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dSpace Based Direct-driven Permanent Magnet Synchronous Wind Power System Modeling and Simulation

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Abstract— **When wind speed is below the rated value, the efficiency of captured wind energy must be maximized and the mechanical oscillation be guaranteed to be small. To deal with these problems, This essay describes the advantages of the direct-driven permanent magnet synchronous wind power system, and then introduces the two-frequency-loop model based on frequency separation principle, The LPV model and LPV control method are suggested for the high-frequency part of the system. The output of the high-frequency part is used to compensate the mechanical torque. The mathematical model is built with MATLAB, and the online test is carried out by dSpace. The simulation results show that the controller reduces mechanical oscillation effectively, and enhances the system reliability.**

Keywords-LPV; direct-driven; permanent magnet synchronous wind turbine; Wind Power Conversion System; dSpace

I. INTRODUCTION

Wind power is one of clean renewable resources. After 20 years development, the system performance of wind power generation is gradually improved, and its cost is greatly reduced. Wind power has become an important strategy for national economic development [1, 2].

The wind power system mostly adopts DFIG at present, with a gearbox between generator and wind turbine. The gearbox not only consumes a part of energy, but also has big noises, high failure rate and high maintenance costs. Permanent magnet synchronous generator is a newer type motor without brush and commutator, so it has big power factor. Without gearbox, namely that the wind turbine and generator is connected directly, it can promote the efficiency, improve the reliability of the system and decrease failure rate and maintenance costs.

In the wind power system, the control objective under rated wind speed is to maximize the efficiency of captured wind energy, but the traditional control methods usually cause high mechanical oscillation. Since the wind energy conversion system (WECS) is a typical strong nonlinear system, many control means need to transform nonlinear model to linear model, such as PI or PID control [3], and with some advanced control ways, like LQ and LQG control [4], however, the robustness of all these control methods is low, this becomes an applying restrictions for these control methods. The randomness of wind often results in low resolution linear model, reference [5] proposed LPV (Linear Parameter Varying) control which can solve above problems efficiently.

Firstly, this paper introduces two frequency loop model of the system [6, 7], and then in the low-frequency part, PI control is employed. After build LPV model for the high-frequency part, the LPV control method is adopted to promote the accuracy of the model, also, maximize the efficiency of captured wind energy and restrain oscillation. This paper built simulation model based on MATLAB, then loaded into dSPACE to make on-line experiment, the experiment result s show LPV control can improve the performance of the system, and it proved the feasibility and superiority of the control method.

II. WIND ENERGY CONVERSION SYSTEM MODEL

It is reasonable to ignore the dynamic process of generator electromagnetic response in this paper, since the electromagnetic time constant is much smaller than the mechanical time constant. The structure of variable speed constant frequency wind power energy conversion system is shown in Fig. 1.

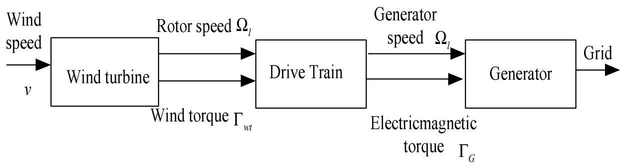

Figure. 1 Structure of Variable Speed Constant Frequency WECS

In Fig. 1, the wind turbine and generator are connected directly, drive train represents the shaft, and there is no gearbox between them. For this reason, they have the same speed Ω.

A. Wind Speed Model

Wind speed $v(t)$ which is a non-statistical random process is decomposed into two components in [8, 9], that is

$$v(t)=\overline{v}(t)+\Delta v(t) \tag{1}$$

Where $\bar{v}(t)$ is the low-frequency component, which describes long-time scale and low-frequency changes, it is usual to assume $\bar{v}(t)$ as a Weibull distribution; and $\Delta v(t)$ is high-frequency component, it is made up of Gaussian white noise $e(t)$ as a disturbance signal composed of a first-order filter.

$$\Delta \dot{v}(t) = -\frac{1}{T_w}\Delta v(t) + \frac{1}{T_w}e(t) \tag{2}$$

Where T_w is the time constant of the filter, and $T_w = L_t/\bar{v}$. L_t is the length of wind speed turbulence.

