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Design and real time implementation of sliding mode supervised fractional controller for wind energy conversion system under sever working conditions

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ABSTRACT

Wind energy conversion system (WECS) is increasingly taking the place to be the most promised renewable source of energy, which obliges researchers to look for effective control with low cost. Thus, this paper proposes to build a suitable controller for speed control loop to reach the maximum power point of the wind turbine under sever conditions and to ensure the stability of the outer voltage regulation loop to meet high range of load variations. In literature, a major defect of the well-used conventional PI controller is the slow response time and the high damping. Nowadays, intelligent controllers have been used to solve the drawbacks of the conventional ones but they demand high speed calculators and expensive cost. Moreover, many solutions proposed the fractional order PI controller (FO-PI) by extending the order of integration from integer to real order. The FO-PI controller presents also some weakness in steady state caused by the approximation methods. The idea of this paper is to propose a Sliding Mode Supervised Fractional order controller (SMSF) which consists of conventional PI controller, FO-PI controller and sliding mode supervisor (SMS) that employs one of the controllers to ensure good steady and transient states. WECS laboratory prototype is built around real-time dSPACE cards and evaluated to verify the validity of the developed SMSF. The results clearly fulfill the requirements, confirm its high performance in steady and transient states and demonstrate its feasibility and effectiveness.

1. Introduction

Recently, the high demand of electrical energy and the decrease in naturel resources lead to look for new, clean and inexhaustible sources of energy. Thus, Renewable energies have received much attention in the last decades [1,2]. Therefore, wind energy is one of the most developed sources by looking to the installed capacity worldwide which is about 485 GW [3] and 12.63 GW for Europe [4]. Actually, permanent magnet synchronous generators (PMSGs) have been gaining much attention in modern wind energy conversation systems (WECSs) due to the variable speed operation, low converter cost, fast dynamical response, high torque to current ratio, reduced power losses brushless system with low noise and high reliability [1,5–7]. However, variable physical parameters, nonlinearity, and variable load torque are some of the important issues to be considered in the control process design of PMSG [7].

Recent developments in control loops are responsible for optimum operation of the wind turbine [8]. Examples include torque control [9], power control loops [10], pitch control [11], feedback linearization control [12]. Moreover, there is still a need for implementing each control loop separately using conventional proportional integral (PI) or proportional integral derivative (PID) controllers, and minimizing the couplings among loops by iterative adjustments [3]. However, the modern wind turbine structure, larger, more flexible and environmental conditions, make the conventional controllers not suitable in transient state even their good steady state. Therefore, the need for advanced control methods is increased. Previous works have focused on improving the dynamic of the PI controllers such as: applying fuzzy logic control [13], and sliding mode control [14,15]. The main limitation of these methods is the need for high speed power converters and powerful calculators.

Until now, PID controllers are still being used in the industry applications for their simple structure, ease of design, and inexpensive cost [16]. In addition, they have good performance, including

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acceptable overshoot with small settling time for slow industrial processes [16,17]. This solution could not be a suitable alternative in high nonlinear systems. Hence, fractional-order (FO) controllers have been applied in several fields with better results in comparison with the traditional ones [1,16]. Appropriate FO integral (I)/derivate (D) can be utilized in order to improve the performance of the PID controller. In recent past, particular interest has been given to the fractional calculus theory and the approximation methods to build suitable controllers for complex systems. Firstly, A. Oustaloup was proposed Commande Robuste d'Ordre Non Entier (CRONE) controller in 1991. Afterwards, I. Podlubny started the FO PID (FO-PID) in the form of $PI^{\lambda}D^{\mu}$ in 1999 [18]. The powers λ, μ are real orders employed by researchers to give more freedom degrees to the FO-PID compared to the integer PID. But, the high order of the approximation method could be a major drawback for the FO-PID controller. Thus, compromising between the order of the approximation and the required performance in experimental application is the real challenge. Lately, more researches have been introduced to the structure of the FO-PI controllers employed in several domains. [17] tries to employ a fractional order integral plus proportional (FO-IP) controller in active power filtering to gain short response time and low overshoot but this kind of controllers presents some limitations in steady state with high distortions. Then, [19] proposed a combination between a conventional PI and FO-PI controllers and switch between them when external disturbances are detected but this approach still have to be improved in order to control the decision maker. In [20], authors introduced an intelligent solution by replacing conventional decision with a fuzzy logic supervisor but the cost of this approach could be a critical issue. After that, authors of [21] applied a new structure of hybrid FO-PI controller on the same system under study of this paper. The obtained results could be satisfying in steady and transient states but the complexity of the proposed controller presents some critical concerns in term of the powerful calculator units needed that lead to increase the implementation cost.

