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Nonlinear predictive control of a DFIG-based wind turbine for power capture optimization

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ABSTRACT

A nonlinear predictive controller is proposed for a variable speed wind turbine. The objective is power capture optimization and transient loads reduction. The controller acts only on low wind speed area. It consists of a doubly fed induction generator controller coupled with a model predictive aeroturbine controller. Unlike the majority of existing work on DFIG, the nonlinear controller deals directly with the generator model without any simplifying assumptions. This makes it possible to remove some assumptions on the DFIG model. The nonlinear DFIG controller achieves asymptotic torque and flux tracking. For the aeroturbine part, the model predictive controller uses predictions of the output to compute the optimal control sequence. It makes a compromise between power capture optimization and loads reduction. The controllers design procedure is detailed. The global controller is tested with the parameters of a real experimental variable speed wind turbine. It is compared with PID and LQG controllers. The simulations show satisfactory results in comparison with these schemes. The proposed controller achieves better power capture optimization and load reduction. It therefore allows a good achievement of the design objectives.

1. Introduction

Control design is a key factor for variable speed wind turbine (VSWT) efficiency enhancement [1]. During the last decades, a considerable amount of literature has been devoted to wind turbines control design. A substantial review of this literature is given from [2] to [3]. A wide variety of advanced control strategies has been applied to VSWT control either in low or high wind speed areas [4]. In general terms, the dedicated literature to wind turbine control can be split in many parts:

1. The first one concerns aeroturbine control. Only the mechanics and aerodynamics of the turbine are considered. The electric generator and power converters models are not considered. It is then assumed that the control inputs are directly the pitch angle and the generator torque [5]. The main control objective in this case is either wind power capture optimization for low wind speeds or electrical power and rotor speed regulation for high wind speed. Almost all classical linear control techniques have been applied to this control problem. PI/PID controllers [6], state space based LQ/LQG controllers [7] linear $\mathscr{H}_\infty$ controllers [8] are widely used. More recently, gain scheduling controllers [9,10]. However, a simple linear wind turbine controller achieves poor dynamic performances. Such a controller can not deal with strong nonlinear aerodynamics and highly turbulent wind. To overcome this limitation, self-tuning regulators, adaptive linear regulators [11,12] and gain-scheduling ones [10] are proposed. In order to take directly into consideration the nonlinear model of the aeroturbine, several nonlinear controllers have been proposed [13]. The main drawback of these techniques is the complexity of the controller. However, the high computing power of recent calculator devices makes the implementation of nonlinear controllers possible.
2. The second part of the literature dedicated to wind turbine control considers a very simplified model of the wind and the aeroturbine. On the other hand, a detailed dynamic model of the electric generator is considered. Generally, the generator model is a two reference frame model ($d-q,\alpha-\beta$). It is obtained using a Park transformation of the generator equations [14]. The control objectives are mainly the control of the active P and reactive Q electrical power. The main considered topology is a variable speed wind turbine equipped with a DFIG generator. This one is fed by a two side PWM back-to-back converters [15]. Different control strategies are used. Classical ones use vector field-oriented control. The stator or rotor flux are then oriented along the d axis [16]. More advanced control strategies use nonlinear control [17], adaptive control [18], sliding mode control [19] and backstepping [20]. These control

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Nomenclature

v	wind speed, $m\cdot s^{-1}$
ρ_{air}	air density, $kg\cdot m^{-3}$
R	rotor radius, m
P_a	aerodynamic power, W
T_a	aerodynamic torque, N·m
$T_{a_{hs}}$	high-speed equivalent aerodynamic torque, N·m
$E_{aero}(\%)$	aerodynamic efficiency, (%)
λ	tip speed ratio
β_p	pitch angle, deg
$C_p(\lambda,\beta_p)$	power coefficient
$C_q(\lambda,\beta_p)$	torque coefficient
ω_t	rotor speed, $rad\cdot s^{-1}$
ω_g	generator speed, $rad\cdot s^{-1}$
ω_{ls}	low speed shaft speed, $rad\cdot s^{-1}$
θ_t	rotor side angular deviation, rad
θ_{ls}	gearbox side angular deviation, rad
θ_g	generator side angular deviation, rad
T_{em}	generator (electromagnetic) torque, N·m
T_{ls}	low speed shaft torque, N·m
T_{hs}	high speed shaft torque, N·m
J_r	rotor inertia, $kg\cdot m^2$
J_g	generator inertia, $kg\cdot m^2$
$J_{t_{hs}}$	high-speed equivalent inertia, $kg\cdot m^2$
K_r	rotor external damping, $N\cdot m\cdot rad^{-1}\cdot s^{-1}$
K_g	generator external damping, $N\cdot m\cdot rad^{-1}\cdot s^{-1}$
K_{ls}	low speed shaft damping, $N\cdot m\cdot rad^{-1}\cdot s^{-1}$
$K_{t_{hs}}$	high-speed equivalent damping, $N\cdot m\cdot rad^{-1}\cdot s^{-1}$
B_{ls}	low speed shaft stiffness, $N\cdot m\cdot rad^{-1}$
n_g	gearbox ration,
ϕ_{sd}	direct axis stator flux, Wb
ϕ_{sq}	quadrature axis stator flux, Wb
i_{rd}	direct axis rotor current, A
i_{rq}	quadrature axis rotor current, A
v_{sd}	direct axis stator voltage, V
v_{sq}	quadrature axis stator voltage, V
v_{rd}	direct axis rotor voltage, V
v_{rq}	quadrature axis rotor voltage, V
ρ	(d,q) reference frame position, rad
p	number of pole pairs,
M	mutual inductance, H
ε_i	tracking error,
WT	Wind Turbine
VSWT	Variable Speed Wind Turbine
DFIG	Doubly Fed Induction Generator

