Design of L1 Adaptive Control for PMSG Wind Turbine System

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Design of L1 Adaptive Control for PMSG Wind Turbine System

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Abstract. This paper focuses on the design of an L1 adaptive controller for variable speed wind turbines on a permanent magnet synchronous generator (PMSG) to maximize the wind power exploited in the presence of parameters uncertainties and wind speed turbulences. This control method based on the class of state feedback state for multiinput multi-output (MIMO) system can be applied to the current control and speed control of the system. The proposed controller successfully deals with the essential nonlinear problems of wind turbines and the effect of unknown parameters. Moreover, the L1 adaptive controller with fast adaptation is not only beneficial for both performance and robustness but also effective for the appearance of the time-delay state variables of wind turbine. Finally, with comparison to the indirect model reference adaptive control (MRAC), the performances of the system are verified by mean of several simulation results.

1. Introduction

The wind turbine is one of the fastest growing renewable energy technologies available today. The Global Wind Energy Council (GWEC) released its Global Wind Report: Annual Market Update today, showing a maturing industry successfully competing in the marketplace, even against heavily subsidized traditional power generation technologies. More than 52GW of clean, emissions-free wind power was added in 2017, bringing total installations to 539 GW globally. With new records set in Europe, India and in the offshore sector, annual markets will resume rapid growth after 2018 [1]. Among currently available wind energy conversion systems (WECSs), variable speed wind turbines are preferable to fixed speed ones because of their ability to maximize power extraction energy and increase efficiency [2]. In variable speed wind turbines, those based on permanent magnet synchronous generator (PMSG) offer several benefits in the wind power applications, such as their high-power density, high efficiency, better reliability and easy maintenance. These features make it an attractive choice in the wind turbine systems [3, 4]. It is widely known that the main control objective for the wind turbine in the low speed region is power efficiency maximization. To achieve this goal, the turbine tip speed ratio should be maintained at its optimum value despite the variation of wind speed.

For such pressing purpose, many different control strategies can be approached. First, proportional-integral (PI) based control schemes were proposed to deal with the problem of the maximum power point tracking [5, 6]. Li et al represented the control methods using the conventional

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and direct-current vector configuration to implement the maximum power extraction. It should be realized that PI control is a linear regulator which is really suitable for linear time invariant systems. However, the electrical and mechanical components in wind turbines work globally as nonlinear systems where electromechanical parameters vary considerably. Additionally, wind turbines are expected to operate effectively under a wide range of wind speeds, therefore the control designs get more difficult. To overcome this drawback, there are many different intelligent and nonlinear control strategies such as, gain scheduling [7], fuzzy logic control [8], neural network [9], feedback linearization [10] and backstepping [11]. Especially, methods based on sliding mode control (SMC) seem to be an interesting approach because they make plants more robust and guarantee high tracking of output signals following their reference in the presence of system uncertainties and disturbances. In this paper, L1 control strategy applied to the PMSGWECS has been proposed to guarantee the high tracking rotor speed of wind turbine following their reference to ensure the maximum power extraction in the presence of nonlinear uncertainties parameters and wind speed turbulences. Compared with the L1 controller in [11] represented by L1 adaptive output feedback for the single input and single output (SISO) system, L1 adaptive state feedback for multi input and multi output (MIMO), which applies to the speed control and the current control, has been presented to ensure the performance of the electromagnetic torque and active power. It reveals the good performance and robustness in the presence of high adaptation gain of L1 controller compared with the indirect MRAC in the simulation section.

2. Wind turbine system description

Wind energy is known to be first transformed into mechanical energy through the wind turbine blades and then into electrical energy through the PMSG. The PMSG is connected into the grid through two-level back to back converter. The electrical power is completely delivered to the grid by regulating the controller of the two-level back to back converter which consists of machine side converter (MSC), grid side converter (GSC) and DC link. The generator side control comprised of the current control loop and speed control loop is shown in figure 1.