B. Wind Turbine Model

According to the Bates theory, the mechanical power captured by turbine is:

$$P_{wt} = 0.5\pi\rho R^2 C_p(\lambda) v^3 \tag{3}$$

Where ρ is air density, R is the radius of wind turbine, v is wind speed, λ is tip speed ratio, and $\lambda = R \cdot \Omega_l / v$, Ω_l is the angular velocity of wind turbine rotor, $C_p(\lambda)$ is the power factor of wind turbine, which is defined as:

$$C_p(\lambda, \beta) = 0.22(\frac{116}{\lambda} - 0.4\beta - 5)e^{\frac{-12.5}{\lambda}}$$

Where β is the pitch angle of variable-pitch control. For the fixed-pitch control $\beta = 0$.

The torque of wind turbine is:

$$\Gamma_{wt} = \frac{P_{wt}}{\Omega_l} = 0.5\pi\rho R^3 v^2 C_\Gamma(\lambda) \tag{4}$$

Where $C_\Gamma(\lambda)$ is torque coefficient which is defined as $C_\Gamma(\lambda) = C_p(\lambda)/\lambda$.

C. Drive Train Model

Neglecting the transients, the rigid drive train is expressed as:

$$J_l \dot{\Omega}_l = \Gamma_{wt} - \frac{i}{\eta}\Gamma_G \tag{5}$$

Where J_l is the total inertia of drive train, i is the gear box ratio, for the direct-driven case, its value is 1, η is the efficiency of the transmission shaft, Γ_G is the electromagnetic torque of the generator. As mentioned above, the formula (4) and (5) constitute the basic low-frequency model of the wind power conversion system.

D. Model of PMSG

Assuming that,

- Ignore the influence of the core magnetic saturation, excluding the eddy current and hysteresis loss.
- The conductivity of permanent magnetic materials is zero.
- There is no damper winding in rotor.
- The three-phase of stator is symmetrical and the induced EMF (electromotive force) is sinusoidal.

The electromagnetic torque of permanent magnet generator in d,q coordinate system is:

$$\Gamma_G = p(\Phi_d i_q - \Phi_q i_d) = p[\Phi_m i_q + (L_d - L_q)i_d i_q] \tag{6}$$

It is assumed that the load of the generator R_l is independent and symmetric three-segment, and the states and input of the system are defined as:

$$x = [x_1(t) \quad x_2(t)]^T \equiv [i_d(t) \quad i_q(t)]^T$$

$$u \equiv R_l$$

The state model of the generator can be expressed:

$$\begin{cases} \dot{x} = \begin{bmatrix} \frac{1}{L_d + L_s}(-Rx_1 + p(L_q - L_s)x_2\Omega_l) \\ -\frac{1}{L_q + L_s}(-Rx_2 - p(L_d + L_s)x_1\Omega_h + p\Phi_m\Omega_h) \end{bmatrix} + \\ \begin{bmatrix} -\frac{1}{L_d + L_s} & 0 \\ 0 & -\frac{1}{L_q + L_s} \end{bmatrix} \\ y \equiv \Gamma_G = p\Phi_m x_2 \end{cases} \tag{7}$$

Where R is the stator resistance, L_d and L_q are the inductance of the stator in d, q coordinate system, i_d and i_q are the stator current, L_s is the equivalent inductance of grid and converter, Φ_m is the flux, and is a constant for the permanent material, p is the pole pairs of the generator.

III. LPV Controller Design

The LPV theory was firstly proposed by Professor Shamma, its dynamic characteristics depend on the adjustable parameters which are measured in real time [5]. Since these parameters can reflect the nonlinearity of the system, LPV system can be applied to describe nonlinear system. The gain scheduling controller is then designed using linear method to make controller gain change with the parameters.

