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Abstract. This paper is about a PhD thesis and includes the study and analysis of the performance of an onshore wind energy conversion system. First, mathematical models of a variable speed wind turbine with pitch control are studied, followed by the study of different controller types such as integer-order controllers, fractional-order controllers, fuzzy logic controllers, adaptive controllers and predictive controllers and the study of a supervisor based on finite state machines is also studied. The controllers are included in the lower level of a hierarchical structure composed by two levels whose objective is to control the electric output power around the rated power. The supervisor included at the higher level is based on finite state machines whose objective is to analyze the operational states according to the wind speed. The studied mathematical models are integrated into computer simulations for the wind energy conversion system and the obtained numerical results allow for the performance assessment of the system connected to the electric grid. The wind energy conversion system is composed by a variable speed wind turbine, a mechanical transmission system described by a two mass drive train, a gearbox, a doubly fed induction generator rotor and by a two level converter.

Keywords: Modelling; simulation; wind energy; controllers, supervision; performance assessment.

1 Introduction

The energy crisis of 1973, when it was increased six-fold the price of oil and the blockage of oil-producing countries to Denmark, the Netherlands, Portugal, South Africa and the United States, provided conditions for the resurgence of renewable energies [1]. This crisis has highlighted political consequences that have materialized in actions whose aim is to ensure diversity and security of energy supply. Thus, the motivation and the interest for renewable energies have emerged, and research and development activities in wind energy, as an alternative source of electricity, were stepped up significantly, particularly in Europe and USA.

With the growing need for electricity production from renewable energy sources, wind turbines are an effective response. Wind turbines are the most common form to describe the wind energy conversion systems (WEnCS) in the form of electricity [2]. After the energy crisis of 1973, in the 80s, the first wind turbines had rotor diameters between 10 m to 20 m and output power ranging from 25 kW to 100 kW. Research yielded the technological development which allowed the growth conditions favorable for mass production, making possible the development of construction techniques for more robust wind turbines and allowing the increase of the installed power [3].

In the period 2011-2014, there was an average annual growth in installed wind power worldwide by 13%, reaching a value of approximately 336 GW in mid 2014 [4]. This production technology is considered one of the technologies with the largest and fastest growing worldwide due to the level of penetration and maturity. The wind power installed worldwide in the period 2011-2014 is presented in Fig. 1.

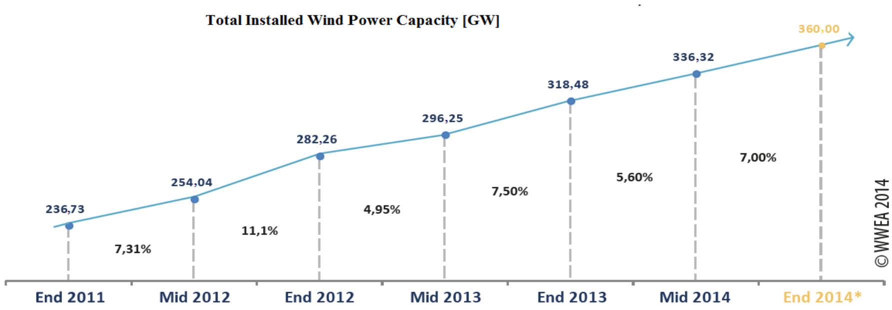


Fig. 1. Installed wind power 2011-2014 [4].

In 2014, India, China, USA, Spain and Germany, are the countries with the largest installed wind power capacity and represent a global market share of 72% of the worldwide installed wind power [4]. Portugal is positioned in 11th place with an installed wind power capacity of 4829 MW, reached in the first half of 2014, and is considered the second largest electricity generation source in Portugal, reaching 11.8 TWh [5].

In the overview of this paper, Section 2 presents the connection of the PhD work to cyber-physical systems. Section 3 presents the modeling and structure of WEnCS connected to the electric grid and the operating regions according to the wind speed are also defined. Control and supervision of WEnCS is presented in Section 4. WEnCS control is achieved using different types of controllers such as integer-order controllers, e.g. classical proportional integral (PI), fractional-order controllers e.g. fractional order proportional integral (FOPI), fuzzy logic controllers (fuzzy PI), adaptive controllers, e.g. linear quadratic Gaussian (LQG) or predictive, e.g. model predictive control (MPC). The supervision system is based on FSM. Section 5 presents the simulation results as well the performance of WEnCS with and without supervisor. Conclusions remarks are given in Section 6.