strategies give good performances. However, they are generally complex to be implemented. Add to this, in many works, the control strategies are tested under unrealistic conditions. Constant wind speed profile or untested aerodynamic wind turbine characteristics are often used for these tests [21].

In this work, a whole nonlinear model is considered for both the DFIG and the aeroturbine. This makes it possible to have a model closer to physical reality. For control objectives, it is desirable to use a control technique which ensures a good compromise between efficiency and complexity. Predictive control is a well known control strategy. It has been used and implemented in many industrial applications (chemical process, metallurgy, paper industry, aerospace and automotive control [22].) Predictive control also has got a great importance in application to wind energy. A review of the predictive control of VSWT is presented in [23]. However, in many works on predictive control of VSWT, the suggested controllers consider only the generator control [24–26] or the aeroturbine control [27,28,7]. It is important to consider both of them together. The new feature of this work is that the presented controller deals either with the generator or with the aeroturbine control. Contrarily to many other works, no simplifying assumptions are made to the DFIG model. In many control schemes in the literature, simplified models are used for the generator for control design [29,30]. Under some conditions, these assumptions can not be maintained. An interesting approach is proposed in [31] using nonlinear model predictive direct power control (PDPC). The aim of this approach is to control the active and reactive power of a DFIG wind turbine. A constrained objective function is adopted to reduces active and reactive power ripples. An optimization algorithm is then used to compute the control actions. In this article, the objective is to optimize aerodynamic power capture. It is a different objective than active and reactive power regulation as done in [31]. A quadratic programming algorithms are used instead of nonlinear multi objective optimization used in [31].

In this work, the whole nonlinear model of the DFIG is used for the design of a nonlinear state feedback controller. This provides a controller that can overcome the simplifying assumptions. The proposed controller acts only on low wind speed region. A whole controller is to be considered in future works. It should cover all the operating area including low and high wind speed regions.

This paper is organized as follows: First, the aeroturbine nonlinear one-mass model is deduced in Section 2. After that, the state-space representation of the DFIG used for the controller design is given. At the end of this section, the objectives of the VSWT control are detailed. A special focus is accorded to the low wind speed area and power capture optimization. The proposed controller is detailed in Section 3 in three steps: Firstly, the nonlinear DFIG state feedback with asymptotic output tracking is deduced. The objective is to track the electromagnetic torque and stator flux references. Secondly, a multi-criteria model predictive controller (MPC) is obtained. The aim is tracking the optimal wind turbine speed to maximize wind power capture. Finally, the scheme of the global controller is presented and the interconnection between the sub-controllers is explained. Section 4 presents the simulation results obtained with the controllers. Real parameters of an experimental wind turbine are used. A conclusion and perspectives are then drawn. Some calculus details and the wind turbine parameters are given in appendixes.

2. Wind turbine modeling

The considered wind turbine in this work is an experimental medium-scale variable speed wind turbine. It is equipped with a doubly fed induction generator associated with a two side back-to-back converter. This configuration is depicted in Fig. 1. This is a common variable speed wind turbine scheme [6]. The used model for controllers design includes the aeroturbine and the generators models.

2.1. Aeroturbine modeling

The mechanical structure of a wind turbine is modeled as a flexible interconnection of rigid rotating mass. Many models are suggested in the literature using one, two or multiple mass [32,33]. A two-mass model is commonly used as a good compromise between efficiency and simplicity. A two-mass model is composed of two rotating inertias connected by a flexible shaft and a gearbox [34]. The gearbox connects the aerodynamic rotor shaft side (low speed side) to the generator shaft side (high speed shaft). From Fig. 2 diagram, the mechanical equation of a two-mass wind turbine model is given by

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