

Viveiros, C.; Melício, R.; Igreja, J.M.; Mendes, V.M.F.

Article

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Energy Reports

Provided in Cooperation with:

Elsevier

Suggested Citation: Viveiros, C.; Melício, R.; Igreja, J.M.; Mendes, V.M.F. (2015) : Supervisory control of a variable speed wind turbine with doubly fed induction generator, Energy Reports, ISSN 2352-4847, Elsevier, Amsterdam, Vol. 1, pp. 89-95, <https://doi.org/10.1016/j.egyr.2015.03.001>

This Version is available at:

<https://hdl.handle.net/10419/187815>

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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.

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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 (García-Sanz and Houppis, 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; Boukhezzer 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), vmendes@deea.isel.pt (V.M.F. Mendes).

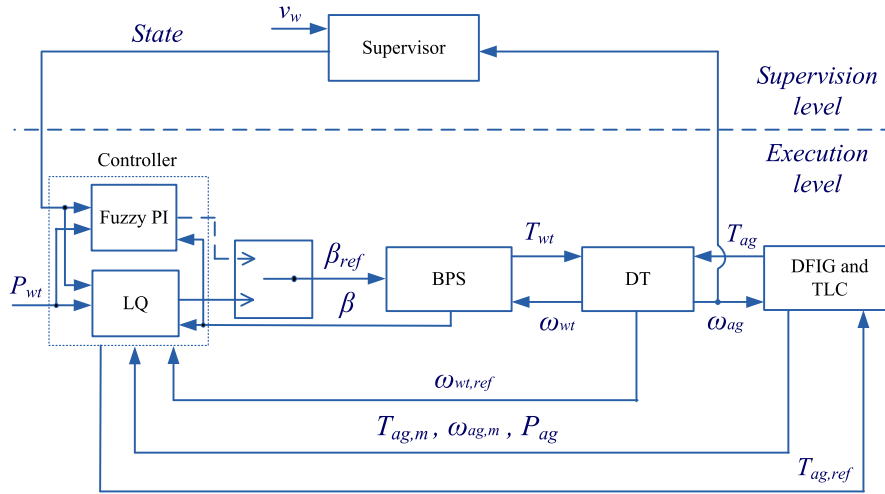


Fig. 1. Supervisory benchmark model block diagram.

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:

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

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.

The shaft damping turbine resistant torque is given by:

$$T_{dr} = B_{dt} \omega_{wt}(t). \quad (5)$$

The resistant torque due to the turbine friction coefficient is given by:

$$T_{tr} = B_r \omega_{wt}(t). \quad (6)$$

The shaft damping generator resistant torque is given by:

$$T_{dg} = B_{dt} \omega_{ag}(t). \quad (7)$$

The shaft stiffness torsional turbine torque is given by:

$$T_{at} = K_{dt} \theta_{\Delta}(t). \quad (8)$$

The resistant torque due to the DFIG friction coefficient is given by:

$$T_{tg} = B_g \omega_{ag}(t). \quad (9)$$

The equations for the two-mass DT model deriving the state equation for the rotor angular speed at the VSWT and for the rotor angular speed at the DFIG are given by:

$$\dot{\omega}_{wt}(t) = \frac{1}{J_{wt}} \left[- (T_{dr} + T_{tr}) + \frac{T_{dg}}{N_g} - T_{at} + T_{wt}(t) \right] \quad (10)$$

$$\dot{\omega}_{ag}(t) = \frac{1}{J_g} \left[\frac{T_{dr}}{N_g} - \left(\frac{T_{dg}}{N_g^2} + T_{tg} \right) + \frac{T_{at}}{N_g} - T_{ag}(t) \right] \quad (11)$$

$$\dot{\theta}_{\Delta}(t) = \omega_{wt}(t) - \frac{1}{N_g} \omega_{ag}(t). \quad (12)$$

2.2. Electric modelling

The configuration of the onshore VSWT have to be properly designed so that wind energy can be converted into electrical energy with DFIG and TLC linked to the EG.

The TLC and EG dynamics are modelled by a first order system given by:

$$\dot{T}_{ag}(t) = -\alpha_{gc} T_{ag}(t) + \alpha_{gc} T_{ag,r}(t) \quad (13)$$

where α_{gc} is the generator and TLC parameter and $T_{ag,r}$ is the reference torque to the DFIG.