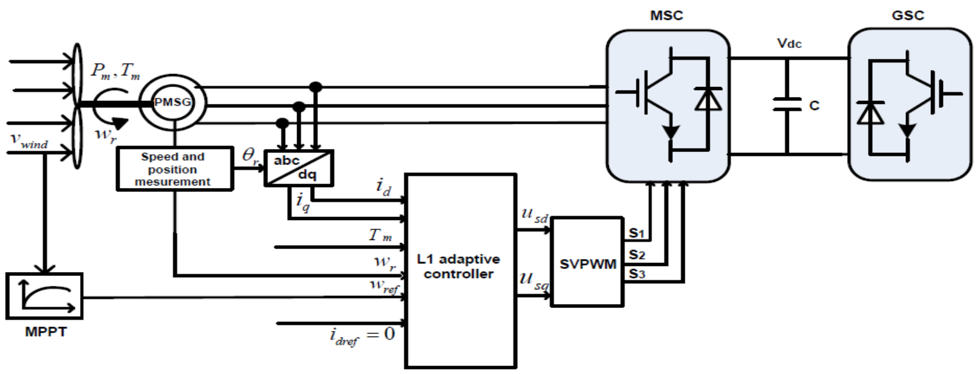

Figure 1. Control block diagram of the wind turbine system.

2.1. Wind turbine modeling

The aerodynamic power extracted from the wind is expressed [8].

$$P_m = 0.5\rho\pi R^2 C_p(\lambda,\beta)v^3 \tag{1}$$

where ρ is the air density, R is the wind turbine rotor radius, v is the wind speed, and $C_p(\lambda,\beta)$ is the turbine power coefficient. This coefficient can be calculated as follows:

$$C_p(\lambda,\beta) = 0.73(\frac{151}{\lambda_i} - 0.58\beta - 0.002\beta^{2.14} - 13.2)\,e^{\frac{-18.4}{\lambda_i}} \tag{2}$$

$$\lambda_i = \frac{1}{\frac{1}{\lambda + 0.002\beta} - \frac{0.003}{\beta^3 + 1}} \tag{3}$$

where β is the blade pitch angle, and λ is the tip speed ratio which is defined in [10].

2.2. PMSG modeling

Dynamic modeling of the PMSG can be described in (d, q) synchronous rotating reference frame. Thus, it is given by the following equations

$$\frac{dw_r}{dt} = \frac{T_m}{j_t} - \frac{k_t}{j_t} w_r - \frac{k_g}{j_t} i_{sq} \tag{4}$$

$$\frac{di_{sq}}{dt} = -\frac{R_s}{L_s} i_{sq} - p i_{sd} w_r - \frac{\psi_m}{L_s} \rho w_r + \frac{1}{L_s} u_{sq} \tag{5}$$

$$\frac{di_{sd}}{dt} = -\frac{R_s}{L_s} i_{sd} + p i_{sq} w_r + \frac{1}{L_s} u_{sd} \tag{6}$$

where T_m denotes the aerodynamic torque, i_{sd} and i_{sq} are d-axis, q-axis stator current, respectively; u_{sd} and u_{sq} are d-axis, q-axis stator voltage, respectively; R_s is the resistance of stator windings, L_s is the inductance of stator windings, ψ_r is the permanent magnetic flux, p is the number of pole pairs of the PMSG; $k_g = 1.5 p \psi_r$.

3. Simulation results

In order to verify the validity of the proposed L_1 adaptive control for the maximum power extraction of the wind turbine system, Matlab-simulink has been performed to illustrate the simulation results of the wind turbine system. The nominal values of the parameters employed in the simulations process. 50% uncertain parameters of wind turbine have been considered in this paper.

Time – delay state variables of wind turbine are defined as:

$$z_d(\mathrm{t}) = \begin{cases} z(\mathrm{t} - \tau) & \mathrm{t} \geq \tau \\ 0 & t < \tau \end{cases} \tag{7}$$

where τ is the time - delay margin.

In these simulations, the wind speed is assumed working under realistic condition which consists of the mean wind speed and its turbulence. The wind speed profile in this paper is divided into two scenarios based on the different turbulence intensity.

