Fractional order control of Wind Energy Conversion System based on DFIG

Samir Metatla, Ali Nesba, and Youcef Soufi

Abstract -- The paper deals with the elaboration of a robust and efficient decoupled active and reactive powers control algorithm of double-fed induction generator (DFIG) using fractional order control based on proportional and integral controllers. First, the models of wind turbine and electrical generator are established as well as a decoupled active and reactive powers control of DFIG. Second, the used fractional order controllers are designed using an analytical design method based on frequency domain specifications, namely phase margin, robustness to gain variations and gain limitation at the crossover frequency. Third, to evaluate the fractional order controller control performances, simulation results are presented and discussed for all the operating region of the WECS. Then, simulation results are presented and interpreted considering a variable wind speed in order to reach all the operating regions of the WECS. Finally, a conclusion is given in the light of the obtained results.

Key words: Fractional order control– WECS–DFIG– analytic design method.

Nomenclature

CRONE	Commande Robuste d'Ordre Non Entier.
DFIG	Doubly Fed Induction Generator.
FOC	Field Oriented Cotrol
FOPI	Fractional Order Proportional and Integral controller
PID	Proportional, Integral and Derivative controller
TID	Tilt Integral and Derivative controller
WECS	Wind Eergy Conversion System.

I. Introduction

Non-integer order or fractional order control is a generalizedform of classical integer order control theory. Although the notion of non-integer differentiation is not new, its origins go back 300 years, its interest was only recognized at the end of the 20th century when many applications were developed using this concept [1]. Indeed, Bode [2] was the first to propose an ideal transfer function whose phase is flat and independent of the gain and the cutoff frequency. This function was then a reference for the most well-known fractional order control techniques.

In the field of process control, the notion of fractional control was given by the publication of the first works on fractional order control by S. Manabe in 1961 [3] then M. Ichise, et al in 1971 [4] . In 1991, Alain Oustaloup proposed the robust control of non-integer order "CRONE" [5] involving a regulator whose transfer function is of non-integer order to take advantage of the advantageous properties of fractional order systems, and ensure the control robustness in a given frequency range. Since this initiative, several fractional order controls have emerged such as controls based on non-integer observers [6], control by sliding mode of fractional order [7] control by PID controller of fractional order [8] and control by TID regulator. The first objective targeted by the use of fractional order controllers in process control is the introduction of additional degrees of freedom, namely the differentiation order of the transfer functions, which gives more adjustment flexibility. The second objective is the robustness of the command vis-à-vis the uncertainty of the process parameters thanks to the constancy of the phase around the resonance frequency of the process that can be satisfied by a good parameterization of the order controllers fractional [5,9,10].

The work that is the subject of this paper focuses on the establishment of a robust and efficient fractional order control by involving proportional and integral type regulators of non-integer order (FOPI) of the form $(PI)^{\alpha}$ in order to ensure the control of a variable speed wind turbine based on double-fed induction generator (DFIG). The sizing of the fractional regulators used is ensured by an analytical method calling on a mathematical development based on the performance and robustness criteria in the frequency domain, namely the phase margin, the robustness to gain variations and the limitation of the gain to the frequency of the cutoff [9]. Simulation results will be presented and discussed in order to evaluate the performance of the proposed fractional control.

II. FRACTIONAL ORDER CONTROL

The main interest of fractional order control is to improve the performance of control systems and to give more tuning flexibility by using the concepts of non-integer differentiation. Indeed, fractional order regulators offer more tuning flexibility thanks to the additional degree of freedom, namely the order of the differentiation.

$$C(s) = (PI)^{\alpha} = \left(k_p + \frac{k_i}{s}\right)^{\alpha} \tag{1}$$

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Such ask_p: Is the proportional gain, k_i: The integral gain and α the integration order.

The ideal power curve ofa variable speed WECS can be described by Fig. 1. As we can see, it ischaracterized by fourdifferentoperating regions with distinct generation objectives. In the first region wind speed is not sufficient to drive the WECS,so the wind turbine remains out of operation. For winds with moderate speed that exceed the cut in wind speed $v_{cut\ in}$, the aerodynamic power is then sufficient to start the aerodynamic conversion process which characterize the second operating region of the WECS. In the second operating region, the main objective is the extraction of maximum power from the wind. However, for wind speed that exceeds the rated value (region III),theconvertedaerodynamic power reachesthe WECS rated power. The pitch control system should act on blade pitch angle so that the generated power remains equal to its rated value in order to avoid mechanical and electrical overloads. In the last region (region IV), wind speedexceeds itslimit value$v_{cut\ off}$, wind turbine should be stopped to avoid WECS destruction.