Nowadays, sliding mode control has been the choice of many researchers in control and could been a good alternative in supervising domain [22]. However, the natural chattering phenomenon of the sliding mode is a major problem for inverters control [22,23]. But, in our case, it could be the major advantage by up or down depending on sliding surface. Thus, this paper proposes a new controller structure named Sliding Mode Supervised Fractional order controller (SMSF) with simple design, suitable for WECS, easy to be implemented, earn the benefits from the efficiency of the conventional PI controller in steady state and accuracy of tracking the wind speed in sever conditions. The SMSF controller combines between conventional PI controller and FO-PI controller and set one of them based on a sliding mode supervisor (SMS). Moreover, the general structure of a PI controller is kept by employing two parallel paths which have tunable scalar gains in order to ensure that the SMSF controller can easily be implemented in control loops.

This paper is divided into six sections. Section 1 is an introduction. Section 2 gives a brief overview of the WECS modelization, Section 3 is the global system control. Section 4 presents the proposed SMSF with detailed analysis and Section 5 shows the experimental results and their interpretation, which conduct us to the Section 6 with the main conclusion.

2. Wind energy conversion system

Fig. 1 shows the general power circuit configuration of the WECS. The system is composed of three parts: an electrical part, a mechanical part, and a control part. Whereas, the mechanical part represented by a wind turbine, which is employed by DC motor with separate excitation used as an emulator. The wind turbine model is practically the same as the one proposed in [1]. The electrical part includes 6.6 kW PMSG connected to the grid (50 V, 50 Hz) via two back-to-back converters (machine side converter (MSC) and grid side converter (GSC)). Indeed, the control part was implemented with two real-time dSPACE1104 cards. The first card contains the improved current vector control [21] with the wind turbine model and wind profile. The direct power control (DPC) [1,21] was implemented in the second one to control the GSC.

2.1. Wind turbine model

The aerodynamic power extracted from the wind is expressed by Eq. (1) [24]:

$$P_w = \frac{1}{2} C_p \rho \pi R^2 V_w^3 \tag{1}$$

Where, ρ is the air density (kg/m^3), R is the turbine radius (m), V_w is the wind speed (m/s), C_p is the coefficient of the turbine given by the wind turbine manufacturer.The tip speed ratio (TSR) λ is defined as [24,25]:

$$\lambda = \frac{\Omega_t R}{V_w} \tag{2}$$

Where, Ω_t is the wind turbine angular shaft speed.

The torque on the wind turbine shaft can be calculated from the power expression as [1,25]:

$$T_w = \frac{P_w}{\Omega_t} = \frac{1}{2} C_p \rho \pi R^2 \frac{V_w^3}{\Omega_t} \tag{3}$$

C_p depends on the TSR and the pitch angle β such as [26]:

$$C_p = (0.5 - 0.00167(\beta - 2)).\ sin\left[\frac{\pi(\lambda + 0.1)}{18 - 0.3(\beta - 2)}\right] - 0.00184(\lambda - 3)(\beta - 2) \tag{4}$$

2.2. Generator model

Park representation of a PMSG model is the commonly used, which its voltage equations are expressed by [25]:

$$\begin{pmatrix} v_{sd} \\ v_{sq} \end{pmatrix} = \begin{pmatrix} -R_s - L_d s & \omega L_d \\ -\omega L_q & -R_s - L_q s \end{pmatrix} \begin{pmatrix} i_{sd} \\ i_{sq} \end{pmatrix} + \begin{pmatrix} 0 \\ \omega.\ \varphi_f \end{pmatrix} \tag{5}$$

Where, R_s, $\omega$are the stator resistance and the generator electrical rotational speed respectively.v_{sdq}, $i_{sdq}$are the d,qstator voltages and currents. L_{dq}, φ_f are the d,q axis inductances and magnetic flux.

The relationship between the electrical speed and the mechanical speed can be expressed as:

$$\omega = \frac{p}{2} \Omega_t \tag{6}$$

p is the poles number of the PMSG.

The mechanical dynamics of the rotating parts can be given by maximum [1]:

$$J \frac{d\omega}{dt} = T_w - T_m - f_r \omega \tag{7}$$

Where, J is the inertia; T_w is the wind turbine torque andf_r is the coefficient of friction.

2.3. Wind turbine emulator

The wind turbine emulator is based on DC-DC converter and DC-Motor with separate excitation as shown in Fig. 2.

The steps proceed to build the wind turbine emulator are very much in the same way as indicated in [1]. First, the wind speed profile and pitch angle are set on the control desk of first dSPACE 1104 card. Then, the sensed current i_a and DC-Motor speed ω_{em} signals are sent as inputs to the wind turbine mathematical model. After that, the model generates a reference current signal i_a^* corresponding to the set wind speed and pitch angle β, then, this reference value is compared to the measured i_a. Finally, the error between sensed and reference current is used