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A coordinated high-order sliding mode control of DFIG wind turbine for power optimization and grid synchronization

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ABSTRACT

This paper aims to propose a coordinated high-order sliding mode control (HOSMC) method for power optimization and grid synchronization of a doubly-fed induction generator (DFIG) based wind energy conversion system (WECS). The super-twisting algorithm is employed to maximize the captured wind energy with optimal rotor speed tracking, and regulate the voltage to fulfill the grid requirement. Subsequently, a grid synchronization scheme is proposed, where the wind turbine stator terminal voltage is controlled to synchronize with the grid voltage without employing the current control loop. Meanwhile, a novel reaching law is employed to accelerate the reaching speed. Simulations are carried out to verify the effectiveness of the novel approach, where the first order sliding mode control and the proportional-integral control are considered for comparison. A stepwise wind speed scenario, a variable wind speed condition, and the scenario under parameter perturbations are included in the comparative study. The simulation results fully reveal the robustness, chattering free property and high tracking precision of the proposed method.

1. Introduction

Wind energy is one of the fastest-growing forms of renewable sources in recent years leaping over other green resources such as solar, hydro, and ocean waves. Doubly-fed induction generator (DFIG) is one of the most significant wind turbines (WT) due to its inherent advantages that outperform other wind turbines, including its variable wind speed operation, high system efficiency, low converter rating, and the controllable power factor [1,2].

The mission of DFIG based wind energy conversion system (WECS) can be generalized as capturing the wind energy to the optimal extent and transfers the wind power to the grid in a continuous, steady and sustainable manner. Hence, power optimization and grid synchronization comprise two important control missions of DFIG based WECS.

The issue of wind turbine power optimization has been extensively investigated in recent years, and numerous control approaches have been proposed, including the feedback scheme based direct torque control (DTC) [3], proportional-integral (PI) based pitch control [4], gain scheduling control assisted by frequency domain design [5], field oriented control [6], and linear quadratic Gaussian (LQS) approach [7]. However, the nonlinear behaviors of the electrical components and the mechanical parameter variations largely limited the applications of those linear or non-robust approaches. Multiple nonlinear and robust approaches, including the feedback linearization method [8], fuzzy logic control [9] and the neural networks based control [10] are proposed. In [11], a grouped grey wolf optimizer is proposed to maximize the wind power harvest of DFIG, where the grey wolves are classified into the hunting group and the scout group and an improved fault ride through capability is provided with this approach. In [12], a feedback linearization approach is presented to linearize the nonlinear system of DFIG into third-order system and a second order system for wind power harvesting optimization. In [13], a robust state feedback control is proposed based on perturbation estimation for maximum power point tracking (MPPT) of DFIG.

Among all the nonlinear control approaches, the sliding mode control (SMC) method is robust to uncertain parametric variations or external disturbances. The application of SMC in a WECS when the grid voltage is in a non-ideal condition is proposed in [15]. The first order sliding mode (FOSM) based SMC approaches are easy to implement and possess high robust performance. However, the chattering phenomenon and the finite time stability problems largely impacted their engineering applications [14]. Countermeasures are proposed to tackle the chattering issues, including the introduction of exponential reaching law (ERL) [16], the employment of sigmoid function [17], the proposal of terminal sliding mode control (TSMC) [18], the perturbation observers based SMC [19] and the fractional order based SMC [20].

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Nomenclature

ω_r	rotor speed
I_{rd}	rotor current in the d axis
I_{rq}	rotor current in the q axis
U_{rd}	rotor voltages in the d axis
U_{rq}	rotor voltages in the q axis
T_a	aerodynamic torque
ΔB	damping coefficient perturbation
ΔR_r	resistance perturbation
J	rotor inertia
N	gearbox ratio
L_m	mutual inductance
L_s	leakage inductance
φ_s	stator flux
n_p	pole pair
L_r	rotor leakage inductance
λ	tip speed ratio (TSP)
R	blade radius
C_p	the power coefficient
β	pitch angle
λ_{opt}	optimal TSP
z_1, z_2	error state variables
λ_{11}, λ_{12}, λ_{21}, λ_{22}	sign function positive gains
α_{11}, α_{12}, α_{21}, α_{22}	super-twisting parameters
$\hat{I}_{rd}$	observed rotor current in the d axis
$\hat{I}_{rq}$	observed rotor current in the q axis
$\tilde{I}_{rd}$, $\tilde{I}_{rq}$	error variables of the rotor currents
b_{d1}, b_{d2}, b_{q1}, b_{q2}	tunable observer parameters
V_{sd}	stator voltage in the d axis
V_{sq}	stator voltage in the q axis
V_{gd}	grid voltages in the d axis
V_{gq}	grid voltages in the q axis
β	sliding manifold gain matrix
z	stator voltages and grid voltages error

However, these methods have their own limits: the exponential reaching law can only reduce the chattering level to a certain level; the introduction of sigmoid function to replace the sign function of SMC will impact its robustness performance; the TSMC method requires augmented observers for parameter tuning and the algorithm is more complicated; the fractional order based SMC involves integer order approximation which impacts its engineering application. Among them, the high-order sliding mode control (HOSMC) has attracted the wide attention of scholars in control theory. A set of HOSMC twisting algorithms are proposed to tackle the harmonic current existing in induction motors [21].