1.1 Motivation

Since 2000, wind technology has seen a continuous growth in Portugal, motivated by a political strategy, at European and National levels, in endogenous and renewable resources with the objective of diversifying sources, improving the security on supply, decreasing of energetic dependency and reducing the environmental impact of electro production system. The promotion of renewable energies, particularly wind energy, is particularly important in this international and community context taking into account the objectives and goals of which the country is committed to progressively decrease external energy dependence and reduce the carbon intensity of its economy.

With recent technological advances and reduction of electronic converters and position actuators costs, most WEnCS are equipped with electronic power converters and servomechanisms that control the blade pitch angle. The widespread use of electronic converters power and position servo allows flexibility and controllability of WEnCS behavior in terms of energy harvesting but increases the level of complexity of the control loop system. Hence, WEnCS should be carefully designed to meet the international specifications of the power quality injected in the power grid. The WEnCS control involving electrical and mechanical subsystems is considered complex, thus challenging.

The motivation to address the issue of control and supervision of WEnCS results from the need to respond to the challenge related to the control of the various subsystems constituting the WEnCS. This paper deal with an interesting, current and important research topic which includes appropriate mathematical models describing WEnCS dynamics, the study of different types of controllers and the study of a supervisor based on FSM. Considering the mentioned above, this work aims providing solutions to answer the following research question:

Q.1 how can the electric power of a complex system meet the international specifications of its quality injected in the electric grid?

The adopted work hypothesis to address the research questions is defined below:

Using a stratified structure with two distinct levels, a FSM supervisor in the supervision level, and five different control approaches in the execution level, to improve the performance of the WEnCS.

1.2 Original Contributions

This paper presents original contributions to the development of hierarchical structures with supervision and control applied to WEnCS with special emphasis on its performance when using different types of controllers with and without supervisor. In particular: the study on the performance of five different controllers, PI, FOPI, Fuzzy PI, LQG and MPC applied to WEnCS [6], [7]; the development of a hierarchical structure with two operating levels: execution and supervision level. The supervision level, based on FSM's which represent the operating regions, determines the operational states. The execution level receives the information from the operational states and acts accordingly using one of the controllers [8], [9]; the comparative study of the performance assessment of the developed hierarchical structure, for five different types of controllers in the absence and presence of supervisor [9], [10].

2 Relationship to Cyber-Physical Systems

In the past few years, control and computer science researchers have come together in the development of dominant engineering methods and tools, namely in the areas of system identification, robust control, optimization and stochastic control. In the meantime, researchers also made significant breakthroughs in embedded architectures and systems software, on programming languages, real-time techniques, and innovative approaches ensuring computer system reliability, fault tolerance and cyber security.

The significant breakthroughs in science and technology allow the opportunity to link cyber space and physical components. This bridge leads to Cyber-Physical Systems (CyPS) [11]. CyPS researches are constantly developing strategies in order to combine knowledge and engineering principles crosswise the computational and engineering areas such as mechanical, electrical, networking, control, learning theory to overcome the difficulties existing in CyPS supporting technology and science.

The conception of CyPS is to use communication, computing, and control to build autonomous and intelligent systems. Autonomous controls are widely used in industrial process with control loops and the production process is monitored using sensors placed along the production line and acts with the industrial process using actuators. CyPS focuses on bridging control network architectures using sensors and actuators in complex processes [12].

Currently, CyPS is too involved in the area of energy distribution and management. The research developments in cyber-physical energy systems (CyPES) are concentrated on demand side management, consumption and distribution of technologies, such as smart grids and energy managements of buildings and physical structures. For the generation phase, the innovative CyPES should be focused on renewable sources such as solar and wind energy. Regarding wind farms, its construction and planning implicates a problematical decision because it depends on economic, technical, social and environmental aspects. Following a detailed investigation of WEnCS, it is possible to formulate physical and cyber layers with diverse technical and non-technical layers. One can consider collaborative wind farms, wind turbine (WiT) and integration with smart grids.

The interaction with social context and coordination of cyber layers and physical components of WEnCS require handling with complex challenges regarding competiveness and practicability of upcoming WEnCS [13].

