Energy Reports 1 (2015) 89–95

Contents lists available at ScienceDirect

Energy Reports

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

Supervisory control of a variable speed wind turbine with doubly fed induction generator

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

[a] IDMEC-LAETA, Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal
[b] Departamento de Física, Escola de Ciências e Tecnologia, Universidade de Évora, Évora, Portugal
[c] Department of Electrical Engineering and Automation, Instituto Superior de Engenharia de Lisboa, Lisbon, Portugal
[d] INESC-ID, Lisbon, Portugal

ARTICLE INFO

Article history:
Received 22 November 2014
Received in revised form
10 March 2015
Accepted 11 March 2015
Available online 5 April 2015

Keywords:
Fuzzy PI
LQ
Wind turbine
Supervisory control

ABSTRACT

This paper is on an onshore variable speed wind turbine with doubly fed induction generator and under supervisory control. The control architecture is equipped with an event-based supervisor for the supervision level and fuzzy proportional integral or discrete adaptive linear quadratic as proposed controllers for the execution level. The supervisory control assesses the operational state of the variable speed wind turbine and sends the state to the execution level. Controllers operation are in the full load region to extract energy at full power from the wind while ensuring safety conditions required to inject the energy into the electric grid. A comparison between the simulations of the proposed controllers with the inclusion of the supervisory control on the variable speed wind turbine benchmark model is presented to assess advantages of these controls.

1. Introduction

Wind energy conversion system (WECS) deployment, whether on onshore or on offshore, has achieved a substantial exploitation contributing to a sustainable energy police of power production (Seixas et al., 2014b). WECS deployment is still seen as a good investment despite a slight decrease (Gsanger, 2014). WECS operating at variable speed due to new requirements (Garcia-Sanz and Houpis, 2012; Burton et al., 2001) and equipped with doubly fed induction generators (DFIGs) is in usage nowadays: a description of this equipment is in Melício and Mendes (2005).

Architecture of control systems are needed to prevent possible degradation on the quality of electrical energy delivered into the electric grid (EG). For instance: a pitch control is needed to ensure the best performance during the capturing of energy under all operational wind scenarios (Zhang et al., 2008; Merabet et al., 2011; Lupu et al., 2006). This control acts by regulating the blade pitch angle of the turbine, thus regulating the energy captured by the blades. The control of power in a variable wind speed turbine is carried out as closed-loop in order to have a correct feasible operation. Otherwise, the conversion of energy is not as efficient or excess of powering is expected and outage is most certain to occur. Control strategies have to deal with the actions over the WECS affecting the performance, such as wind speed variability and intermittence, to achieve the goal of an overall acceptable performance.

This goal has been and is a motivation for researchers to consider the architecture of control strategies using for instances: classical technique (Bianchi et al., 2010), fuzzy proportional integral (Scherillo et al., 2012; Torres-Salomao and Gamez-Cuatzin, 2012; Aissaoui et al., 2013; Bououden et al., 2012) and adaptive linear quadratic control (Mateescu et al., 2012; Nourdine et al., 2010; Boukhezzar et al., 2007; Cutululis et al., 2006). The supervisory control theory (Ramadge and Wonham, 1984) is behind the architecture proposed in this paper and is suitable for control application with event-based operations as can be seen in previous works (Johnson and Fleming, 2011; Qi et al., 2011; Sarrias et al., 2011). An event-based simulation on an onshore variable speed wind turbine (VSWT) benchmark using a model predictive pitch controller is proposed in Viveiros et al. (2015). A comparison between fuzzy proportional integral (PI) and linear quadratic controllers (LQ), but only in what concerns the execution level, is proposed in Viveiros et al. (2013).

* Correspondence to: Departamento de Física, Largo dos Colegiais 2, 7004-516 Évora, Portugal. Tel.: +351 266745372; fax: +351 266745394.
E-mail addresses: ruimelicio@gmail.com (R. Melício), vfmendes@deea.isel.pt (V.M.F. Mendes).

http://dx.doi.org/10.1016/j.egyr.2015.03.001

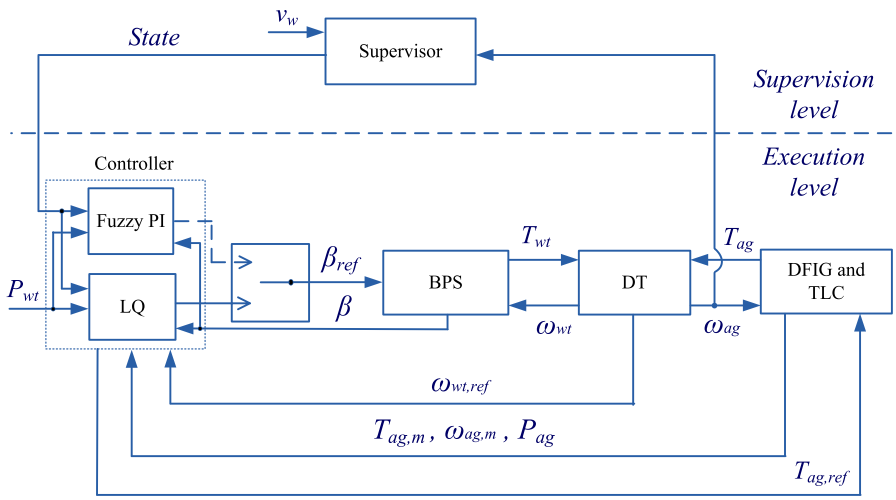

Fig. 1. Supervisory benchmark model block diagram.