In order to protect the WECS from excessive rotational speeds, the second operating region is often subdivided into two different subregions with distinctcontrol objectives. In fact, forrotational speed lower than the rotorrated speed value, the control objective is the maximum power point tracking. In this case the optimal aerodynamic conversion efficiency is achieved which characterize the first subregion. However, in the second subregion, the control system should limit the wind turbine speed to its rated valuedue to mechanical and acoustic constraints [11].

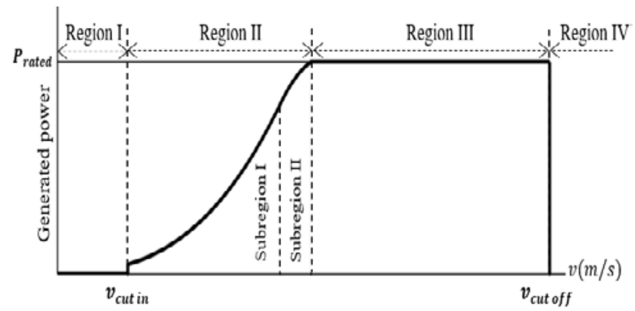

Fig. 1: Wind turbine ideal power curve

III. WIND ENERGY CONVERSION SYSTEM MODELING AND CONTROL

A wind energy conversion system (WECS) is often composed of three essential parts. A wind turbine, an electrical generator and a control and management. in fact, WECS modeling consists of modeling each of its components.

A. Wind turbine modeling

The main interest of the wind turbines is theconversion of aerodynamicpower into mechanical power. The aerodynamic conversion theory is widely developed and discussed in the literature [12,13]. The aerodynamic conversion process of a variable speed wind turbine can be described by the following bloc diagram [11].

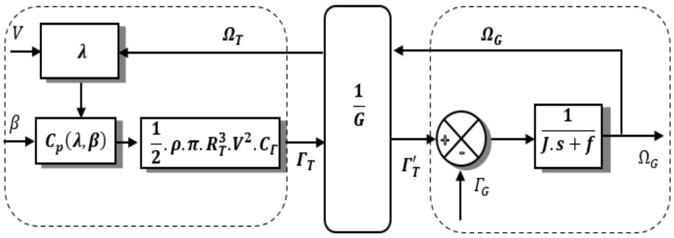

Fig. 2: Wind turbine model block diagram

Where:

$\boldsymbol{\lambda} = \frac{\boldsymbol{R_T}.\boldsymbol{\Omega_T}}{\boldsymbol{V}}$ is the tip speed ratio, $\boldsymbol{R_T}$ and $\boldsymbol{\Omega_T}$ are turbine radius and speed respectively.

The power coefficient of the wind turbine is given by:

$$C_p(\lambda,\beta) = C_1.\left(C_2.\frac{1}{\Lambda} - C_3.\beta - C_4\right)e^{\frac{-C_5}{\Lambda}} + C_6.\lambda \qquad (2)$$

Whereβ is the blade pitch angle and $C_1, \ldots, C_6$ are parameters which dependon the aerodynamic of the wind turbine.

The wind turbine aerodynamic torque is given by:

$$\Gamma_T = \frac{1}{2}.\rho.\pi.R_T^3.V^2.\frac{C_p(\lambda,\beta)}{\lambda} \qquad (3)$$

Where ρ is the air density and V is the wind speed.

Γ_G is the generator torque,G is the gearbox ratio, f, J and$\Gamma'_T = \frac{\Gamma_T}{G}$are the friction coefficient, inertia and theaerodynamic torque,of the wind turbine referred to high speed shaft respectively.

B. DFIG modeling and control

DFIG modeling and control is widely discussed in the literature [11,14-16]. The mathematical model ofDFIGreferred to an arbitrary rotating reference frame can be expressed by the following equations:

$$\begin{cases} V_{ds} = R_s I_{ds} + \dfrac{d}{dt}\varphi_{ds} - \omega_s.\varphi_{qs} \\ V_{qs} = R_s I_{qs} + \dfrac{d}{dt}\varphi_{qs} + \omega_s.\varphi_{ds} \\ V_{dr} = R_r I_{dr} + \dfrac{d}{dt}\varphi_{dr} - (\omega_s - \omega).\varphi_{qr} \\ V_{qr} = R_r I_{qr} + \dfrac{d}{dt}\varphi_{qr} + (\omega_s - \omega).\varphi_{dr} \end{cases} \qquad (4)$$

Where$I_{ds}, I_{qs}, V_{ds}, V_{qs}, \varphi_{ds}, \varphi_{qs}$ are the stator current, voltage and flux along the d and q axis, $I_{dr}, I_{qr}, V_{dr}, V_{qr}, \varphi_{dr}, \varphi_{qr}$ are the rotor current, voltage and flux along the d and q axisrespectively andR_s, R_r are the stator and rotor winding resistances; ω_s and ω are the synchronous and rotor speeds.

