}$$

Selected switching gain $\eta > k\tilde{d}^2 / |S_m| + \sigma_m$, In addition, σ_m is an arbitrary normal number, so equation (20) can be simplified as:

$$\dot{V} < -\sigma_m |S_m| \tag{21}$$

According to reference[10] and equation (21) the system is stable.

4. SIMULATION VERIFICATION

In order to verify the effectiveness of the proposed control strategy, this paper selects NERL 5MW barge floating wind turbine as the research object, and uses FAST / Matlab software for simulation analysis. The selected working condition is 12 m / s turbulent wind, and the wave is an irregular wave with wave height of 5m and spectral peak period of 12.4s. Fig.2 and Fig.3 are wind speed curve and wave curve respectively. The controller parameters designed in this paper are $c_1 = 0.2, c_2 = 0.001, r_1 = 0.468, r_2 = 0.002; k = 0.005; a = 0.005$

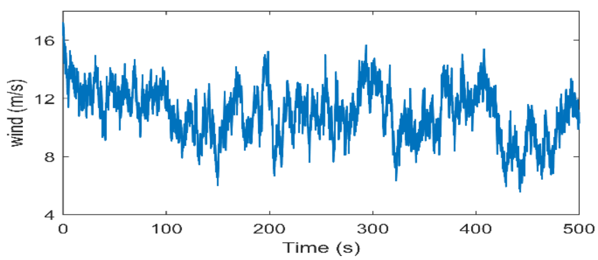


Fig.2 Wind speed curve

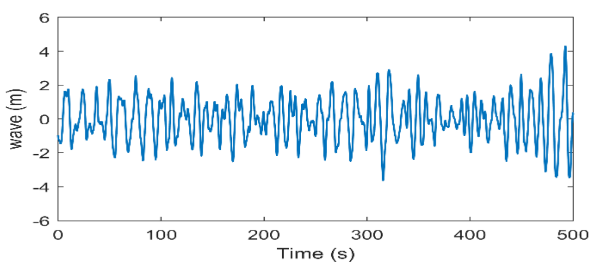


Fig.3 Wave curve

① Power stability analysis

In order to prove the effectiveness of the proposed nonsingular fast Integral-type terminal sliding mode control (FITS) method, it is compared with the traditional baseline controller gain scheduling proportional integral (GSPI). Below, we make a comparison from three aspects: power stability, load shedding and platform motion.

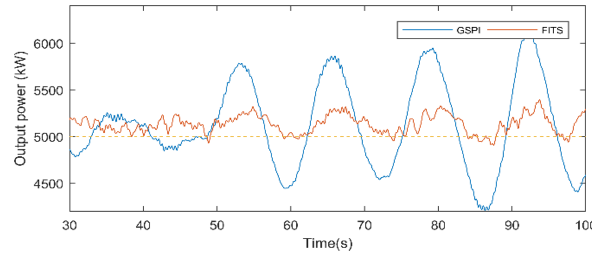


Fig.4 Comparison of output power

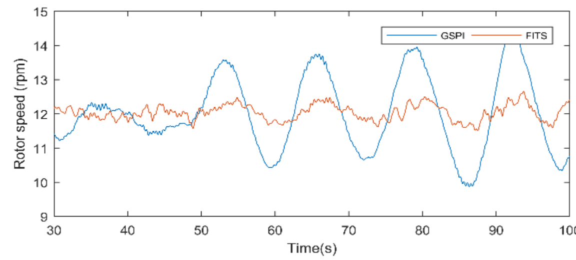
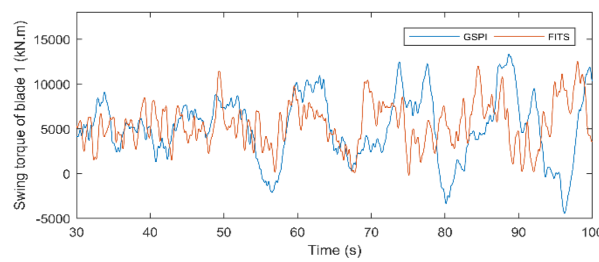


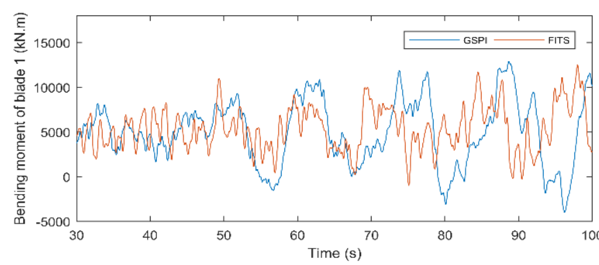
Fig.5 Rotor speed

Fig.4 shows the comparison diagram of output power. It can be seen from the figure that FITS controller can be more stable near the rated power than GSPI controller. Fig. 5 is the speed diagram of wind energy. It can be seen from the figure that the wind turbine speed of FITS controller has been stable between 12.1rad/s of rated speed, while GSPI is gradually away from the rated value.