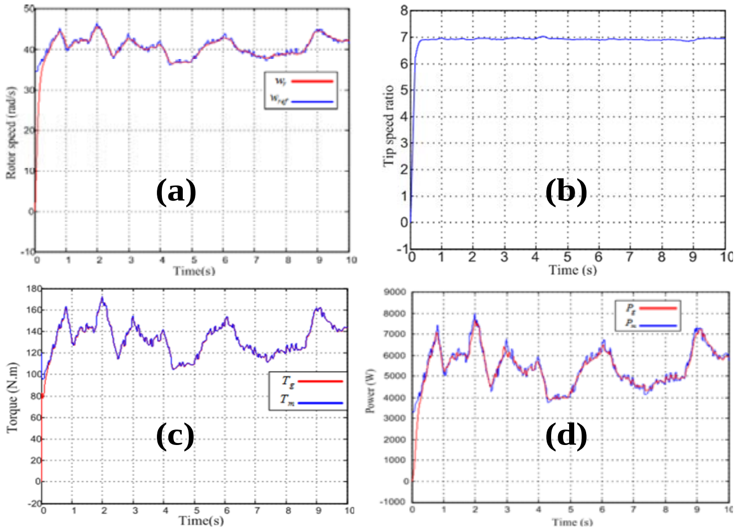

Figure 2. (a) Rotor speed and rotor speed reference; (b) Tip speed ratio; (c) Electromagnetic torque and aerodynamic torque; (d) Active power and mechanical power.

Figure 2 shows the tracking performance of actual variables tracking their reference variables in the scenario 1 by utilizing the L_1 adaptive controller. In response to the wind speed profile, the actual rotor speed W_r and its reference value W_{ref} are shown in figure 2a. It is clear that the rotor speed tracks more closely its reference value with good transient (the transient time 0.5 second and no overshoot phenomenon). Figure 2b shows that the uncertain tip speed ratio $\left(\lambda_{opt} = 6.91\right)$ with small oscillation. Figure 2c and 2d reveal that despite the wind speed turbulences and parameters uncertainties, the electromagnetic torque and the active power of the PMSG accurately follow their reference values (P_m is the maximum power of wind turbine, T_m denotes the aerodynamic torque). For the scenario 2, the turbulence intensity is much larger than it in the scenario 1. Figure 3 also shows the high tracking performances of rotor speed, electromagnetic torque and active power. It can be noted that the oscillations of wind turbine variables are bigger than them in the scenario 1, thus the tracking performances of this controller are influenced and become worse compared with scenario 1. However, these oscillations are still small and considered acceptable.

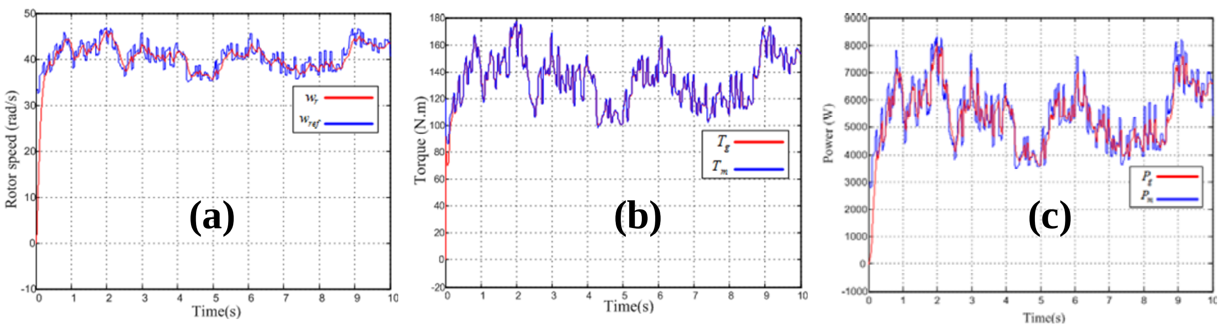

Figure 3. (a) Rotor speed and reference rotor speed; (b) Electromagnetic torque and aerodynamic torque; (c) Active power and mechanical power.

Figure 4 shows the expression of the tracking performance of the rotor speed regulated by L_1 adaptive controller and indirect MRAC controller under different step change of wind speed. Figure 4a (L_1 adaptive controller) reveals that increasing adaptive gain improves the tracking performance. When Γ is large value $(\Gamma \geq 10)$, the distinction of their tracking performance is not remarkable. Moreover, the fast adaptive gain ($\Gamma \geq 10$), does not influence the robustness of the system. The improvement of system performance by increasing Γ is also exposed in figure 4b (indirect MRAC).