The stator and rotor flux equations are given by:

$$\begin{cases} \varphi_{ds} = L_s I_{ds} + M.I_{dr} \\ \varphi_{qs} = L_s I_{qs} + M.I_{qr} \\ \varphi_{dr} = L_r I_{dr} + M.I_{ds} \\ \varphi_{qr} = L_r I_{qr} + M.I_{qs} \end{cases} \qquad (5)$$

With L_s, L_r and M are the stator inductance, the stator inductance and the mutual inductance respectively.

The objective of DFIG control is to achieve decoupled power control. By applying a field-oriented control strategy (FOC) to the DFIG model described by equations (4) and (5), we can derive the DFIG model depicted in the block diagram in Fig.3 below [17, 18].

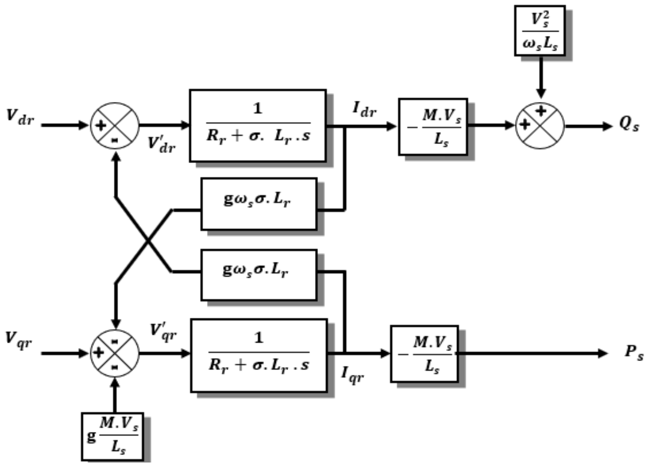

Fig. 3: DFIG model block diagram

Taking into account the DFIG block diagram shown in Fig. 3, decoupled equations for active and reactive powers can be derived to establish separate control of active and reactive powers for the DFIG. Assuming that cross-coupling terms between the d and q axes are fully compensated, active and reactive powers can be expressed as functions of the direct and quadrature rotor voltages, respectively.

$$\begin{cases} P_s = \left(-\dfrac{M.V_s}{R_r L_s}\right)\dfrac{1}{\left(1+\sigma.\frac{L_r}{R_r}.s\right)}.V'_{qr} \\ Q_s - \dfrac{V_s^2}{\omega_s.L_s} = \left(-\dfrac{M.V_s}{R_r L_s}\right)\dfrac{1}{\left(1+\sigma.\frac{L_r}{R_r}.s\right)}.V'_{dr} \end{cases} \quad (6)$$

By setting: $T=\frac{L_r}{R_r}$and $k=-\frac{M.V_s}{R_r L_s}$, we can write:

$$\begin{cases} P_s = \dfrac{k}{1+\sigma.T.s}.V'_{qr} \\ Q_s - \dfrac{V_s^2}{\omega_s.L_s} = \dfrac{k}{1+\sigma.T.s}.V'_{dr} \end{cases} \quad (7)$$

Then we can deduce the DFIG model for decoupled active and reactive powers control as presented below.

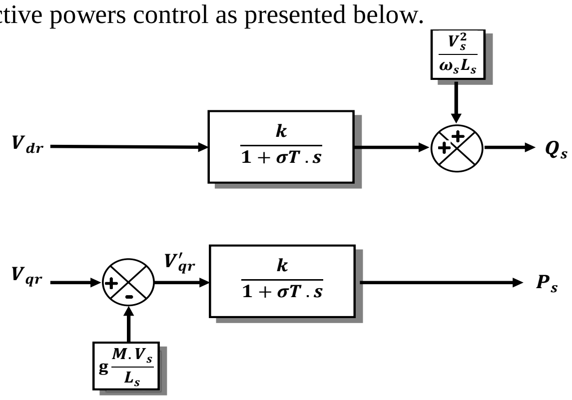

Fig. 4: DFIG model block diagram for decoupled powers control

With: $\sigma=\left(1-\frac{M^2}{L_s.L_r}\right)$the dispersion coefficient, $T=\frac{L_r}{R_r}$ the rotor time constant and $k=-\frac{MV_s}{R_r.L_s}$ a constant depends on DFIG parameters.

The decoupled control loop of active and reactive powers can be presented by the block diagram presented in Fig. 5.

