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Robust sliding-mode control of wind energy conversion systems for optimal power extraction via nonlinear perturbation observers

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HIGHLIGHTS

- A robust sliding-mode controller has been designed for DFIG to achieve MPPT.
- Only the measurement of rotor speed and reactive power is required.
- An enhanced FRT capability can be realized with proper control efforts.
- Significant robustness can be provided against to various modelling uncertainties.

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ABSTRACT

This paper designs a novel robust sliding-mode control using nonlinear perturbation observers for wind energy conversion systems (WECS), in which a doubly-fed induction generator (DFIG) is employed to achieve an optimal power extraction with an improved fault ride-through (FRT) capability. The strong nonlinearities originated from the aerodynamics of the wind turbine, together with the generator parameter uncertainties and wind speed randomness, are aggregated into a perturbation that is estimated online by a sliding-mode state and perturbation observer (SMSPO). Then, the perturbation estimate is fully compensated by a robust sliding-mode controller so as to provide a considerable robustness against various modelling uncertainties and to achieve a consistent control performance under stochastic wind speed variations. Moreover, the proposed approach has an integrated structure thus only the measurement of rotor speed and reactive power is required, while the classical auxiliary dq-axis current regulation loops can be completely eliminated. Four case studies are carried out which verify that a more optimal wind power extraction and an enhanced FRT capability can be realized in comparison with that of conventional vector control (VC), feedback linearization control (FLC), and sliding-mode control (SMC).

1. Introduction

Due to the astonishingly ever-increasing population issue and environmental crisis, both the social and industrial demands of renewable energy keep growing rapidly in the past decade around the globe. As one of the most abundant and mature renewable energy, wind energy conversion systems (WECS) have been paid considerable attention and their proportion in nationwide energy production will rise even faster in future [1]. Nowadays, the most commonly used wind turbine in WECS is based on doubly-fed induction generator (DFIG) because of its noticeable merits: variable speed generation, the reduction of mechanical stresses and acoustic noise, as well as the improvement of the power quality [2].

So far, an enormous variety of studies have been undertaken for DFIG modelling and control, in which vector control (VC) incorporated with proportional-integral (PI) loops is the most popular and widely recognized framework in industry, thanks to its promising features of decoupling control of active/reactive power, simple structure, as well as high reliability [3]. The primary goal of DFIG control system design is to optimally extract the wind power under random wind speed variation, which is usually called maximum power point tracking (MPPT) [4]. Meanwhile, a fault-ride through (FRT) capability is often required so that DFIG can withstand some typical disturbances in power grids [5]. However, one significant drawback of VC is that it cannot maintain a consistent control performance when operation conditions vary as its PI parameters are determined by the one-point linearization, while

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DFIG is a highly nonlinear system resulted from the fact that it frequently operates under a time-varying and wide operation region by stochastic turbulent wind. Several optimal parameter tuning techniques have been examined to improve the overall control performance of PI control, such as the differential evolutionary algorithm (DE) employed for the performance enhancement of DFIG in the presence of external disturbances [6]. Reference [7] proposed a meta-heuristic algorithm called grouped grey wolf optimizer to achieve MPPT together with an improved FRT capability. In addition, literature [8] adopted particle swarm optimizer (PSO) to enhance the building energy performance. Moreover, a genetic algorithm was developed to minimize the energy consumption of the hybrid energy storage system in electric vehicle [9].

On the other hand, plenty of promising alternatives have been investigated attempting to remedy such inherent flaws of VC. For example, fuzzy-logic was used to deal with onshore wind farm site selection [10]. In reference [11], a feedback linearization control (FLC) was designed for MPPT of DFIG with a thorough modal analysis of generator dynamics, which internal dynamics stability is also proved in the context of Lyapunov criterion. Besides, both the rotor position and speed are calculated based on model reference adaptive system (MRAS) control strategy by [12], such that a fast dynamic response without the requirement of flux estimation can be realized. Furthermore, a robust continuous-time model predictive direct power control of DFIG was proposed via Taylor series expansion for stator current prediction, which is directly used to compute the required rotor voltage in order to minimize the difference between the actual stator currents and their references over the prediction period [13]. Meanwhile, literature [14] developed an internal model state-feedback approach to control the DFIG currents, which is able to provide robustness to external disturbances automatically and to eliminate the need of disturbance compensation. Additionally, a Lyapunov control theory based controller was devised for rotor speed adjustment without any information about wind data or an available anemometer [15]. A nonlinear robust power controller based on a hybrid of adaptive pole placement and backstepping was presented in [16], which implementation feasibility is validated through field-programmable gate array (FPGA). Moreover, an approximate dynamic programming based optimal and adaptive reactive power control scheme was applied to remarkably improve the transient stability of power systems with wind farms [17].