The electric output power is given by:

$$P_{ag}(t) = \eta_{ag} \omega_{ag}(t) T_{ag}(t) \quad (14)$$

where the efficiency of the DFIG is represented by variable η_{ag} .

3. Control strategy

The onshore VSWT components, the wind speed and the wind turbulence, the tip speed ratio and the pitch angle are some of the variables considered in the control design to achieve the rated power with an acceptable overall performance.

The tip speed ratio is given by:

$$\lambda(t) = \frac{\omega_{wt}(t)R}{v_w(t)} \quad (15)$$

where ω_{wt} is the angular turbine rotor speed.

With a specific pitch angle, the optimum value of the $\lambda(t)$ is obtained, thus achieving maximum power. A broad review of literature on onshore VSWT gives as a conclusion that the power maximization occurs when the power is within Region II and Region III. Four regions of onshore VSWT power operation are shown in Fig. 2, where v_{min} and v_{max} are respectively the minimum and maximum wind speed.

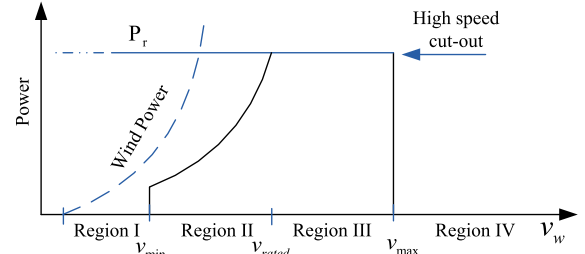


Fig. 2. Power regions of the onshore VSWT (Johnson et al., 2006).

The startup of the turbine occurs in the Region I. The power optimization occurs in Region II and the control objective, regarding pitch angle of the blade, is to maintain its value at zero degrees, capturing all wind power available. Region III can be denoted as power generation and the control objective is to regulate the pitch angle in order to maintain the power produced by the generator at the rated power. Finally, the shutdown of the onshore VSWT in order to prevent eventual damages occurs in Region IV due to high values of wind speed.

In this paper, only Region II and Region III are considered. For both regions, the proposed controllers provide pitch angle reference $\beta_{ref}(k)$ and generator torque reference $T_{ag,ref}(k)$. In Region II, power optimization, the pitch angle reference is zero degrees and the electric torque reference equations are given by:

$$T_{ag,ref}(k) = K_{opt} \left(\frac{\omega_{ag}(k)}{N_g} \right)^2 \quad (16)$$

$$K_{opt} = \frac{1}{2} \rho A R^3 \frac{C_{p,max}}{\lambda_{opt}^3} \quad (17)$$

where λ_{opt} is found as the optimal choice for the tip speed ratio and A is the area swept by the blades. In Region III the pitch angle reference is given by the different control Eqs. (20) and (23) and electric torque reference is given by:

$$T_{ag,ref}(k) = \frac{P_{wt}(k)}{\eta_{ag} \omega_{ag}(k)}. \quad (18)$$

3.1. Fuzzy PI controller

The fuzzy proportional integral inference is based on Mamdani-type inference (Driankov et al., 1996), the controller output, $u(k)$, is based on the centroid defuzzification technique and the input variables are the error between reference and output, $e_{fuzz}(k)$, and the error variation, $\Delta e_{fuzz}(k)$. The inference fuzzy system consists of four steps, fuzzification, knowledge base, inference engine and defuzzification step. In the fuzzification step, the input variables which are crisp numbers are transformed into fuzzy sets according to a membership function. Two types of membership functions are defined, trapezoidal function is defined for the fuzzy sets located at the end of universe of discourse and triangular function is defined for the rest of the fuzzy sets.

The description of input and output variables based on the IF-THEN rules provided by experts is stored in the knowledge base. The rule base format is implemented by seven fuzzy sets defined by the normalized variables, error \tilde{e}_{fuzz} and $\Delta \tilde{e}_{fuzz}$. Negative Big and Positive Big $\{-3, 3\}$; Negative Medium and Positive Medium $\{-2, 2\}$; Negative Small and Positive Small $\{-1, 1\}$ and Zero $\{0\}$ are assigned to those normalized variables given the total of forty-nine rules. The rule base format is presented in Table 1.