The success of the integration of wind power into the electric power grid depends on interconnected, distributed CyPS, which is evolving in the engineering industry. The models of CyPS components are composed by state variables, usually discrete values that are updated at discrete events. FSM's are systems with finite states, inputs and outputs assuming values from discrete sets that are updated at discrete transitions triggered by its inputs. The FSM can be used to describe CyPS.

3 WEnCS Modeling

In this chapter it is developed a mathematical model that represents an appropriate dynamic of a WEnCS. The model should be thorough enough to be used as a simulation model. The development of the mathematical model is based on the standard model developed in [14], whose electric power output is 4.8 MW.

3.1 WEnCS

WEnCS are designed in order to convert wind kinetic energy into electrical energy. The wind kinetic energy is captured by the blades causing the rotation of the blades; this rotation transforms the wind kinetic energy into mechanical energy increasing the speed of an electric generator thus obtaining electrical energy. WEnCS operation can be divided into functional subsystems that describe the WEnCS overall operation. The subsystems of the benchmark structure with a supervisor are shown in Fig. 2.

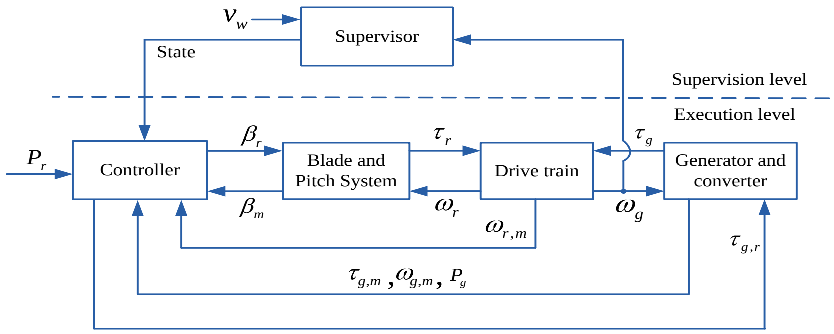


Fig. 2. Benchmark model structure [14].

Figure 2 shows the relationship between the functional subsystems and the variables involved. The variables are: v_w is the wind speed; τ_r is the turbine rotor torque; ω_r is the turbine rotor speed; τ_g is the generator rotor torque; ω_g is the generator rotor speed; β_r is the rated pitch angle; P_r is the turbine rated power and P_g is the generator output power. The *m* subscripts designate measured values.

Blade and Pitch Subsystem: This subsystem combines the aerodynamic with blade and pitch models. The torque acting on the blades can be determined by the aerodynamics of the WiT. The aerodynamic torque is expressed as:

$$\tau_r(t) = \frac{\rho \pi R^3 C_p\left(\lambda(t), \beta(t)\right) {v_w}^2(t)}{2\lambda} \quad . \tag{1}$$

where ρ is the air density, $C_p(\lambda(t), \beta(t))$ is the power coefficient, which is, respectively, a function of the tip speed ratio and the pitch angle and R is the radius of the blades. The tip speed ratio is given by:

$$\lambda(t) = \frac{\omega_r(t)R}{v_w(t)} \ . \tag{2}$$

Observing (2), the variation of the wind speed can lead to two consequences: if the mechanical speed is constant, then $\lambda(t)$ will change, leading to a consequent change in C_p hence in the power capturing; if the mechanical speed is suitably adjusted, then $\lambda(t)$ can be held at a reference point and as a result C_p can be kept at a desired value. The power coefficient of a WiT using pitch control [15] is expressed as:

$$C_p(\lambda, \beta) = 0.73\,(\frac{151}{\lambda_i} - 0.58\beta - 0.002\beta^{2.14} - 13.2\,)\ e^{\frac{-18.4}{\lambda_i}} \ . \tag{3}$$

where λ_i is expressed as:

$$\lambda_i = \frac{1}{\frac{1}{(\lambda - 0.02\beta)} - \frac{0.003}{(\beta^3 + 1)}} \ . \tag{4}$$

The pitch angle is defined by three hydraulic actuators and can be modeled as a second order system [14] expressed as:

$$\ddot{\beta}(t) = -2\xi\omega_n(t)\dot{\beta}(t) - \omega_n^2\beta(t) + \omega_n^2\beta_r(t) \ . \tag{5}$$

The C_p curve is shown in Fig. 3.