This paper is a contribution on the integration of the supervision level with the execution level in what regards the performance of the VSWT system. A hierarchical control architecture is proposed by the inclusion of an event-based supervisor at the supervision level and two distinct controller approaches at the execution level. This hierarchical control architecture is implemented in order to achieve acceptable closed loop system performance while ensuring safety conditions required to inject the energy into the electric grid. The Sateflow chart, a Matlab toolbox, is used in the implementation of the supervision level, collecting the operational state of the onshore VSWT according to the operating conditions and delivering this state to the execution level. In the execution level, the control strategies are addressed as alternative options to be researched in what regards the advantages for the performance of the variable speed wind turbine, implementing by two totally independent alternative strategies Fuzzy PI or by a discrete adaptive LQ. The control simulations are implemented by Matlab/Simulink language and comparisons between the proposed controllers including the supervisor action are reported on what regards the onshore VSWT performance.

The paper is organized as follows: Section 2 presents the WECS mechanical and electrical modelling, including the notions for the benchmark model and the supervisor. Section 3 presents the control strategy modelling using fuzzy PI, discrete adaptive LQ controllers and the supervisory control system. Section 4 presents the case studies with proposed controllers. Finally, conclusions are provided in Section 5.

2. Modelling

The onshore VSWT considered in this paper has a horizontal axis turbine with a three-bladed rotor design. The controllers have to regulate the position of the blades, i.e., the pitch angle value, being possible for the output electric power follow nominal power. For modelling the onshore VSWT benchmark model is considered and details of the description can be found in Odgaard et al. (2013). Onshore VSWT have to be properly designed so that wind energy can be converted into electrical energy. The blades receive a twist action force due to the wind kinetic energy causing the rotation of the blades and deliver the necessary mechanical energy to rotate the speed shafts of the DFIG.

The upgraded benchmark block diagram model of the WECS has the following functional systems: blade and pitch (BPS) system, controller, drive train (DT) system, generator and two-level converter (TLC) system and supervisor. The benchmark block diagram model shown in Fig. 1, is composed by the following variables: v_w is the wind speed in m/s, T_{ag} and T_{wt} are the generator and turbine rotor torques in N m, ω_{ag} and ω_{wt} are the generator and turbine rotor speed in rad/s, β is the pitch angle in degrees and P_{ag} and P_{wt} are the generator and turbine rated power in MW. The *ref* and *m* subscripts designate respectively reference and measurements values.

2.1. Mechanical modelling

This model combines aerodynamic with BPS model.

The torque applied on the onshore VSWT due to aerodynamics (Odgaard et al., 2013) is given by:

$$T_{\omega t}(t) = \frac{\rho \pi R^3 C_p(\lambda(t), \beta(t))\, v_w(t)^2}{2\lambda} \quad (1)$$

where C_p is the power coefficient, depending on the tip speed ratio $\lambda(t)$ and pitch angle $\beta(t)$, ρ is the air density and R is the radius of the blades.

The power coefficient of a wind turbine using pitch control (Melício, 2010) is given by:

$$C_p(\lambda,\ \beta) = 0.73\left(\frac{151}{\lambda_i} - 0.58\,\beta - 0.002\beta^{2.14} - 13.2\right) e^{\frac{-18.4}{\lambda_i}} \quad (2)$$

where $\lambda_i(t)$ is given by:

$$\lambda_i = \frac{1}{\frac{1}{(\lambda - 0.02\,\beta)} - \frac{0.003}{(\beta^3+1)}}. \quad (3)$$

The BPS model has three hydraulic actuators to rotate the blades along the wingspan and can be modelled as a second order system given by:

$$\ddot{\beta}(t) = -2\xi\omega_n(t)\dot{\beta}(t) - \omega_n^2\beta(t) + \omega_n^2\beta_{ref}(t). \quad (4)$$

The DT model configured by a two-mass model (Seixas et al., 2014a) has a first mass J_{wt} to concentrate inertia of the turbine blades, low-speed shaft inertia and hub; B_r is the turbine bearing friction coefficient and a second mass to concentrate the generator inertia and high-speed shaft having inertia J_{ag} and friction coefficient B_g. Between the low-speed shaft (rotor side) and the high-speed shaft (generator side) is a gear box ratio N_g, with torsion shaft stiffness K_{dt}, and torsion shaft damping B_{dt}. This results in the angular deviation θ_Δ due to the damping and stiffness coefficients between turbine and generator; T_{ag} is the electric torque; T_{wt} is the turbine torque and ω_{ag} is the angular DFIG speed.