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Research Article

Robust fractional order sliding mode control of doubly-fed induction generator (DFIG)-based wind turbines

Sadegh Ebrahimkhani *

Department of Electrical and Robotics Engineering, Shahrood University, 36199-95161, Shahrood, Iran

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ABSTRACT

Wind power plants have nonlinear dynamics and contain many uncertainties such as unknown nonlinear disturbances and parameter uncertainties. Thus, it is a difficult task to design a robust reliable controller for this system. This paper proposes a novel robust fractional-order sliding mode (FOSM) controller for maximum power point tracking (MPPT) control of doubly fed induction generator (DFIG)-based wind energy conversion system. In order to enhance the robustness of the control system, uncertainties and disturbances are estimated using a fractional order uncertainty estimator. In the proposed method a continuous control strategy is developed to achieve the chattering free fractional order sliding-mode control, and also no knowledge of the uncertainties and disturbances or their bound is assumed. The boundedness and convergence properties of the closed-loop signals are proven using Lyapunov's stability theory. Simulation results in the presence of various uncertainties were carried out to evaluate the effectiveness and robustness of the proposed control scheme.

1. Introduction

Wind power is one of the cleanest sources of renewable energy that allow producing the green energy. DFIG play an essential role in the wind energy conversation systems and widely utilized in the modern wind power generation, due to variable speed operation, low converter cost, reduced power loss and four quadrant active and reactive power capabilities [1].

Development of control systems for the DFIG-based wind turbines, is an important issue. The vector control using proportional–integral (PI) controller is broadly employed for the control of the DFIG-based wind turbines [2–5]. However, there are many challenges in the design of a controller for this system, for example, nonlinear dynamics and many uncertainties such as unknown nonlinear disturbances and parameter uncertainties. Therefore, it seems to be quite difficult to perform a high-precision control by using linear control methods.

The performance of the PI control method degrades when the system to be controlled characterized by nonlinearities and uncertainties, to improve the system performance many linear methods have been proposed. A model-based predictive power control of DFIG is presented in [6], optimization of variable speed wind power system based on LQG (linear quadratic Gaussian) approach is in [7]. A robust state feedback which can reject disturbances at the input of the plant is proposed in [8], simulation results show that the proposed state-feedback robustly suppresses the disturbances in the plant input and it converges faster to the reference signal when compared with the response of the PI and the variable-structure control strategy. In [9] the application of the PID and the robust H_∞ control strategy for the improvement of the wind-turbine output power is investigated in the presence of model/environmental uncertainties, it has been shown that H_∞ controller guarantees the robust stability and performance of the uncertain system.

However, precise control of the DFIG-based wind turbines, due to their inherent nonlinear characteristics and uncertainties, cannot be easily obtained with conventional linear controllers. On the other hand, intelligent control approaches such as neural networks and fuzzy systems do not require mathematical models and have the ability to approximate nonlinear dynamics and functions, as a result, they can be a good choice for control of the DFIG. In [10] an online training fuzzy neural network (FNN) controller with a sliding mode speed observer for the induction generator is proposed. Two fuzzy logic controllers are proposed to direct power control for a DFIG-based wind turbine in [11], which are robust against machine parameters mismatches and grid voltage disturbances. Fuzzy logic based maximum power point tracking for DFIG-based wind turbine system is reported in [12], where provides the same output electrical power compared to the conventional MPPT method, while the size of the power converter is reduced by around 40%. Despite the many benefits, but stability analysis of these intelligent systems is a challenge.

* Tel./fax: +98 273 3393116.
E-mail address: Sadeghebrahimkhani@gmail.com

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Nonlinear control can be employed in order to ensure stability and the performance in a global sense [13]. A stable nonlinear control based on the adaptive Backstepping approach is presented in [14]. In [15] input–output feedback linearization (IOFL) is used to improve the transient stability of the power system, experimental results demonstrate the feasibility of the IOFL control strategy. In [16] an adaptive IOFL equipped with a disturbance observer for estimation of parameter uncertainties is proposed. Maximum power point tracking control using IOFL is presented in [17]. IOFL which combined with the model predictive control is suggested in [18], the proposed method has satisfactory performance when compared with the response of the PI and the sequential quadratic program (SQL) controller. In [19] with using the IOFL and predictive control method, a nonlinear generalized predictive control for wind energy conversion system with a nonlinear disturbance observer is proposed. However, feedback linearization is based on canceling nonlinear terms, the robustness of this method with respect to the parameter variations and uncertainties is an important consideration.

Uncertainties in DFIG system, such as parameter uncertainties and external disturbances may cause the malfunction in the closed loop control of DFIG, therefore, robust control laws should be introduced to control them and to ensure the performance. In [20] a coordinated robust control is proposed with using a power damping oscillator for DFIG. In [21] a robust nonlinear controller based on the backstepping control approach is designed for the control problem of the variable-speed wind turbine, which uniformly ultimately boundedness of the generator velocity tracking error signal is guaranteed.