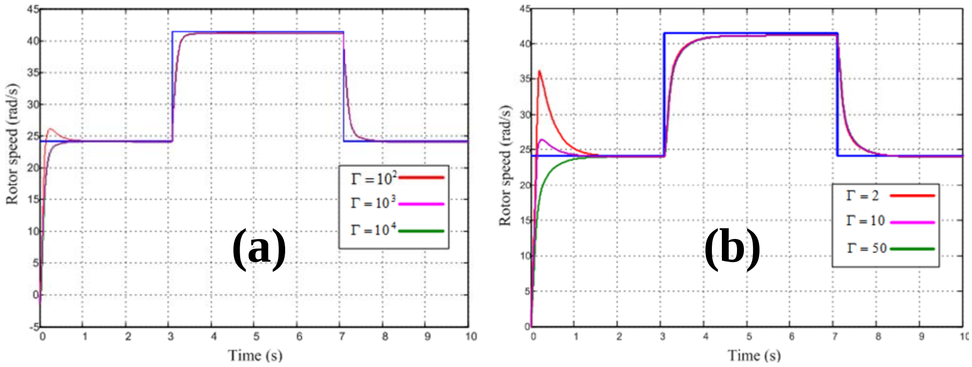

Figure 4. (a) Step respond of rotor speed (L_1 adaptive controller);
(b) Step respond of rotor speed (indirect MRAC controller).

Figure 5 illustrates the tracking performance of the rotor speed regulated by L_1 adaptive controller and indirect MRAC controller under different step change of wind speed with time-delay margin $\tau = 0.005s$. In figure 5a, it is clear that the tracking performance of the proposed control with time-delay state variables is unchanged compare with the proposed control described in figure 5a. Meanwhile, in figure 5b, with the small adaptive gain $\Gamma, \Gamma \leq 10$ the tracking performance of the indirect MRAC under time-delay margin $\tau = 0.005s$ is also unchanged compare with the performance presented in figure 4b. However, when high adaptive gain Γ the system controlled by the indirect MRAC controller may loses robustness. So, it can be seen that increase of the adaptive gain Γ affects the negative robustness of system. The loss of robustness happens regardless of the small adaptive gain $(\Gamma = 12)$ under appearance of delay-time state variables.

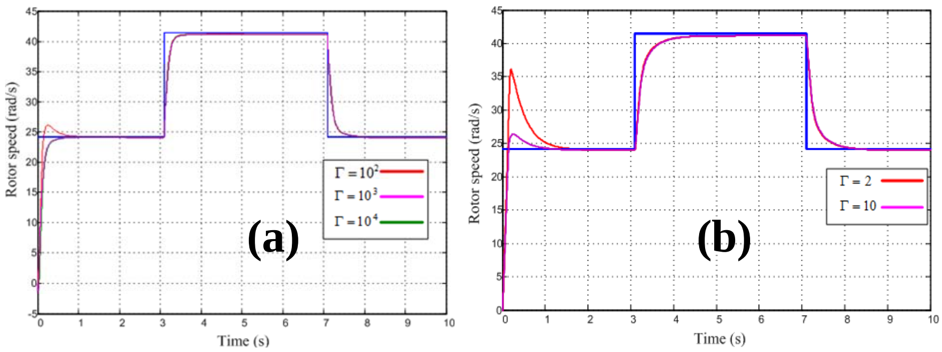

Figure 5. (a) Step respond of rotor speed (L 1 adaptive controller) with time-delay margin $\tau = 0.005s$;
(b) Step respond of rotor speed (indirect MRAC controller).

4. Conclusions

L_1 adaptive controller was proposed here for the PMSG wind energy conversion system to ensure the maximum power extraction from the wind. The control design using a low-pass filter in the definition of the control signal to appropriately limit the frequencies of the signal; therefore, it guarantees the robustness regardless of the fast adaptation. Consequently, the proposed controller showed a high tracking performance of those values such as the speed, the torque and the power toward their references and robustness with fast adaptation under the parameter uncertainties and wind turbine turbulences as shown in the detailed simulation section. Compared with the indirect MRAC, L_1 adaptive control is

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more robust while the indirect MRAC loses the robustness because of the fast adaptation. L_1 adaptive control also reached good performance and robustness under time-delay effects on the system.

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