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Robust Control Design of Permanent Magnet Direct-drive Wind Power System

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Aiming at the difficulty of rapid response control in the system caused by the high inertia of the wind turbine system with large capacity, the work studied the robust control of nonlinear speed of direct-drive permanent magnet wind turbine. After analyzing the characteristics of wind turbine as well as the nonlinear dynamic structure of permanent magnet synchronous motor, we proposed a comprehensive control strategy combining Backstepping control technology and L_2 disturbances attenuation to design the speed regulation controller of wind turbine. On the basis, the method of load torque feedforward compensation was introduced to form a quick-response control strategy that is easy to be realized. Simulation shows compared with the traditional vector control and the voltage feedforward decoupling control, the proposed control strategy has the effectiveness and robustness for the quick-response control of wind turbine with large capacity.

1. Introduction

Compared with the traditional doubly-fed induction wind turbine, the direct-dive permanent magnet synchronous turbines eliminates the speed gearbox, thus simplifying the mechanical transmission, improving the wind energy utilization rate and reducing the cost of operation and maintenance. It has been widely used in wind power generation systems with large capacity, especially offshore wind power (Sriram et al., 2017; Liao et al., 2015).

Permanent magnet synchronous turbine is a complex object with multivariable, strong coupling, nonlinearity and variable parameters. Furthermore, the high inertia of turbine wheel with large capacity causes the difficulty in the quick-response control of the system. It has become a new hot spot in wind power control.

In Reference (Verrelli et al., 2017), a nonlinear adaptive position/speed tracking control for sensorless PMSMs, with simultaneous estimation of uncertain constant load torque and stator resistance.In Reference (Liu and Pan 2015), it adopts the voltage feed forward decoupling current vector control. Meanwhile, the real-time dynamic compensation is performed to stator current by the online observation of load, which effectively improves the system speed control. In Reference (Verrelli, 2012), if the exogenous rotor position reference signal (which is to be globally tracked without assuming its foreknowledge) is restricted to the class of sinusoidal signals with uncertain bias, amplitude, frequency and phase, a stronger result can be derived by resorting to nonlinear advanced identification techniques.It is applied to industrial PMSM speed control. In Reference (Xi et al., 2015), a multi-objective control strategy is proposed based on the feedback linear model, which achieves the MPPT below the rated wind speed and the minimum system loss.

It does not take into account the situation of high inertia load in the nonlinear modes and the strategies of permanent magnet direct-drive wind turbine or PMSM, with little attention to the dynamic quick response of the system and the problem of robust. The work proposed a comprehensive control strategy combining Backstepping control technology and L_2 disturbances attenuation to design the speed regulation controller of wind turbine meanwhile, combined with the dynamic compensation of load torque feedforward, it realized the quick-response control of large direct-drive wind power system. The simulation shows the feasibility and effectiveness of the proposed control strategy.

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2. The mathematic models of Permanent-magnet Direct-driven wind power system

Permanent-magnet Direct-driven wind power system generally includes wind machine, PMSM, Dual PWM rectifying device system and so on, the basic structure can be seen from Figure 1

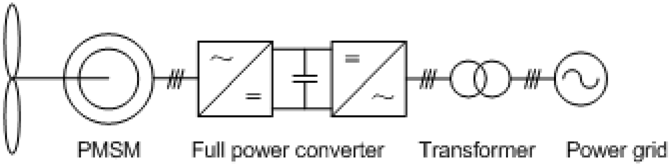


Figure 1: Permanent magnet direct drive wind power system

2.1 Features and models of wind machine

The wind machine is the main part for the energy conversion of wind system. Tip speed ratio, pitch angle of blade and power coefficient are three important parameters of wind machine. Assuming that the aerodynamic characteristics of the blades of wind machine are normal, the aerodynamic performance of a non-dimensional wind machine will depend on the tip speed ratio and the pitch angle of blade (Liu et al., 2006).

$$T_{\mathrm{l}} = \frac{P}{\omega} = \frac{\rho\pi R^2 v^3 C_{\mathrm{P}}(\lambda,\beta)}{2\omega} \tag{1}$$

In this formula, P is the output power of the wind machine, W is the speed of blade angle, *ρ is* air density, Mechanical output power is proportional to power coefficient CP, CP is a function of the tip of the blade *λ* and the pitch angle *β.* When the air speed V is certain, rotor power coefficient C_p (λ, β) determines the ability of wind machine to absorb the wind.