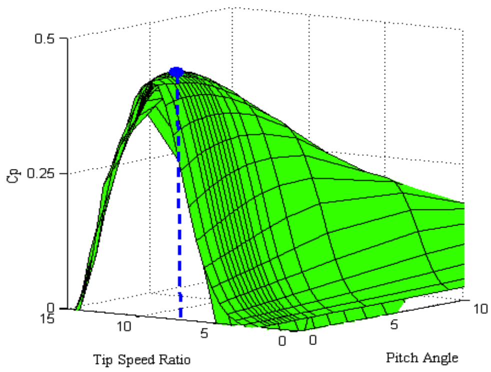


Fig. 3. Power coefficient curve.

Drive Train Subsystem. This subsystem is configured by a two-mass model has a first mass J_r to concentrate the inertia of the turbine blades, hub and low-speed shaft inertia and a second mass J_g to concentrate the generator inertia and high-speed shaft.

The low-speed and high-speed shafts are connected by a gear box ratio N_g, with torsion shaft stiffness K_{dt} and torsion shaft damping B_{dt}. This results in the angular deviation $\theta_\Delta(t)$ due to the damping and stiffness coefficients between turbine and generator. The linearized model for this subsystem is expressed as:

$$J_r\dot{\omega}_r(t) = \tau_r(t) + \frac{B_{dt}}{N_g}\omega_g(t) - K_{dt}\theta_\Delta(t) - \left(B_{dt} + B_r\right)\omega_r(t) \ . \quad \textbf{(6)}$$

$$J_g\dot{\omega}_g(t) = \frac{K_{dt}}{N_g}\theta_\Delta(t) + \frac{B_{dt}}{N_g}\omega_r(t) - (\frac{B_{dt}}{N_g^2} + B_g)\omega_g(t) - \tau_g(t) \ . \quad \textbf{(7)}$$

$$\dot{\theta}_\Delta(t) = \omega_r(t) - \frac{1}{N_g}\omega_g(t) \ . \quad \textbf{(8)}$$

Generator and Converter Subsystem. This subsystem dynamics is described by a first order system. The generator and the power converter model as well as the generator output power are expressed as:

$$\dot{\tau}_g(t) = \alpha_{gc}\left(\tau_{g,r}(t) - \tau_g(t)\right) \ . \quad \textbf{(9)}$$

$$P_g(t) = \eta_g\omega_g(t)\tau_g(t) \ . \quad \textbf{(10)}$$

where α_{gc} is a first order time constant and η_g denotes the generator efficiency.

3.2 Operating Regions

The overall goal of WEnCS control is to optimize the power supplied to the electric grid within a certain range of wind speed, and to minimize energy production and maintenance costs [16]. These costs depend on the conditions in which the WiT is subjected while converting the wind energy captured. Hence, four operating regions are considered, according to the wind variation [17], shown in Fig. 4.

The maximum electrical power associated with energy supplied to the electric grid is also known as rated or nominal power. The rated wind speed, v_{rated}, is the wind speed at which the rated power is reached.

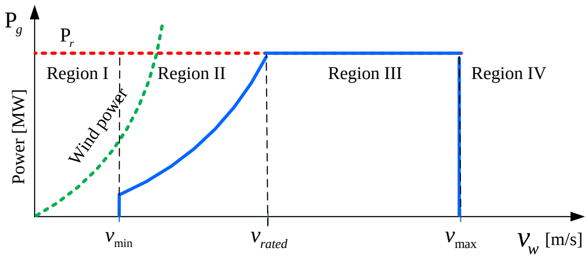


Fig. 4. Operating regions by wind speed.

When the wind speed is too slow, i.e., below 5 m/s [14] the operating region is classified as Region I, and the wind turbine is stopped in this region. When the wind speed is between 5 m/s and 13 m/s the operating region is classified as Region II [14]. The control objective is to capture all available wind power by forcing the pitch angle equal to zero degrees within safety conditions.

Above the nominal wind speed, i.e., 14 m/s the operating region is classified as Region III [14], and the wind turbine operates at the rated power of the generator. The control objective is to operate the WiT at the rated power. When the wind speed is above 25 m/s [14], the operating region is classified as Region IV and the wind turbine is shut down for its own protection.

For control purpose, only Region II and Region III are considered. For those regions, the implemented controllers provide the pitch angle and the generator torque reference.