The LPV model of the system can be expressed in [6, 7],

$$\begin{aligned} \dot{x}(t) &= Ax(t) + Bu(t) + Le(t) \\ y(t) &= Cx(t) \end{aligned} \tag{8}$$

The formula (8) shows that external interference $e(t)$ exists in the LPV model. In order to effectively suppress wind disturbance and improve the system dynamic performance, the controller is designed based on the LPV dynamic model, making the H_∞ norm of the closed-loop transfer function $T_{ez}(s)$ from the disturbance input $e(t)$ to the control output $y(s)$ less than a given performance index, that is,

$$\left\| \boldsymbol{T}_{ez\infty}(s) \right\|_\infty < \gamma_\infty$$

Then the designed state feedback controller is:

$$u(t) = K(\rho(t)) \cdot x(t)$$

The closed-loop system is obtained as:

$$\begin{aligned} \dot{x}(t) &= (A(r(t)) + B(r(t))K(r(t)))x(t) + Le(t) \\ y(t) &= C(\rho(t))x(t) \end{aligned} \tag{9}$$

The affined parameters of this LPV model depend on $\rho(t)$, and the controller matrix is solved according to theorem 1.

Theorem 1[10]:

For the LPV model described by formula(8) and a given positive constant, if there are continuously differentiable symmetric positive definite matrix $X(\rho(t))$, symmetric positive definite matrix Y, matrix V and $R(\rho(t))$ satisfying formula(10) for all the parameters, then the parameters of closed-loop (9) are quadratic stability and meet the given H_∞ performance.

$$\begin{bmatrix} -(V+V^T) & * & * & * & * & * \\ M & -X(\rho(t))+Y & * & * & * & * \\ 0 & 0 & -Y & * & * & * \\ L^T(\rho(t)) & 0 & 0 & -\gamma_\infty I & * & * \\ 0 & C(\rho(t))V & 0 & 0 & -\gamma_\infty I & * \\ V^T & 0 & 0 & 0 & 0 & -X(\rho(t)) \end{bmatrix} < 0 \tag{10}$$

where $M = V^T A^T(\rho(t)) + R^T(\rho(t))B^T(\rho(t)) + X(\rho(t))$. If the inequality (10) has feasible solution, then the state feedback controller gain matrix which dependent on the parameters is

$$K(\rho(t)) = R(\rho(t))V^{-1}$$

According to the formula (5),

$$J_T \dot{\overline{\Delta\Omega_l}} = \overline{\Delta\Gamma_{wt}} - \frac{1}{\eta} \frac{\overline{\Gamma_G}}{\overline{\Gamma_{wt}}} \overline{\Delta\Gamma_G} \tag{11}$$

Where $J_T = J_l \overline{\Omega_l} / \overline{\Gamma_{wt}}$, $\overline{\Delta\Omega_l} = \dfrac{\dot{\Delta\Omega_l}}{\overline{\Omega_l}}$, $\dot{\Omega_l} = \Omega_l - \dot{\overline{\Omega_l}}$, $\overline{\Omega_l}$ is the stable value of the Ω_l, also for the $\overline{\Omega_l}$, $\overline{\Delta\Omega_l}$ and $\overline{\Delta\Gamma_{wt}}$.

According to the high-frequency pulsation wind speed modeling method in [9] and formula (2), there is

$$\dot{\overline{\Delta v}} = \frac{1}{T_w}\left(e - \overline{\Delta v}\right) \tag{12}$$

From formula (4) and low-frequency sub-model,

$$\dot{\overline{\Delta\Gamma_{wt}}} = \gamma \cdot \dot{\overline{\Delta\Omega_l}} + (2-\gamma)\dot{\overline{\Delta v}} \tag{13}$$

Where γ depends on the low-frequency operating point of the system, its value is $\gamma = \dfrac{\overline{\lambda} C_p'(\overline{\lambda})}{C_p(\overline{\lambda})} - 1$, and $C_p'(\overline{\lambda}) = \dfrac{dC_p(\overline{\lambda})}{d\lambda}$.