2.2 model of permanent magnet synchronous generator

Assuming that the sinusoidal distribution of gas gap field and the magnetic circuit is unsaturated, ignoring the eddy current and the hysteresis loss, the equation under the d-q axis PMSM stator voltage will be as follow (Geng et al., 2009; Guan et al., 2014):
Electromagnetic torque equation

$$T_{\mathrm{e}} = \frac{3}{2} p_{\mathrm{n}}[\psi_{\mathrm{f}} i_q - (L_d - L_q) i_d i_q] \tag{2}$$

Mechanical equation of wind machine

$$J\frac{\mathrm{d}\omega_{\mathrm{m}}}{\mathrm{d}t} = T_{\mathrm{l}} - T_{\mathrm{e}} - B\omega_{\mathrm{m}} \tag{3}$$

In this formula, U_d, U_q, i_d i_q, L_d, L_q, are components of epaxial *d*, *q* of stator voltage, electricity and inductance. Ψ_{f} is the magnetic chain of the permanent magnet rotor, *J* is the inertia of the motor rotor, *B* is the viscous friction system, ω_{m} is the rotation speed of the motor rotor, p_{n} is the logarithmic magnetic poles. When the motor is used as an implicit PMSM, which means $L_d=L_q=L$. Thus, the PMSM of the wind system in the d-q coordinate system comes out.

$$\begin{bmatrix} \dot{i}_d \\ \dot{i}_q \\ \dot{\omega}_{\mathrm{m}} \end{bmatrix} = \begin{bmatrix} -\frac{R_{\mathrm{s}}}{L} & p_{\mathrm{n}}\omega_{\mathrm{m}} & 0 \\ -p_{\mathrm{n}}\omega_{\mathrm{m}} & -\frac{R_{\mathrm{s}}}{L} & \frac{p_{\mathrm{n}}\psi_{\mathrm{f}}}{L} \\ 0 & -\frac{3p_{\mathrm{n}}\psi_{\mathrm{f}}}{2J} & -\frac{B}{J} \end{bmatrix} \begin{bmatrix} i_d \\ i_q \\ \omega_{\mathrm{m}} \end{bmatrix} + \begin{bmatrix} -\frac{u_d}{L} \\ -\frac{u_q}{L} \\ \frac{T_{\mathrm{l}}}{J} \end{bmatrix} \tag{4}$$

2.3 Robust nonlinear mathematical model of permanent magnet synchronous

When there is interference in the system, system (4) (ω_{m0}, i_{q0}, i_{d0})'s defined state variable is $x_1=\omega_m-\omega_{m0}$, $x_2=i_q-i_{q0}$, $x_3=i_d-i_{d0}$, the model can be described as:

$$\begin{cases} \dot{x}_1 = -\dfrac{B}{J}\left(x_1+\omega_{m0}\right)-\dfrac{3p_n\psi_f}{2J}\left(x_2+i_{q0}\right)+\dfrac{T_1}{J} \\ \dot{x}_2 = -p_n\omega_m\left(x_3+\omega_{d0}\right)-\dfrac{R_s}{L}\left(x_2+i_{q0}\right)+\dfrac{P_n\psi_f}{L}\left(x_1+\omega_{m0}\right)-\dfrac{u_q}{L}+\varepsilon_1 \\ \dot{x}_3 = -\dfrac{R_s}{L}\left(x_3+\omega_{d0}\right)+p_n\omega_m\left(x_2+i_{q0}\right)-\dfrac{u_d}{L}+\varepsilon_2 \end{cases} \tag{5}$$

Obviously, system (5) is the robust nonlinear mathematical model of the third order double input. It has parametric uncertainty and unknown disturbance .On this basis, the controlling target is: under the uncertainty of parameter and the unknown disturbance of ε_1, ε_2, use u_d, u_q to control x_1, x_2, x_3. We adopt integrated control system which combines L_2 interference suppression and Backstepping.

3. Design of the robust controller for permanent magnet direct drive system

The controlling design method of Backstepping is a great robust controlling tool which solves the nonlinear system that has three-legged structure. It can construct the Lyapunov function by recursion and give the full analytical solution of controlling input.

