Energy Conversion and Management 93 (2015) 40–48

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Performance assessment of a wind energy conversion system using a hierarchical controller structure

C. Viveiros [a,b,c], R. Melício [a,b,*], J. Igreja [c], V.M.F. Mendes [b,c,*]

[a] IDMEC/Associated Laboratory for Energy, Transports and Aeronautics, Instituto Superior Técnico, Universidade de Lisboa, Portugal
[b] Department of Physics, Universidade de Évora, R. Romão Ramalho 59, 7002-554 Évora, Portugal
[c] Department of Electrical Engineering and Automation, Instituto Superior de Engenharia de Lisboa, R. Conselheiro Emídio Navarro, 1950-062 Lisbon, Portugal

ARTICLE INFO

Article history:
Received 28 September 2014
Accepted 1 January 2015
Available online 19 January 2015

Keywords:
Wind turbine
Fractional-order
Fuzzy proportional-integral
Controller performance
Event-based supervisor

ABSTRACT

This paper deals with a hierarchical structure composed by an event-based supervisor in a higher level and two distinct proportional integral (PI) controllers in a lower level. The controllers are applied to a variable speed wind energy conversion system with doubly-fed induction generator, namely, the fuzzy PI control and the fractional-order PI control. The event-based supervisor analyses the operation state of the wind energy conversion system among four possible operational states: park, start-up, generating or brake and sends the operation state to the controllers in the lower level. In start-up state, the controllers only act on electric torque while pitch angle is equal to zero. In generating state, the controllers must act on the pitch angle of the blades in order to maintain the electric power around the nominal value, thus ensuring that the safety conditions required for integration in the electric grid are met. Comparisons between fuzzy PI and fractional-order PI pitch controllers applied to a wind turbine benchmark model are given and simulation results by Matlab/Simulink are shown. From the results regarding the closed loop point of view, fuzzy PI controller allows a smoother response at the expense of larger number of variations of the pitch angle, implying frequent switches between operational states. On the other hand fractional-order PI controller allows an oscillatory response with less control effort, reducing switches between operational states.

1. Introduction

Wind energy conversion system (WECS) deployment is in expansion, whether onshore or offshore [1], given the economic advantages of wind power and the increased competitiveness regarding other sources of electric energy. The wind power exploitation continues to grow and has increased substantially in the first half of 2014 when compared to previous years [2]. The increasing integration of wind power has led to modern megawatt WECS running at variable speed having some advantages such as: mechanical stress is reduced, torque oscillations are not transmitted to the electric grid and the rotor speed is controlled to achieve the best aerodynamic efficiency between the cut-in and the rated wind speed [3,4]. In this paper the WECS connection to the electric grid is accomplished by a doubly fed induction generator (DFIG) in order to achieve a moderate range of variable speed [5].

The DFIG variable speed wind turbine generators are often addressed by the scientific community, for instance: an efficient control strategy to improve the fault ride through capability of the DFIG during the symmetrical and asymmetrical grid faults is shown in [6]; a design and the implementation of a model reference adaptive control of the active and reactive power regulation of a grid connected wind turbine based on a DFIG is shown in [7].

The architecture of a control system is important not only for the WECS integration into an electric grid preventing performance degradation on the quality of electrical energy injected into the electric grid, but also to ensure the best performance on following the rated power. Therefore, the design of a control strategy for a wind turbine must consider a series of important aspects such as wind speed measurement, wind turbine components, the influence of the wind speed on these components and the performances that the closed loop system must have [8]. Pitch control system is the most suitable for controlling the power captured by the blades by regulating the pitch angle, ensuring the best performance during the capture of energy under all operational wind scenarios.

* Corresponding authors at: Department of Physics, Universidade de Évora, R. Romão Ramalho 59, 7002-554 Évora, Portugal. Tel.: +351 266 745372; fax: +351 266 745394.

E-mail addresses: ruimelicio@gmail.com (R. Melício), vfmendes54@gmail.com (V.M.F. Mendes).

http://dx.doi.org/10.1016/j.enconman.2015.01.002
0196-8904/

Nomenclature

A	area covered by the blades	τ_g	generator torque
B_{dt}	torsion damping	$\tau_{g,r}$	generator torque reference
B_g	generator friction coefficient	τ_r	turbine rotor torque
B_r	turbine rotor friction coefficient	ω_{nom}	omega nominal
C_P	power coefficient	ω_g	generator speed
J_g	generator moment of inertia	ω_r	turbine rotor speed
J_r	turbine rotor moment of inertia	ω_Δ	small offset
K_{dt}	torsion stiffness	β	pitch angle
N_g	ratio gear	β_r	pitch angle reference
P_g	generator power of the wind turbine	θ_Δ	torsion angle
P_r	rated power of the wind turbine	ρ	air density
R	radius of the turbine rotor	λ	tip speed ratio
r	references or rotor values	η_g	generator efficiency
m	measurements values	v_{min}	cut-in wind speed
v_w	wind speed	v_{max}	cut-out wind speed