For power optimization region, the reference for pitch angle is equal to zero degrees and the electric torque reference is given by:

$$\tau_{g,r}(k) = K_{opt}\left(\frac{\omega_g(k)}{N_g}\right)^2 . \quad \textbf{(11)}$$

$$K_{opt} = \frac{1}{2}\rho A R^3 \frac{C_{p\max}}{\lambda_{opt}^3} . \quad \textbf{(12)}$$

where λ_{opt} is the optimal point in C_p and A is the area swept by the blades. The optimal solution can be seen in Fig. 4 and is given by:

$$\begin{cases} C_{p\max}(\lambda_{opt}(0), 0) = 0.4554 \\ \lambda_{opt}(0) = 6.743 \end{cases} . \quad \textbf{(13)}$$

For rated power region, the pitch and generator torque reference should be tuned at the same time and the latter is expressed as:

$$\tau_{g,r}(k) = \frac{P_r(k)}{\eta_g \omega_g(k)} . \quad \textbf{(14)}$$

4 WEnCS Control and Supervision

The control of WEnCS is achieved using different types of controllers such as integer and fractional-order controllers, fuzzy logic controllers, adaptive and predictive controllers. The supervision system is based on FSM.

4.1 Control Strategies

The control strategies used in this paper include the switching of the control mode from Region II to Region III if $P_g(k) > P_r(k)$ or $\omega_g(k) > \omega_{nom}(k)$ and switching back from Region III to Region II if $\omega_g(k) < \omega_{nom}(k) - \omega_\Delta$, where ω_Δ is a small offset used to avoid numerous switches between control modes. The mathematical equations that describe the dynamics of the controllers are described thoroughly in [18], thus, in the current section it will only be presented the final control action equation regarding each controller.

Integer-Order Proportional Integral Controller. The integral proportional integral control action is given by:

$$\begin{cases} u(k) = u(k-1) + K_p e(k) + \left(K_i T_s - k_p\right) e(k-1) \\ e(k) = \omega_g(k) - \omega_{nom}(k) \end{cases} . \quad \textbf{(15)}$$

where ω_{nom} is the nominal WiT speed, K_p is the proportional gain and K_i is the integral gain.

Fractional-Order Proportional Integral Controller. This controller is based on power series expansion of the trapezoidal rule [19], the controller is expressed as:

$$\begin{cases} G(s) = K_p + K_i \, s^{-\mu} \\ s^{\mu} \approx \left[\dfrac{2}{T_s} \dfrac{1 - z^{-1}}{1 + z^{-1}} \right]^{\mu} \end{cases} . \quad \textbf{(16)}$$

where μ is the integral fractional-order satisfying $0 < \mu < 1$ and T_s is sampling time. The discrete PI^{μ} control parameters were obtained using a MATLAB function [20].

Fuzzy Proportional Integral Controller. This controller is expressed as:

$$\begin{cases} u(k) = u(k-1) + k_{\Delta u} f_{NL}(e(k), k_e, \Delta e(k), k_{\Delta e}) \\ e(k) = \omega_g(k) - \omega_{nom}(k) \end{cases} . \quad \textbf{(17)}$$

where *r(k)* is the input, *y(k)* is the output, f_{NL} is a non linear function which represents the inference fuzzy system with scaling factors $k_e, k_{\Delta e}, k_{\Delta u}$.

Linear Quadratic Gaussian Controller. This controller is expressed as:

$$u(k) = \frac{\hat{b}_0}{\hat{b}_0^2 + \rho^2}\left[\left(\frac{\rho^2 - \hat{b}_1 \hat{b}_0}{\hat{b}_0}\right)u(k-1) + \hat{a}_1 y(k) + \hat{a}_2 y(k-1) + \omega_{nom}(k)\right]. \quad (18)$$

where $\hat{\theta}(k) = [\hat{a}_1 \; \hat{a}_2 \; \hat{b}_0 \; \hat{b}_1]$ are estimated using recursive least squares (RLS) algorithm.

Model Predictive Controller. The minimization of cost function in order to determine the optimal control action is given by:

$$u^*(k) = \min_{u(k)\cdots \hat{u}(k+Np-1)} J(k) = \overbrace{\sum_{j=1}^{Np}\left[e(k+j)\middle|k\right]^{\mathrm{T}} Q(j)\left[e(k+j)\middle|k\right]}^{quadratic\ error} + \cdots$$
$$\cdots + \overbrace{\sum_{j=0}^{Np-1}\left[u(k+j\middle|k\right]^{\mathrm{T}} R(j)\left[u(k+j\middle|k\right]}^{control\ effort}. \quad (19)$$

4.2 Supervisor

The WEnCS operational state is determined by the event-based supervisor in the supervision level. To model the event-based controller, the following operational states, shown in Fig. 5, are used. It is considered the following operational states: park, start-up, generating and brake.