3.1 The L_2 robust controlling machine' s design which basis on Backstepping

Since (5) is not a standard form of deduction, we need to choose variable $y=x_3$ and make $y=0$, and then, the zero dynamic second order model of (5) will be as follow:

$$\begin{cases} \dot{x}_1 = -ax_1-bx_2+c \\ \dot{x}_2 = dx_1-ex_2+f-\dfrac{u_q}{L}+\varepsilon_1 \end{cases} \tag{6}$$

Where

$a=\frac{B}{J}, b=\frac{3p_n\psi_f}{2J}, c=-\frac{B}{J}\omega_{m0}+\frac{T_1}{J}-bi_{q0}, e=\frac{R_s}{L}, f=-p_n\omega_{m0}\omega_{d0}-\frac{R_s}{L}i_{q0}+\frac{P_n\psi_f}{L}\omega_{m0}$, $d=-p_n\omega_{d0}+\frac{P_n\psi_f}{L}$, we get the penalty signals of the system (5): $z=x_2$, The virtual controller was chosen. $\widehat{x}_2=\frac{1}{b}\left(k_1-a\right)x_1+\frac{c}{b}$, We construct the coordinate transformation was as follows. $e_1=x_1$, $e_2=x_2-\widehat{x}_2$, Form of (6) as follows:

$$\begin{cases} \dot{e}_1 = -k_1e_1-be_2 \\ \dot{e}_2 = \left(d-\dfrac{ak_1}{b}+\dfrac{a^2}{b}\right)x_1-k_1x_2+\left(f+\dfrac{c}{b}k_1-\dfrac{ca}{b}\right)-\dfrac{u_q}{L}+\varepsilon_1 \end{cases} \tag{7}$$

We choose the Lyapunov function $V_1=\frac{1}{2}\sigma_1e_1^2, V_2=V_1+\frac{1}{2}\sigma_2e_2^2$, Then $\dot{V}_1=-k_1\sigma_1e_1^2-b\sigma_1e_1e_2$,

$H_1=\dot{V}_2+\frac{1}{2}\|z\|^2-\frac{\gamma^2}{2}\varepsilon_1^2=-\left(k_1\sigma_1-\frac{1}{2}\right)e_1^2-\left(\frac{\gamma}{2}\varepsilon_1-\frac{\sigma_2}{\gamma}e_2\right)^2-\frac{\gamma^2}{4}\varepsilon_1^2-\sigma_2e_2^2$, There existed the controller:

$$u_q=L\left[\frac{\sigma_2}{\gamma^2}e_2-\frac{b\sigma_1}{\sigma_2}e_1+\left(d-\frac{ak_1}{b}+\frac{a^2}{b}\right)e_1-k_1x_2+\left(f+\frac{c}{b}k_1-\frac{ca}{b}\right)+e_2\right] \tag{8}$$

It was assumed that $V_3=V_2+\frac{1}{2}\sigma_3y^2, \omega_1=\left(\varepsilon_1 \quad \varepsilon_2\right)^T$, We obtained the Equation by derivation.

$$\begin{aligned} H_2 &= \dot{V}_3+\frac{1}{2}\|z\|^2-\frac{\gamma^2}{2}\omega^2 \\ &= -\left(k_1\sigma_1-\frac{1}{2}\right)e_1^2-\left(\frac{\gamma}{2}\varepsilon_1-\frac{\sigma_2}{\gamma}e_2\right)^2-\frac{\gamma^2}{4}\varepsilon_1^2-\sigma_2e_2^2-\left(\frac{\gamma}{2}\varepsilon_2-\frac{\sigma_3}{\gamma}y\right)^2-\frac{\gamma^2}{4}\varepsilon_2^2-\sigma_3y^2 \end{aligned}$$

Controller was selected as follows:

$$u_d = -R_s\left(x_3+\omega_{d0}\right)+Lp_n\omega_m\left(x_2+i_{q0}\right)+y+\frac{1}{\gamma^2}y \tag{9}$$

To fully consider the features of high-capacity machine unit's disadvantage like big rotational inertia and slow response speed, it is especially important to design reasonable load torque observer and use the observed data to realize feed-forward compensation of load torque.