The output of the controller is obtained according to the IF-THEN rules stored in knowledge base. Last but not the least, the

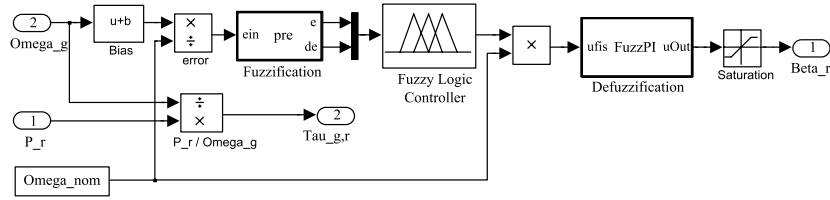


Fig. 3. Simulink implementation of fuzzy PI controller.

Table 1
Rule base format.

$\tilde{e}_{fuzz}, \Delta\tilde{e}_{fuzz}$	3	2	1	0	-1	-2	-3
-3	0	-1	-2	-3	-3	-3	-3
-2	1	0	-1	-2	-3	-3	-3
-1	2	1	0	-1	-2	-3	-3
0	3	2	1	0	-1	-2	-3
1	3	3	2	1	0	-1	-2
2	3	3	3	2	1	0	-1
3	3	3	3	3	2	1	0

defuzzification step transforms the fuzzy set obtained through the inference engine into a crisp value.

Table 1 shows that the output is zero in the diagonal, negative above the diagonal and positive below the diagonal.

The fuzzy PI control error and control action formulas are given by:

$$e_{fuzz}(k) = sp(k) - y(k) \quad (19)$$

$$u(k) = u(k-1) + k_{\Delta u} f_{NL}(e_{fuzz}(k), k_e, \Delta e_{fuzz}(k), k_{\Delta e}) \quad (20)$$

where $sp(k)$ is the set-point, $y(k)$ is the output, f_{NL} is a nonlinear function representing the inference fuzzy system and k_e , $k_{\Delta e}$, $k_{\Delta u}$ are the scaling factors.

The simulink implementation of this controller is shown in Fig. 3.

3.2. Linear quadratic controller

Discrete adaptive linear quadratic control deals with unpredictable variables and the adaptation depends on estimation of parameter $\hat{\theta}(k)$. Using recursive least squares algorithm, polynomials' parameters from $A_1(z^{-1})$ and $B_1(z^{-1})$ can be estimated, obtaining parameters $\hat{\theta}(k) = [\hat{a}_{11} \hat{a}_{12} \hat{b}_{11} \hat{b}_{12}]$. The dynamic development of this controller is presented in William (2010). The dynamical system of the onshore VSWT benchmark around a nominal set-point $r(k)$ is represented by an ARX model, thus the linear quadratic control transfer function is given by:

$$\frac{Y(z)}{U(z)} = \frac{(b_{11}z^{-1} + b_{12}z^{-2})}{(1 + a_{11}z^{-1} + a_{12}z^{-2})} \quad (21)$$

where the Z-transform of the system output and control input are respectively $Y(z)$ and $U(z)$. The performance index H is given by:

$$H(k) = (Py(k+d) - Qr(k))^2 + (\chi u(k))^2 \quad (22)$$

where P and Q assume a unit value, the scalar $\chi = 0.4$ is chosen to achieve an acceptable closed-loop performance and optimal control $u(k)$ minimizes performance index. The polynomials $F(z^{-1})$ and $G(z^{-1})$ can be determined by solving the Diophantine equation.

The optimal control that minimizes the performance index is given by:

$$u(k) = \frac{\hat{b}_{11}}{\hat{b}_{11}^2 + \chi^2} \left[\left(\frac{\rho^2 - \hat{b}_{12}\hat{b}_{11}}{\hat{b}_{11}} \right) u(k-1) + \hat{a}_{11}y(k) + \hat{a}_{12}y(k-1) + r(k) \right] \quad (23)$$

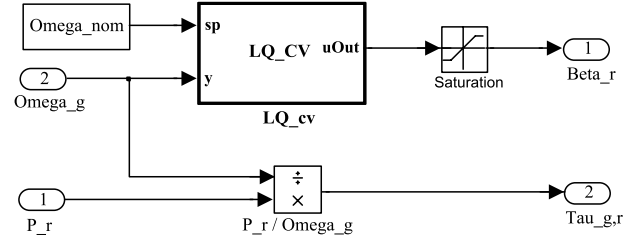


Fig. 4. Simulink implementation of LQ controller.