In the park state, Region I, the WiT should be stopped and the generator should not be connected to the grid.

In the start-up state, Region II, the wind must be above a minimum speed, hence, the WiT should be rotating in order to capture all available power. The generator is connected to the electric grid, but not necessarily at rated power the majority of the time.

The power production state or generating state, Region III, is the region where the turbine speed is in the rated wind range, hence, the generator is connected to the electric grid at rated power all the time.

The brake state is based on a number of conditions which will allow the supervisor to exit the generating state, enter into the start-up state or enter into the park state.

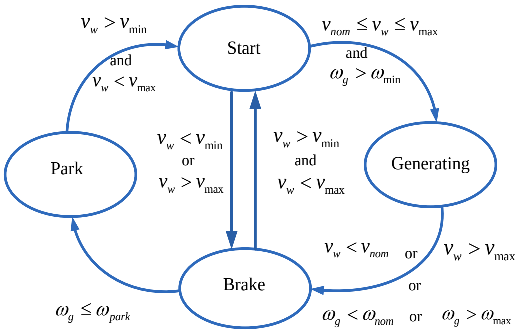


Fig. 5. Representation of the operational states and conditions.

4.3 Performance Assessment of the Controllers

The metrics used in the evaluation of the performance of the controllers are the integral of time multiplied by the absolute value of the error (ITAE) given by:

$$ITAE = \int_0^{t_f} t.|e(t)|dt \ . \tag{20}$$

and the integral of the square value (ISV) of the control input given by:

$$ISV = \int_0^{t_f} u^2(t)dt \ . \tag{21}$$

where ITAE is used as numerical measure of tracking performance for the entire error curve and ISV is used as numerical measure of the control effort.

5 Results

The numerical results and the conclusions about the performance of the WEnCS, using computer simulations are presented. The performance of WEnCS is studied using the PI controllers, FOPI, Fuzzy PI, LQG or MPC with or without the inclusion of the supervisor. The mathematical model for the WEnCS and the simulations with the two-level power converter topology are implemented in Matlab/Simulink. The time horizon considered in the simulations is of 4500 s, and the sampling time T_s = 0.01 s.

The wind speed considered in the simulations has a profile in the range of 7.5 m/s to 22.5 m/s (between Region II and Region III) and white noise is added to the wind speed to make it more realistic. The wind speed with white noise is shown in Fig. 6.

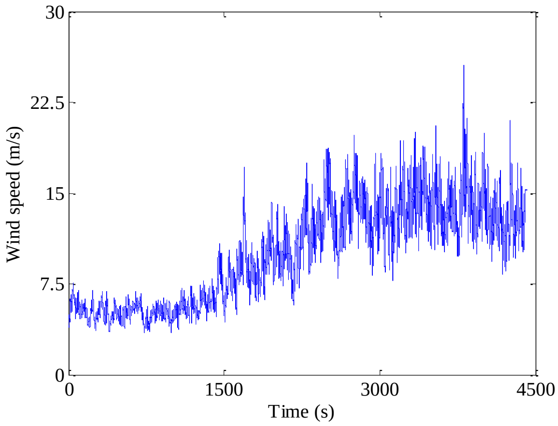
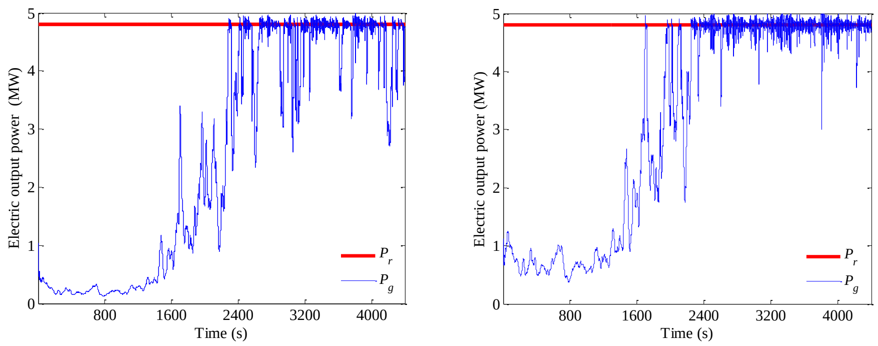


Fig. 6. Wind speed sequence with white noise.