3.2 The feedforward control of load torque

Analyzing the features of wind machine, we can know from (1), for large inertia wind machine, the pneumatic torque T_l speed ω_m , environmental wind speed V, and pitch angle are directly correlated. Generally speaking, large capacity direct drive unit is low speed unit, the environmental wind speed is continuously and slowly. When the unit is operating under the rated wind speed, pitch angle not changed, the torque of wind wheel also changes slowly, it can be regarded as unknown constant in a limited time. We design air wheel pneumatic torque T_F's disturbing observer on this assumption basis.

$$T_F = B\omega_m + T_e = T_l - J\frac{d\omega_m}{dt} \tag{10}$$

And the component of accelerating torque can be write as:

$$J\frac{d\omega_m}{dt} = \frac{J}{9.55}\cdot\frac{\Delta n}{\Delta t} \tag{11}$$

As to nonsalient pole PMSM, substitute electromagnetic torque (3) into (11), we can get :

$$T_F = \frac{3}{2}p_n\psi_f i_q + \frac{J}{9.55}\cdot\frac{\Delta n}{\Delta t} \tag{12}$$

In the formula, linkage of permanent magnet Ψ_f and the sampling period can be all considered as constant. Thus formula (12) can be simplified to: $T_F=K_1i_q+K_2\Delta n$, $K_1=(3/2)p_n\Psi_f$, $K_2=J/9.55\Delta t$. Under the normal operation of the system. The load torque and actual system load torque can be approximately equal. Thus, we can design load torque disturbing observe on the basis of (13). Using its output data as the compensation of disturbance and the given information of signal speed together to be the given input of speed regulator, which makes the dynamic response of the ring of rotational speed control improve prominently. The controlling structure is as Figure 2.

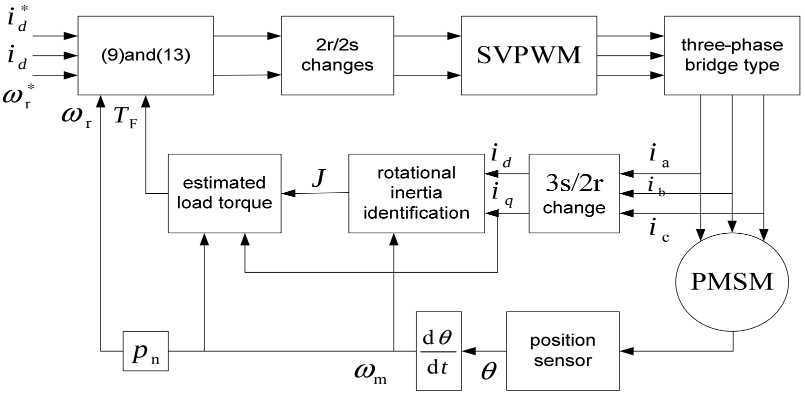


Figure 2: Overall structure of control system

Above all, feedback control u_d、u_q can be expressed further as:

$$u_q=L\left[\frac{\sigma_2}{\gamma^2}e_2-\frac{b\sigma_1}{\sigma_2}e_1+\left(d-\frac{ak_1}{b}+\frac{a^2}{b}\right)e_1-k_1x_2+\left(f+\frac{c}{b}k_1-\frac{ca}{b}\right)+e_2\right]+k_4T_F \tag{13}$$

4. Simulation analysis

To verify the validity of the proposed nonlinear robust control strategy, the nonlinear robust control combing the load torque feed forward. The simulation model used 2MW W82 permanent magnet direct-drive wind turbine from Waned Company. Table 1 shows the parameters.

Table 1: The simulation model of the main parameters

Name	Technical parameters	Name	Technical parameters
rotor diameter	82m	form of dinamo	REPMSG
rated wind speed	10m/s	the static data of rotational inertia of system	50000kg·m2
the range of wind speed while working	3m/s-25m/s	number of pole pairs	60
speed adjustment mode	adjust the rotor	nominal voltage	690V
utilization of wind energy	≥0.45	the direct axis component of the stator winding inductance	0.3mH
rated power	2000kW	stator phase winding resistance	0.05 Ω

First, we need to verify the veracity of load torque disturbing observer during the observation, Assuming that the initial value of wind speed V is 5m/s, slowly changes in the simulation time 0.5s and stable at 10m/s. through the theoretical calculation of actual load torque changes from 190000N·m to 764000N·m. Figure 3 is the load torque disturbance observer output waveform.

We can know from Figure 3, the designed load torque disturbance observer can track the actual load torque value correctly and track the changes of actual load torque quickly and in time when the mutation happens.