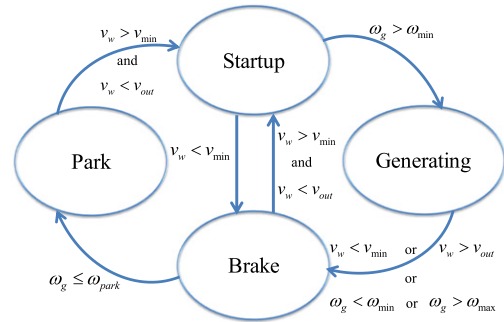


Fig. 5. Representation of the operational states and conditions.

The simulink implementation of this controller is shown in Fig. 4.

3.3. Event-based supervisor

The operational state of the onshore VSWT is determined by the event-based supervisor in the supervision level. Four operational states are considered such as startup, generating, brake and park. The operational states used to model the event-based controller are shown in Fig. 5.

In the startup operational state, Region II, the wind speed must be higher than v_{min} , the VSWT blades should capture all power available and the DFIG is connected to the EG, but not necessarily most of the time at rated power. In the generating operational state, Region III, the wind speed is within v_{rated} and v_{max} and DFIG is connected to the EG at rated power all the time. The brake operational state, or VSWT slow down state, depending on the value of the wind speed and on the operational conditions, can enter into the startup operational state or into the park operational state. In the park state, the blades of onshore VSWT are stopped and the DFIG is disconnected from EG.

4. Case studies

The simulations for the case studies are performed in Matlab/Simulink environment. The time horizon for the simulation is 4500 s, sampling time is $T_s = 0.01$ s and the elapsed times are 139 s for the fuzzy PI controller and 429 s for the LQ controller. The wind speed has a profile in the range of 7.5–22.5 m/s (between Region II and Region III) and white noise is added to the wind speed sequence in order to simulate a wind disturbance. The wind speed with white noise is shown in Fig. 6.

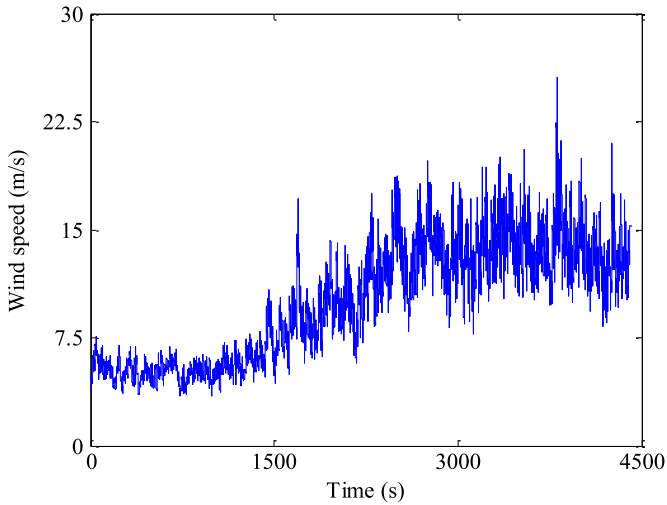


Fig. 6. Wind speed with noise (Odgaard et al., 2013).

The onshore VSWT parameters are the following: $R = 57.5$ m, $\xi = 0.6$, $\omega_n = 11.11$ rad/s, $\alpha_{gc} = 50$, $\eta_{ag} = 0.98$, $\omega_{nom} = 162$ rad/s, $\rho = 1.225$ kg/m³. The nonlinear function f_{NL} is represented by fuzzy logic controller and scaling factors are

obtained through trial. The values assigned are the following: $k_e = 0.4$; $k_{\Delta e} = 0.5$ and $k_{\Delta u} = 1.5$. All control strategies should have the control mode switching from Region II to Region III if $P_{ag}(k) > P_{wt}(k)$ or $\omega_{ag}(k) > \omega_{nom}(k)$ rad/s and switching back from Region III to Region II if $\omega_{ag}(k) < \omega_{nom}(k) - \omega_{\Delta}$, where ω_{Δ} is a small offset used to prevent several switches between control modes.