5.1 Generated and Reference Power Simulation

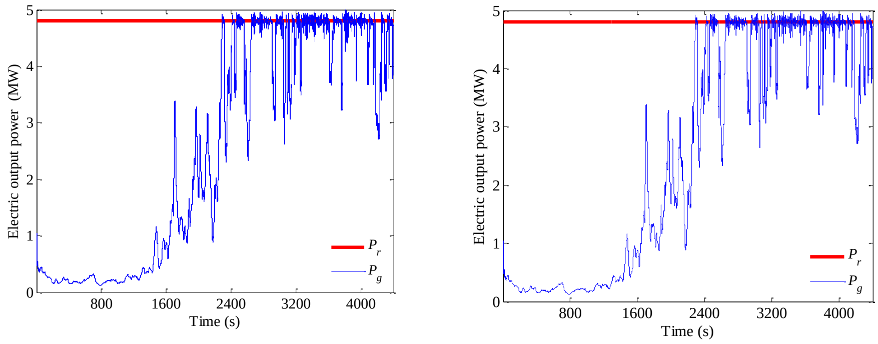
All the generated and reference power without the supervisor are shown in Fig. 7a) and with the supervisor are shown in Fig. 7b).

PI controller. With the PI controller, one can see that the electric output power, with or without the supervisor, follows the reference power presenting higher levels of oscillation.



(a) (b)

Fig. 7. Generated and reference power (PI): a) without supervisor, b) with supervisor.



(a) (b)

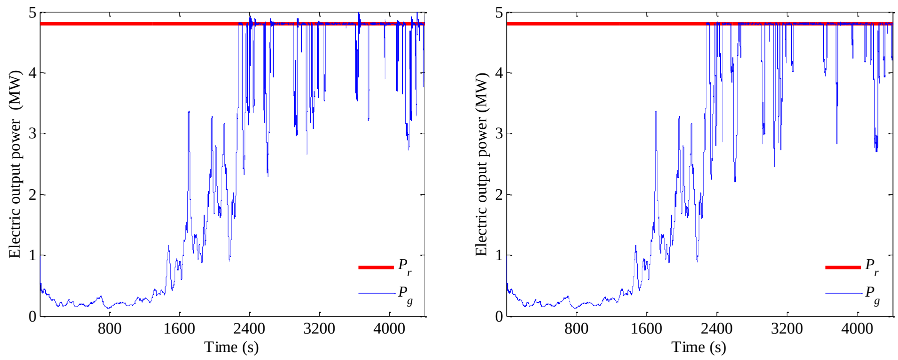
Fig. 8. Generated and reference power (FOPI): a) without supervisor, b) with supervisor.

FOPI controller. The generated and rated power without the supervisor is shown in Fig. 8a) and with the supervisor is shown in Fig. 8b).

With the FOPI controller, it can be seen that the electric output power still presents higher level of oscillation around the reference power, with or without the presence of the supervisor and also presents frequent decreases in electric output power due to wind variations.

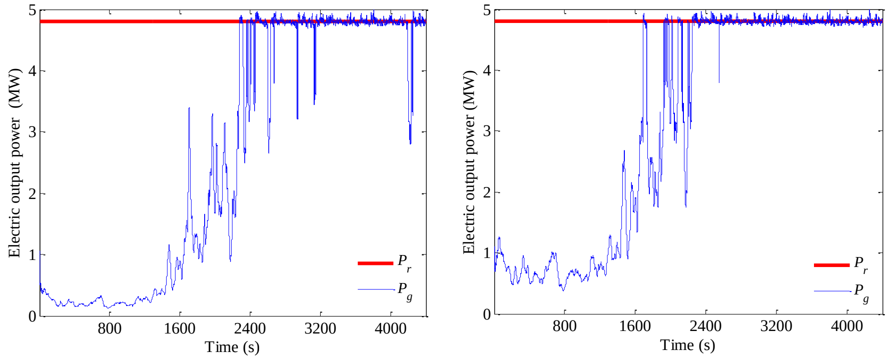
Fuzzy PI controller. The generated and rated power without the supervisor is shown in Fig. 9a) and with the supervisor is shown in Fig. 9b).

With the Fuzzy PI controller, in both situations, the electric output power follows the reference power with a smoother response around the reference power having some decreases in the electric output power due to sudden wind variations.