② Load reduction

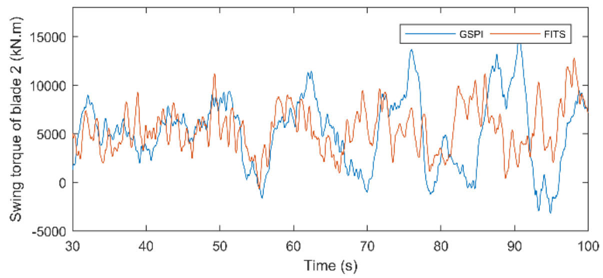


(a) Swing torque

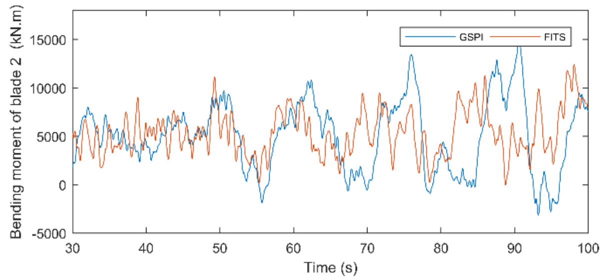


(b) Bending moment

Fig.6 Swing moment and bending moment of blade1

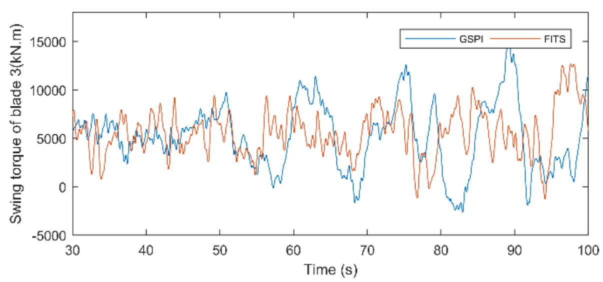


(a) Swing torque

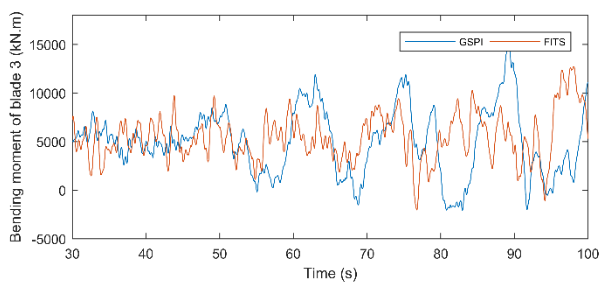


(b) Bending moment

Fig.7 Swing moment and bending moment of blade2



(a) Swing torque



(b) Bending moment

Fig.8 Swing moment and bending moment of blade3

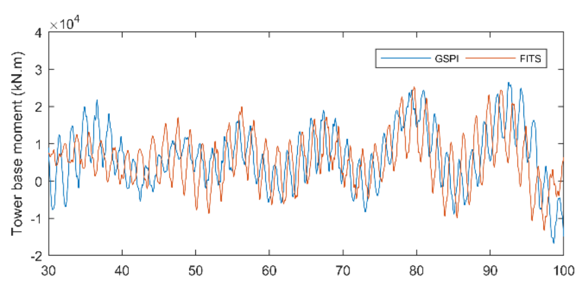


Fig.9 Tower foundation moment

Fig.6 to Fig.8 show the Swing torque and bending torque of three blades. From the figure, it can be seen that FITS can better reduce its swing torque and bending torque than GSPI. It can be seen from Fig.9 and Fig.10 that FITS has better performance than GSPI in reducing tower foundation torque and pitching torque.