The electric output and nominal power of the fuzzy PI and the LQ controllers are shown in Fig. 7(a) and (b). Regarding closed loop response, the fuzzy PI controller allows a smoother response around rated power, when compared to the one obtained with the LQ controller, but presents several peaks.

The fuzzy PI controller and the LQ controller pitch angles are shown in Fig. 8(a) and (b). Fuzzy PI controller provides pitch angle variations between 15° and 25° having one peak above 30°. With the LQ controller the pitch angle variation only occurs in a small interval of time reaching the maximum of 40°. LQ controller contributes to less variation on the pitch angle.

The switching between Region II and Region III is shown in Fig. 9(a) and (b), where Region II (0) corresponds to startup operational mode and Region III (1) corresponds to generation operational mode.

The frequent switches between regions, i.e. transition between the two operational states, are due to the need of sustaining the electric output at the rated power. The LQ controller allows a

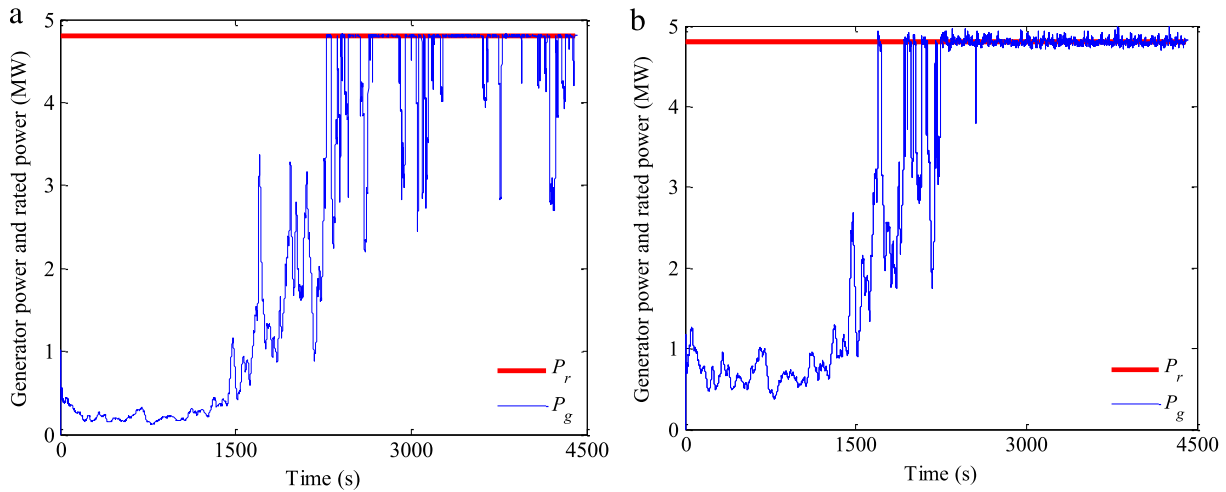


Fig. 7. Electric and rated power (a) Fuzzy PI; (b) LQ.