(a) (b)

Fig. 9. Generated and reference power (Fuzzy PI): a) without supervisor, b) with supervisor.



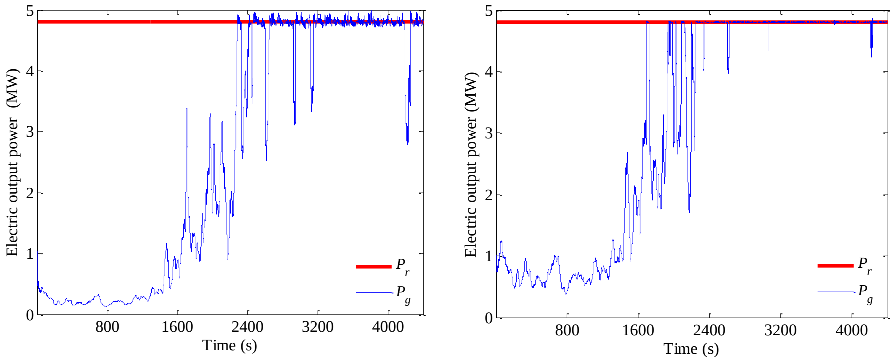
(a) (b)

Fig. 10. Generated and reference power (LQG): a) without supervisor, b) with supervisor.

LQG controller. The generated and rated power without the supervisor is shown in Fig. 10a) and with the supervisor is shown in Fig. 10b).

With the LQG controller, in both situations, the electric output power follows the rated power with few oscillations around the reference power having some decreases in the output power without the supervisor.

MPC controller. The generated and rated power without the supervisor is shown in Fig. 11a) and with the supervisor is shown in Fig. 11b).



(a) (b)

Fig. 11. Generated and reference power (MPC): a) without supervisor, b) with supervisor.

With the MPC controller, without the supervisor, the electric output power follows the rated power with few oscillations around the reference power having some decreases in the output power. With the supervisor, the electric output power follows the rated power with a smoother response around the reference power.

5.2 Performance Assessment

Table 1 summarizes the controller performance results.

Table 1. Controller performance results.

Controller	PI	FOPI	Fuzzy PI	LQG	MPC
without Supervisor					
ITAE	1.2103×10^{15}	1.2073×10^{15}	1.1752×10^{15}	1.0792×10^{15}	1.0886×10^{15}
ISV	6.054×10^{6}	5.7895×10^{6}	6.4604×10^{6}	1.0770×10^{7}	1.4791×10^{7}
with Supervisor					
ITAE	1.2048×10^{15}	1.2087×10^{15}	1.1643×10^{15}	7.0328×10^{14}	7.0250×10^{14}
ISV	5.7652×10^{6}	5.8518×10^{6}	6.1677×10^{6}	2.7171×10^{5}	1.7276×10^{7}

Considering the values obtained without the action of the supervisor, the error between electric output and reference power is smaller with LQG controller, meaning that the electric output power follows the rated power more accurately. From a control effort point of view, FOPI consumes less energy given the narrower variation of the pitch angle. Considering the values obtained under the action of the supervisor, the error between electric output and reference power is smaller with LQG and MPC controllers. Regarding energy consumption, LQG presents a superior performance.

6 Conclusions

A hierarchical structured is presented composed by a FSM supervisor in the top level and five distinct controllers: PI, FOPI, Fuzzy PI, LQG and MPC in the lower level. The WEnCS operational state is determined by the operating conditions, which are analyzed by the event-based supervisor. The implemented controllers in the lower level are intended to process the operational state information provided by the supervisor. The controllers in the lower level act in order to sustain the output power near the region of the nominal value by acting on the pitch angle of the blades.

Comparisons between the implemented controllers regarding closed loop response, without supervisor, unveil the fact that the LQG controller outperforms the remaining controllers at expense of higher control effort. Regarding control effort, FOPI controller presents better performance in what regards the expenditure effort, i.e., the controller presents lower control effort but at expense of an oscillatory closed loop response.

Comparisons between the implemented controllers regarding closed loop response, with supervisor, show that LQG and MPC controllers follow the reference power with a smoother response outperforming the remaining controllers. Regarding control effort, LQG controller presents better performance while MPC continues to have high values of control effort.

Overall, the simulation results with supervisor presented better performance, where LQG controller stood out among the other controllers.

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