Put the formula (11) and (12) into (13), there is

$$\begin{aligned} \dot{\overline{\Delta\Gamma_{wt}}}(t) &= \left(\frac{\gamma}{J_T} - \frac{1}{T_w}\right)\overline{\Delta\Gamma_{wt}}(t) + \frac{\gamma}{T_w}\overline{\Delta\Omega_l}(t) \\ &- \frac{\gamma}{J_T \eta} \frac{\overline{\Gamma_G}}{\overline{\Gamma_{wt}}} \overline{\Delta\Gamma_G}(t) + \frac{2-\gamma}{T_w} e(t) \end{aligned} \tag{14}$$

Formula (11) and (14) constitute the high-frequency sub-model of the conversion system, for this model and according to the theory above, $u(t) = \overline{\Delta\Gamma_G}$ is chose as the control input, $x(t) = \begin{bmatrix} \overline{\Delta\Omega_l} & \overline{\Delta\Gamma_{wt}} \end{bmatrix}^T$ is the state vector, $y(t) = \overline{\Delta\lambda}(t) = C(\rho(t))x(t)$ is defined to be the output vector, and the matrixes obtained by formula (14) are

$$A = \begin{bmatrix} 0 & 1/J_T \\ \gamma/T_w & \gamma/J_T - 1/T_w \end{bmatrix},\ B = \begin{bmatrix} \dfrac{-1}{J_T} \dfrac{\overline{\Gamma_G}}{\overline{\Gamma_{wt}}} \\ \dfrac{-\gamma}{J_T} \dfrac{\overline{\Gamma_G}}{\overline{\Gamma_{wt}}} \end{bmatrix},\ L = \begin{bmatrix} 0 & (2-\gamma)/T_w \end{bmatrix}^T,$$

$$C = \begin{bmatrix} \dfrac{2}{2-\gamma} & -\dfrac{1}{2-\gamma} \end{bmatrix}$$

Use the LMI toolbox to describe the matrix of the theorem 1 to obtain the controller K.

IV. Online Simulation And Results Analysis

According to Fig. 1 and the analysis above, the general structure diagram of the direct-driven permanent magnet synchronous wind power system based on LPV is shown in Fig. 2, and the online experiment is done by dSPACE. dSPACE system is a development and testing platform based on MATLAB/Simulink in real-time environment, it can be connected with MATLAB/Simulink seamlessly, and can realize real-time control and modify for the control system, so it is much easier and overcomes some inconvenience of on-line simulation.

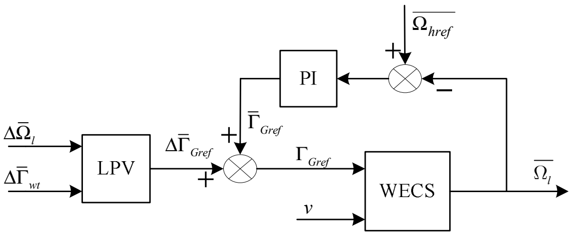

Figure. 2 Gain Scheduling Control Structure Based on LPV

In MATLAB simulation environment, find the solution of matrix in theorem 1 with LMI and Simulink toolbox, and build the general simulation diagram of the system, then download the simulation to the dSPACE to do the real-time simulation experiment. The parameters of the experiment are shown in Table 1.

TABLE I. EXPERIMENT PARAMETERS

Name	Value	Name	Value
R	2.5 m	ρ	1.25kg/m^3
T_w	21.4286s	η	0.95
J_T	0.563kg*m2	C_{pmax}	0.476
T_{Gmax}	40Nm	λ_{out}	7

The experiment results of power factor of the wind turbine C_p and tip speed ratio λ (lam) are shown in Fig. 3 and Fig. 4.