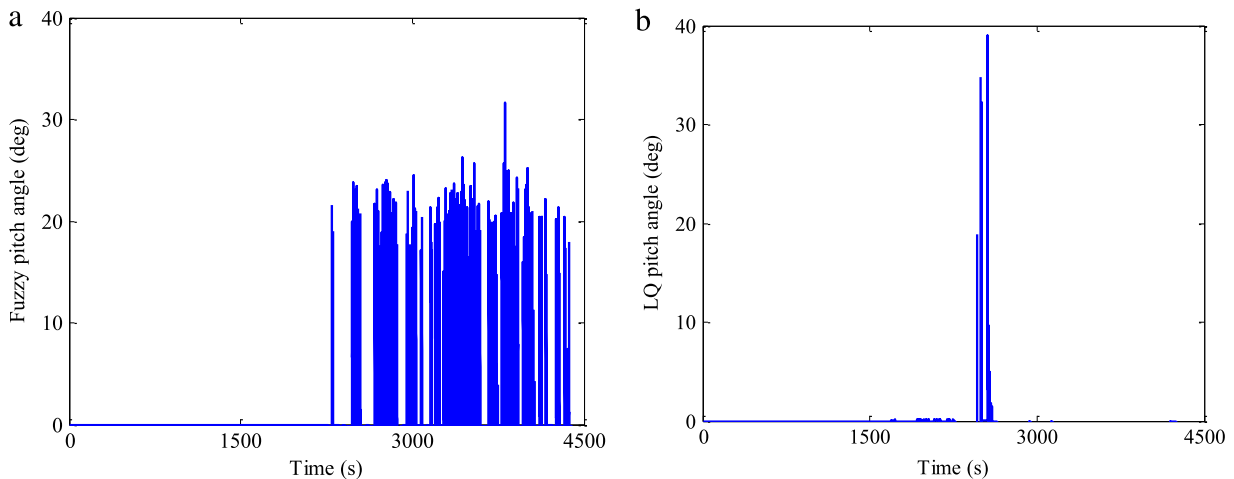


Fig. 8. Pitch angle (a) Fuzzy PI; (b) LQ.

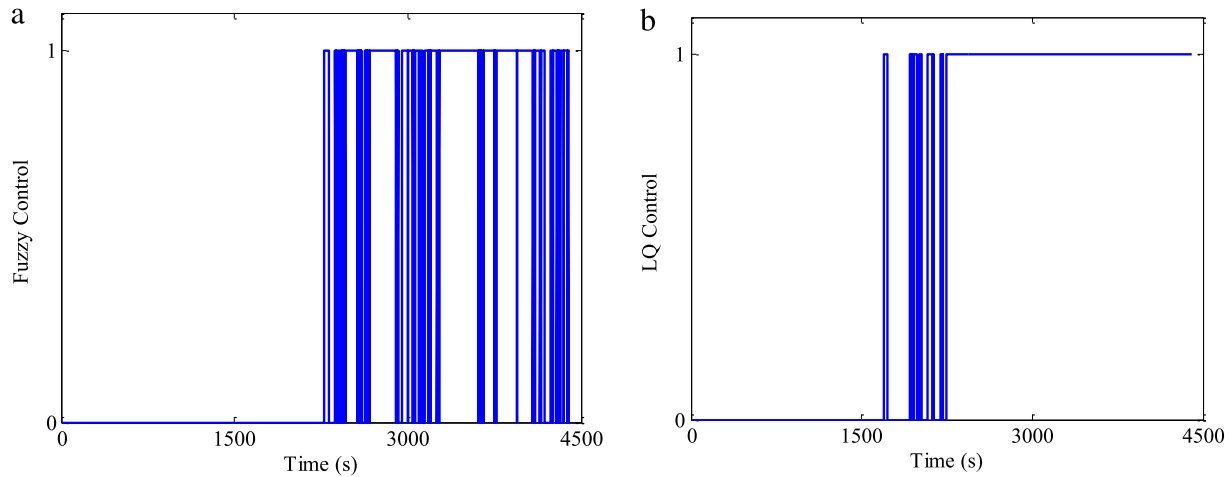


Fig. 9. Switching between regions (a) Fuzzy PI; (b) LQ.

reduction on the switches between regions when compared to fuzzy PI controller, leading to an oscillatory closed loop response.

5. Conclusions

An event-based supervisor deployment for supervision level and two distinct controllers for the execution level are proposed for an onshore WECS with DFIG, using simulations in Matlab/Simulink to determine the performance of the proposed controllers.

The supervisory control determines the operational state according with the data from the wind and generator speed and sends the state to the controllers in the execution level. The fuzzy PI and discrete adaptive LQ controllers regulate the VSWT blades to maintain the generated power around the rated power.

Overall, fuzzy PI controller allows a smoother closed loop response at the expense of large variations of the pitch angle and frequent switches between regions while LQ controller presents larger consumption of control and oscillatory closed loop response.

Acknowledgement

This work is funded by Portuguese Funds through the Foundation for Science and Technology-FCT under the project LAETA 2015–2020, reference UID/EMS/50022/2013.

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