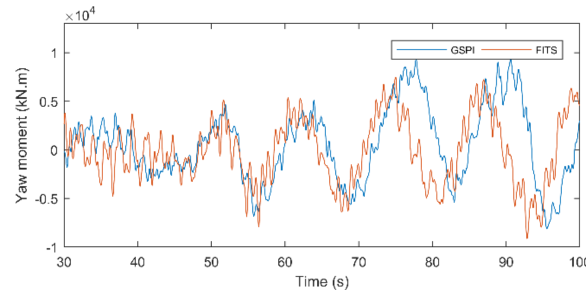
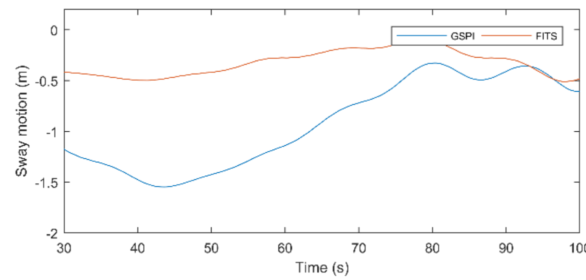
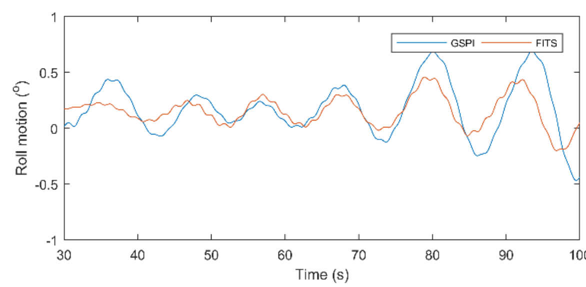


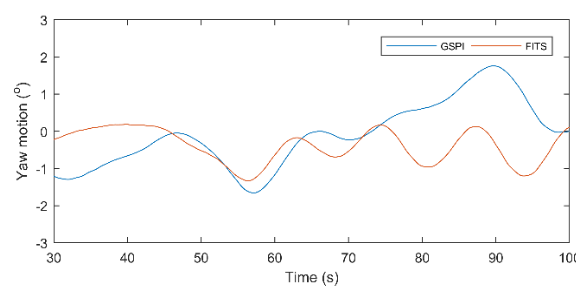
Fig.10 Yaw moment



(a) Sway motion



(b) Roll motion



(c) Yaw motion

Fig.11 Motion characteristics of barge platform

③ Motion performance of floating platform

The translational displacement and yaw angle of the floating platform can represent the stability of the floating platform. As shown in (a), (b) and (c) of Fig.11, the motion performance of FITS in the sway, roll and yaw directions of the control platform is better than that of GSPI.

To sum up, the FITS proposed in this paper is much better than GSPI in stabilizing power output and reducing load, while FITS is slightly better than GSPI in motion performance of floating platform. Table 1 shows the specific percentage performance improvement. In this paper, the quantitative analysis of the two controllers is compared, and the maximum value of each group of data is used. The calculation formula is as follows:

$$Q = (GSPI_{\max} - FITS_{\max}) / GSPI_{\max} \times 100\% \tag{22}$$

Where Q represents the percentage of performance improvement of FITS compared with GSPI.

Table.1 Performance improvement percentage

Performance index	$GSPI_{\max}$	$FITS_{\max}$	Q
Power(KW)	6094	5394	14%
Bending moment of blade 1 (KN.m)	12875	12505	6.9%
Bending moment of blade 2 (KN.m)	14975	12448	16.9%
Bending moment of blade 3 (KN.m)	15227	12729	17.7%
Swing moment of blade 1 (KN.m)	13314	12525	5.9%
Swing moment of blade 2 (KN.m)	14971	12806	14.5%
Swing moment of blade 3(KN.m)	15268	12709	16.8%
Tower foundation moment (KN.m)	26456	25210	4.7%
Yaw moment(KN.m)	9423	9143	2.97%
Sway(m)	1.55	0.5	67.7%
Roll(deg)	0.69	0.46	33.3%
Yaw(deg)	1.76	0.19	89.4%

5. CONCLUSION

In this paper, a pitch controller based on fast integral-type terminal sliding mode (FITS) method is proposed, which is verified by simulation experiments with OpenFAST / Matlab software, and compared with the traditional baseline gain scheduling proportional integral(GSPI) controller from three aspects: power stability, load shedding and motion performance of barge floating platform. The following conclusions are drawn: 1) FITS controller has better performance in stable power balance than GSPI; 2) It has better performance than GSPI controller in reducing blade swing torque and bending torque, and FITS has better performance than GSPI in reducing blade root load, tower base load and yaw torque; 3) The motion performance of FITS in the sway, roll and yaw directions of the control platform is better than that of GSPI. The simulation results show the effectiveness of the pitch controller based on the fast terminal sliding mode method.

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