Among all sorts of advanced approaches, sliding-mode control (SMC) is a powerful high-frequency switching control scheme for nonlinear systems with various uncertainties and disturbances, which elegantly features effective disturbance rejection, fast response, and strong robustness [18], thus it is appropriate to tackle the above obstacles. In work [19], the dynamics of a small-capacity wind turbine system connected to the power grid was altered under severe faults of power grids, in which the transient behaviour and the performance limit for FRT are discussed by using two protection circuits of an AC-crowbar and a DC-Chopper. A high-order SMC was applied which owns prominent advantages of great robustness against power grid faults, together with no extra mechanical stress on the wind turbine drive train [20]. In addition, reference [21] wisely chose a sliding surface that allows the wind turbine to operate very closely to the optimal regions, while PSO was used to determine the optimal slope of the sliding surface and the switching component amplitude. Further, an intelligent proportional-integral SMC was proposed for direct power control of variable-speed constant-frequency wind turbine systems and MPPT under several disturbances [22]. Moreover, literature [23] designed a robust fractional-order SMC for MPPT and robustness enhancement of DFIG, in which unknown nonlinear disturbances and parameter uncertainties are estimated via a fractional-order uncertainty estimator while a continuous control strategy is developed to realize a chattering-free manner.

Nevertheless, an essential shortcoming of SMC is its over-conservativeness stemmed from the use of upper bound of uncertainties, while these worst conditions in which the perturbation takes its upper bound does not usually occur. As a consequence, numerous disturbance/perturbation observer based controllers have been examined which aim to provide a more appropriate control performance by real-time compensation of the combinatorial effect of various uncertainties and disturbances, e.g., a high-gain state and perturbation observer (HGSPO) was adopted to estimate the unmodelled dynamics and parameter uncertainties of multi-machine power systems equipped with flexible alternating current transmission system devices, such that a coordinated adaptive passive control can be realized [24]. Alternatively, a nonlinear observer based adaptive disturbance rejection control (ADRC) was proposed to improve the power tracking of DFIG under abrupt changes in wind speed, which can be applied for any type of optimal active power tracking algorithms [25]. Moreover, reference [26] described a linear ADRC based load frequency control (LFC) to maintain generation-load balance and to realize disturbance rejection of power systems integrated with DFIG. In work [27], sliding-mode based perturbation observer was used to design a nonlinear adaptive controller for power system stability enhancement. On the other hand, disturbance observer based SMC was studied for continuous-time linear systems with mismatched disturbances or uncertainties [28], while the applications of disturbance/perturbation observer based SMC can be referred to the current regulation of voltage source converter based high voltage direct current system [29], LFC of power systems with high wind energy penetration [30], position and velocity profile tracking control for next-generation servo track writing [31], etc. In addition, a derivative-free nonlinear Kalman filter was redesigned as a disturbance observer to estimate additive input disturbances to DFIG, which are finally compensated by a feedback controller that enables the generator's state variables to track desirable setpoints [32].

This paper proposes a perturbation observer based sliding-mode control (POSMC) of DFIG for optimal power extraction, which novelty and contribution can be summarized as the following four points:

- The combinatorial effect of wind turbine nonlinearities, generator parameter uncertainties, and wind speed randomness is simultaneously estimated online by a sliding-mode state and perturbation observer (SMSPO), which is then fully compensated by a robust sliding-mode controller. Thus no accurate system model is needed. In contrast, other nonlinear approaches need an accurate system model [11] or can merely handle some specific uncertainties, e.g., wind speed uncertainties [15] or parameter uncertainties [16];
- Only the measurement of rotor speed and reactive power is required by POSMC, while various generator variables and parameters are required by references [12,14]. Hence POSMC is relatively easy to be implemented in practice;
- Compared to other SMC schemes [22,23], as the upper bound of perturbation is replaced by its real-time estimate, the inherent over-conservativeness of SMC can be avoided by the proposed method;
- POSMC employs a nonlinear SMSPO to estimate the perturbation, which does not have the malignant effect of peaking phenomenon existed in HGSPO [24], Moreover, its structure is simpler than that of another typical nonlinear observer called ADRC [25].

Four case studies have been undertaken to evaluate the effectiveness of the proposed approaches and compare its control performance against other typical methods, such as VC, FLC, and SMC. The remaining of this paper is organized as follows: Section 2 is devoted for DFIG modelling while Section 3 develops the POSMC scheme. In Section 4, the POSMC design of DFIG for optimal power extraction is investigated. Section 5 provides the simulation results. Lastly, some concluding remarks are summarized in Section 6.

2. DFIG modelling

A schematic diagram of DFIG connected to a power grid is illustrated in Fig. 1, in which the wind turbine is connected to an induction