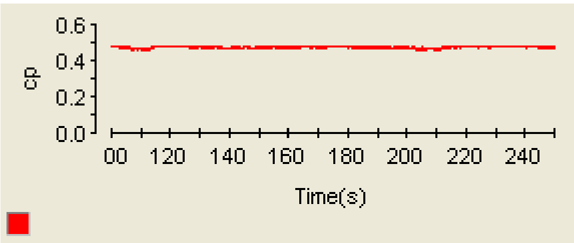

Figure. 3 Power Factor

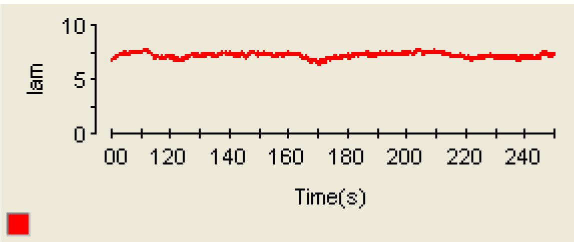

Figure. 4 Tip Ratio

From Fig. 3, it is easy to see that the value of C_p is stable and very closed to the maximum value 0.476; and the Fig. 4 shows that the accuracy of tip speed ratio tracking the best value is high, and the robustness of the system is good, so the controller can capture the wind energy as much as possible, and the oscillation is small, solve the contradictions between the wind energy capturing and big oscillation. The experiment results show the effectiveness and advantages of this control method.

V. CONCLUSIONS

The situation discussed in this paper is below the rated wind speed of the direct-driven permanent magnetic synchronous wind power system, we need to capture the maximum wind energy and to ensure the smaller mechanical vibration, while increasing the model precision, firstly we build the basic model of the system, then for the high-frequency part, according to the LPV theory to linear the part and design the LPV controller, with PI control of the low-frequency part, the torque can be controlled well. The simulation results based on the dSPACE show that the control method of this paper can fulfill the control objective and efficiently improve the performance, while the real-time experiments are still on research. The research of this paper has broad application prospects in direct-driven permanent magnetic synchronous wind power system.

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REFERENCES

[1] Akpinar, E.K, Akpinar, S, “An investigation for wind power potential required in installation of wind energy conversion system,” Proceedings of the Institution of Mechanical Engineers, vol. 220, pp. 1-13, 2006.

[2] Yazhou Lei, Gordon Lightbody, “Wind power and electricity market,” Automation of Electric Power Systems, vol. 29, pp. 1-5, 2005.

[3] Tapia A, Tapia G, Ostolaza Jx, José Ramón Sáenz, “Modeling and control of a wind turbine driven doubly fed induction generator,” IEEE Trans-actions on Energy Conversion, vol. 18, pp. 194-204, 2005.

[4] Muhando Be, Senjyu T, Urasaki N, Naomitsu Urasaki, Atsushi Yona, Hiroshi Kinjo, Toshihisa Funabashi., “Gain scheduling control of variable speed WTG under widely varying turbulence loading,” Renewable Energy, vol. 32, pp. 2407-2423, 2005.

[5] Shamma,J., Athans,H, “Guaranteed properties of gain scheduled control for linear parameter-varying plants,” Automatica, vol. 27, pp. 559-564, 1991.

[6] Inlian Munteanu, Antoneta Iuliana Brarcu, Nicolaos-Antonic Cutululis, Emil Ceanga, Optimal Control of Wind Energy Systems, London: Springer, 2008.

[7] Inlian Munteanu, Nicolaos Antonio Cutululis, Antoneta Iuliana Bratcu, Emil Ceanga, “Optimization of Variable Speed Wind Power Systems Based on a LQG Approach,” Control Engineering Practice, vol. 13, pp. 903-912, 2005.

[8] Bianchi F, De Battista H, Mantz RJ, Wind turbine control systems principles, modelling and gain scheduling design. London: Springer, 2008.

[9] Nichita C, Luca D, Dakyo B, Ceang E, “Large band simulation of the wind speed for real time wind turbine simulators,” IEEE Transactions on Energy Conversion, vol. 17, pp. 523-529, 2005.

[10] Junling Wang, Delay Linear parameter varying system stability analysis and gain scheduling control. Beijing: science press, 2008.