Sliding mode control, due to its robustness to parameter uncertainty and external disturbance, is a common robust control method. In sliding mode control, one of the most important steps in controller design procedure is to find the proper bounds of uncertainties. Also, when the first order sliding mode approach is used, the chattering effect appears. Chattering is an undesirable phenomenon of oscillations having finite frequency and amplitude [22]. Chattering is a harmful phenomenon because it leads to low control accuracy, high wear of moving mechanical parts, and high heat losses in power circuits. In [23–27] first order sliding mode controller for DFIG have been reported. In [23] to reduce the chattering effect a boundary layer is used. In [24] discrete sliding mode switch free robust control strategy with adaptive reaching law is proposed for direct active and reactive power regulation of wind driven DFIG. In [25] an appropriate finite gain is used to eliminate the chattering in control system. In [26] in order to reduce the chattering phenomenon, discontinuous control is substituted by a fuzzy mode control.

Another way to avoid the chattering phenomenon is using high order sliding mode techniques [28–30]. In higher order sliding mode control approaches, the discontinuous term is moved into higher order derivatives of the control signal, thus they remove the chattering effect and guarantee even higher accuracy in presence of uncertainties [31,32]. In [33–35] second order sliding mode control for wind energy system is developed. A practical application of second order sliding mode observer can be found in [36]. Applications of Adaptive second order sliding mode, which the boundaries of first derivative of uncertainties are unknown is introduced in [37,38]. In [39] an adaptive second order sliding mode observer is proposed to state estimation and fault reconstruction, the requirement of the bound of fault and its first derivative is removed.

In the aforementioned sliding mode methods, it is assumed that the uncertainties (and/or their first derivative) are bounded with a positive constant. In some cases (such as parametric uncertainties) system states are included in the uncertainties, thus the upper bound of uncertainties (or their derivatives) vary as long as the states change, in this case if bounds of uncertainties assumed to be positive constant, then only the local stability can be obtained, and the closed loop system may be unstable if the initial states are large enough [40], an adaptive second order sliding mode controller is proposed in [40] which uncertainties bounded by a positive function.

The aim of this study is actively estimate and compensate of the uncertainties and disturbances, which that does not require the knowledge of the bounds of uncertainties, also control law is continuous. As a result, the problems of the chattering and the upper bound of uncertainties are resolved. In this field, extended state observer (ESO) [41] is a high gain observer, which widely have been used in various applications, such as the disturbance estimation [42] the nonlinear dynamics estimation [43], the fractional order dynamics estimation [44]. In [45], an ESO based robust control strategy is proposed for DFIG-based wind turbines, nonlinear dynamics and external disturbances are estimated and compensated with using the ESO. In ESO-based uncertainty estimation, if the rth-order derivative of uncertainties is zero, then rth-order ESO should be used to achieve asymptotic convergence of the ESO [46]. In [47] a low pass filter is proposed to estimate uncertainty in sliding mode control, in this approach if rth-order derivative of uncertainties is zero, then if rth-order low pass filter is used, uncertainty can be estimated asymptotically. In this paper, we propose a fractional order low pass second order filter, to estimate the lumped uncertainties in the DFIG control system, which that does not require the knowledge of bounds of uncertainties. It is shown that, the proposed second order filter can asymptotically estimate uncertainties, if the 2μth-order derivatives of disturbance is zero (where $0<\mu<2$). The proposed filter have two tuning parameter, frequency response of the filter is analyzed and tuning criteria is introduced.

Fractional calculus is an extension of regular integer calculus to non-integer case [48]. Recently, several authors show great interests to integrate fractional calculus into sliding mode control to obtain better performance. Fractional order sliding surfaces as a generalization of integer order sliding surfaces have been introduced to improve the performance of the sliding mode controller [49,50]. A fractional order sliding mode control scheme based on parameters auto-tuning for the velocity control of permanent magnet synchronous motor is presented in [49]. In [50] to make anti-lock brake system possess better braking performance, a fractional order sliding mode controller is developed. In [51] a control strategy based on fractional-order PI controllers is proposed for the variable-speed operation of wind turbines.

The main contributions of this paper are as follows:

- High performance nonlinear control design using FOSM law to achieve maximum power point tracking.
- Robust chattering-free control design, which that does not require the knowledge of the bound of uncertainties.

This paper is organized as follows. In Section 2 the basic of fractional calculus are briefly reviewed. Section 3 presents the dynamics of the wind energy conversion system. Section 4 presents details of the FOSM system design. In addition, the uncertainty estimation method and adaptive learning algorithms of the proposed FOSM and the robust controller are described in details in this section. As well, the stability analysis of the proposed control system is introduced. Simulation results are given in Section 5. The validity of the design procedure and the robustness of the proposed controller is verified by means of computer simulation analysis. Finally, Section 6 concludes the paper.