For a grid-connected WECS based on DFIG, the machine side should be synchronized before grid connection other than the power decoupled control. Conventional control technique of grid connected WECSs are generally focused on the control of rotor side converter (RSC) and the grid side converter (GSC) in the vector reference frame [22], wherein the active/reactive power and the machine torques are controlled by regulating the parallel and orthogonal component of the rotor current.

Nevertheless, since the stator of DFIG is directly connected to the grid, it is extremely sensitive to grid voltage disturbances. When a grid fault occurs, the stator flux will contain transient and negative-sequence components which can induce large electromotive force (EMF) in the rotor circuit. Smooth and fast grid synchronization is capable of minimizing the impact of DFIG on the grid and reclosing the DFIG with the power grid in the advent of some major grid faults, therefore the WECS fault ride through (FRT) capability can be enhanced. However, there are only a few reports focused on the issue of grid synchronization [23,24]. A set of cascaded approaches are employed in [23], wherein the inner loop is utilized to regulate the rotor current and the outer loop is employed to mitigate the voltage differences in the synchronization process. In [24], grid synchronization is accomplished by directly regulating the stator voltage instead of cascaded loops. These approaches are all based on state transformation and linearization, which requires the knowledge of parameters of the WECS. However, most of those literatures fail to consider the impact of parameter perturbations caused by temperature and exciting saturation.

This paper aims to propose a coordinated high order sliding mode control (HOSMC) approach for DFIG based WECS to optimize the wind power harnessing process and synchronize the stator voltages with the grid. The main contribution of this paper is given as follows. We proposed a novel HOSMC scheme which aims to optimize the power harnessing process, wherein a robust exact differentiator is utilized to implement the super-twisting algorithm in order to resolve the chattering phenomenon of SMC. Unlike traditional HOSMC schemes, we employ the block control approach to decompose the control mission into multiple stages, and we impose the state equations with the desired dynamics in order to improve the dynamic performance of the HOSMC. Subsequently, a sliding mode angular velocity observer is proposed to obtain the rotor angular velocity; meanwhile, the problem of grid synchronization is presented, and a coordinated HOSMC approach is proposed which considers the multi objective optimization problem of both wind energy capturing and grid voltage synchronization, wherein a novel reaching law is utilized in the SMC based grid voltage synchronization procedure. Ultimately, the controller parameters are obtained based on the imposed state equations dynamics and a stability analysis. The remaining part of the paper is organized as follows: in Section 2, the power optimization control with HOSMC approach is presented; in Section 3, the grid synchronization procedure will be conducted and the control parameters will be tuned to coordinate the aforementioned control mission; in Section 4, simulations will be conducted considering stead state operation, variable wind speed scenario, and operation with parameter perturbations.

2. Power optimization control

2.1. DFIG based WECS modeling

The system configuration of DFIG based WECS is shown in Fig. 1 [20], where the wind turbine blades are implemented to capture the wind energy and transfer the wind energy to the RSC and the GSC through a gear box. Meanwhile, a rotor side controller and a grid side controller are applied to control their corresponding converters. The mission of power optimization control is to maximize the power efficiency under different wind speed scenario. Fig. 2 shows four different operation regions of a wind turbine. This paper mainly considers the

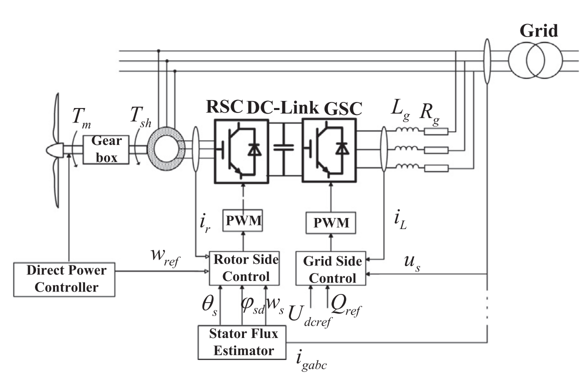

Fig. 1. System configuration of DFIG based WECS.