It is fully verified that the observation of the load torque and the rotational inertia is correct and effective during the above experiment. When the environmental wind speed changes, the wind system speed control command signal changes. To realize the MPPT of wind system, we need to adjust PMSM. The simulation model conduct simulation experiment in the field of voltage feedforward decoupling control and the L_2-gain control control strategy combined load torque feedforward compensation. The tracking waveform of motor speed can be seen in Figure 4. Simulation of wind speed value is set as shown in figure 4 (a).Motor speed tracking waveform as shown in figure 4 (b), the local details as shown in figure 4 (c), red curve by L_2 -gain control strategy, the blue curve for traditional voltage feedforward decoupling control strategy.

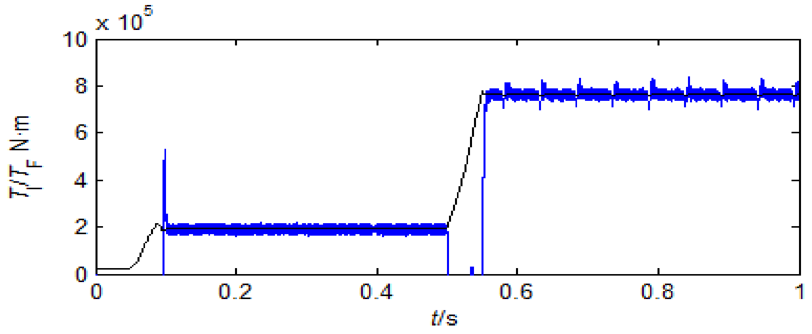
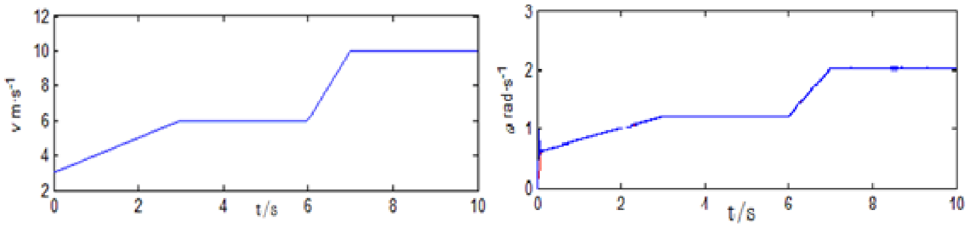


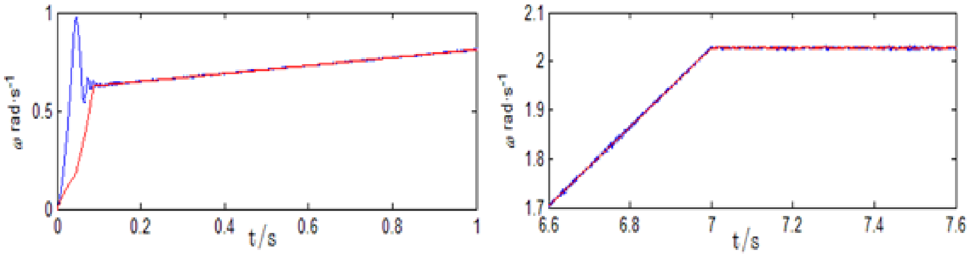
Figure 3: load torque disturbance observer output waveform

Figures 4 show the voltage feedforward decoupling control, the actual motor speed can quickly track the given speed. Furthermore, when the load torque changes abruptly, it can well suppress the disturbance. The fluctuation of the actual speed of the motor is obviously reduced, but with the increase of adjustment time, not conducive to the quick response of the system. respectively. By adjusting the L_2-gain control and combing the control strategy of load torque feedforward compensation, the overshoot and adjustment time are ideal with good dynamic performance, under the premise of accurate and quick tracking.



(a) The simulation wind speed value

(b) Motor speed tracking waveform comparison chart



(c) Motor speed waveform comparison chart

Figure 4: The simulation of dynamic curve

5. Conclusions

Aiming at the high inertia load of the large-capacity wind turbine as well as the nonlinearity of the system, the work established an affine robust nonlinear model. Moreover, a control strategy was proposed based on the L_2 gain control and the load torque feedforward compensation. In the theoretical derivation, we objectively introduced the speed differential and the load torque feedforward compensation. It fundamentally speeded up the tracking of system speed, thus greatly improving the dynamic response speed of wind power system in the case of high inertia load. Due to the full consideration of the nonlinearity of the system, the controller could effectively suppress the interference to the stable generator system. Simulation shows the proposed control strategy has the effectiveness and feasibility for the quick-response control of wind turbine with large capacity.

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