Pitch control systems are widely reported. A proportional integral pitch controller is analyzed and designed for a large wind turbine generator (WTG) using a graphical approach in [9]. Comparison between multiple linear parameter-varying controllers is presented in [10]. Since WECS is highly nonlinear, other control strategies have been applied for nonlinear systems, such as fuzzy controllers. Fuzzy logic controllers for small wind turbine can be found in [11,12]. An adaptive fuzzy PI speed controller based on permanent magnet synchronous generator is proposed in [13]. A fuzzy controller applied to the control of generator speed and blade pitch angle, presenting improved system responsiveness and reduced overshoot has been proposed in [14]. Moreover a control scheme based on a self-tuning fuzzy PI to control the power electronic converters of the DFIG is proposed in [15]. Despite the fact that the model for a WECS is a nonlinear one, fractional-order control has, in recent years, captured the attention of the scientific community given its capability to improve the dynamic behaviour of closed loop systems [16–18]. Some applications for fractional-order control can be found in [19,20]. The control speed of the wind turbine, based on a linearization model of a wind turbine system using a new fractional-order controller and having the ability to be supported by a simple and practical design method, is proposed in [21]. The fractional-order proportional integral controller (FOPI) takes advantage over the integer order proportional integral controller given the introduction of one additional tuning parameter, the integral fractional-order, providing additional potential to the design specifications in order to achieve a better performance [22–24].

The supervisory control system provides the capability to conveniently schedule the different phases of the system operation, i.e., start-up, production and shutdown, in order to achieve the specification required on the operation, based on the information observed for the current state. An event-based supervisor is based on supervisory control theory and has an important role in control applications such as monitoring, fault detection, diagnosis, and production optimization [25]. A study concerning fault detection strategies presenting a development and implementation with the emphasis on supervisory control is reported in [26].

This paper is about a hierarchical structure with an event-based supervisor in a higher level using two distinct control strategies: fuzzy PI and FOPI, applied to a variable speed wind turbine in a lower level. The wind turbine benchmark model used in this paper was developed by [27]. The event-based supervisor is implemented using a Matlab toolbox, the Sateflow chart, and its function is to analyze the operating conditions to determine the state of the wind turbine. The state information is sent to the lower level where the controllers must act on the pitch angle of the blades in order to maintain the electric output power around the nominal value, i.e., 4.8 MW.

Simulation studies using Matlab/Simulink language to support comparisons between the two modelled controllers, the fuzzy PI and the FOPI, implemented in the lower level of the proposed architecture, are carried out in order to prove the effectiveness of this architecture. The rest of the paper is organized as follows: Section 2 presents the WECS modelling, taking into consideration the benchmark model notions, the blade and pitch systems, the drive train assuming a two-mass modelling for the rotor of the wind turbine and generator, and the electric dynamics modelling considering a DFIG with a two-level converter configuration. Section 3 presents the supervisory control system implemented at a higher level, as well the control strategy modelling at the lower level based in a fuzzy PI or a FOPI controller. Section 4 presents the case studies. Finally, concluding remarks are provided in Section 5.

2. Modelling

The variable speed WECS considered in this paper is a conventional horizontal axis turbine with a three-bladed rotor design having a rotor positioned upwind of the tower. In order to maintain the output electric power around the rated power of the wind turbine, the controllers must act on the pitch angle of the blades. A more detailed description for the wind turbine benchmark model used in this paper is presented in [27].

2.1. Wind turbine benchmark model

WECS are designed in order to allow for electrical energy to be conveniently attained from the conversion of wind kinetic energy. Wind kinetic energy is captured by the blades receiving a twist action force which causes the blades to rotate and deliver the mechanical energy to turn the speed shafts of an electric generator. The WECS can be analyzed on a benchmark block diagram model with several functional systems namely: the blade and pitch system, the drive train system, the generator and power converter system and the controller. The block diagram of the benchmark model with a supervisor is shown in Fig. 1.

2.1.1. Blade and pitch system model

The blade and pitch system model is a combination of the aerodynamic and pitch system models. The aerodynamics of the wind