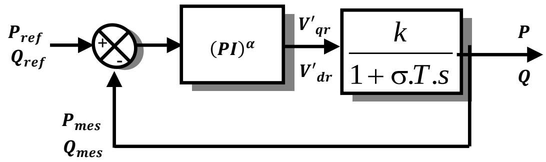

Fig. 5: Control loop of active and reactive powers decoupledcontrol

IV. FRACTIONAL ORDER CONTROLLER DESIGN

In industrial process control systems, controller design is a crucial step. Tuning the parameters of these controllers is critical for ensuring robustness, stability, and performance of the entire process. The non-integer controllers used in this study are designed based on frequency domain specifications using an analytic design method. The design specifications include phase margin, robustness to gain variation, and gain margin [11].

A. Phase margin ϕ_m

Phase margin is an importantperformance and robustness criteria and can affects thesystem damping [14, 19, 20]. The phase margin is given by:

$$arg[plant + controller]_{\omega_c} = \phi_m - \pi \quad (8)$$

Where ω_c is the crossover frequency.

By applying the phase margin specification on the decoupled active and reactive powers control loop in Fig. 5 we find:

$$arg[C(s).P(s)]_{\omega_c} = \phi_m - \pi$$

Introducing transfer fuctions expressions we can write.

$$arg\left[\left(k_p+\frac{k_i}{s}\right)^{\alpha}.\left(\frac{k}{1+\sigma T.s}\right)\right] = \phi_m - \pi$$

Replacing Laplace operator s by $j\omega_c$ at crossover frequency we can write.

$$-\alpha\, arctan\left(\frac{k_i}{k_p.\omega_c}\right) - arctan(\sigma T.\omega_c) = \phi_m - \pi \quad (9)$$

Equation (9) can be simplified by setting $A=(\pi-\phi_m-arctan\sigma T.\omega c$ as:

$$k_i = k_p.\omega_c\, tan\left(\frac{A}{\alpha}\right) \quad (10)$$

B. Robustness to gain variation

The use ofrobustness to gain variation specification can ensures a flat phase around ω_c which gives more statbility and mor robustness against internal perturbations like parameters variation [11,14,19,20,21]. Robustness to gain variation cretaria is defined by:

$$\left.\frac{d(arg[C(s).P(s)])}{d\omega}\right|_{\omega_c} = 0 \quad (11)$$

By applying on decoupled powers control loop we can find.

$$\alpha.\frac{k_i/(k_p.\omega_c^2)}{1+\left(k_i/k_p.\omega_c\right)^2} - \frac{\sigma.T}{1+(\sigma T.\omega_c)^2} = 0 \quad (12)$$

In order to simplify (10) we set $B = \frac{\sigma.T}{1+(\sigma T.\omega_c)^2}$, so (12) can takes the forme:

$$\alpha.\frac{k_i/(k_p.\omega_c^2)}{1+(k_i/k_p.\omega_c)^2} = B \quad (13)$$

C. Gain limitation at crossover frequency

This specification reflects the stability margin of the controled system. It is an important creteria for non-integerorder controllers design [11, 19,20,22].

$$|C(j\omega).P(j\omega)|_{\omega_c} = 1 \quad (14)$$

Which gives.

$$(k_p)^2 + \left(\frac{k_i}{\omega_c}\right)^2 = \left[\frac{\sigma.T}{k.B}\right]^{\frac{1}{\alpha}} \quad (15)$$

The substitution of (10) in (15) and (10) in (13) leads to the following equations.

$$k_p = \left[\frac{\left[\frac{\sigma.T}{k.B}\right]^{\frac{1}{\alpha}}}{1+tan^2\left(\frac{A}{\alpha}\right)}\right]^{\frac{1}{2}} \quad (16)$$

$$\frac{\alpha}{\omega_c}.\frac{tan\left(\frac{A}{\alpha}\right)}{1+tan^2\left(\frac{A}{\alpha}\right)} = B \quad (17)$$

Using trigonometric relations, (17) can takes the following form:

$$\frac{\alpha}{\omega_c}.\frac{1}{2}sin\left(2.\frac{A}{\alpha}\right) = B \quad (18)$$

Therefore, (18) may be written as:

$$\frac{sin\left(2.\frac{A}{\alpha}\right)}{2.\frac{A}{\alpha}} = \frac{B.\omega_c}{A} \quad (19)$$

Then we can express (19) as:

$$\text{sinc}\left(2.\frac{A}{\alpha}\right) = \frac{B.\omega_c}{A} \quad (20)$$

Where sinc is cardinal sine function.

Indeed, the used FOPI controller design strategy can be resumed by (10), (16) and (20) equations. In fact, fractional order integration α can be fined from (20), then we can deduceproportional gaink_p from (16) and integration gaink_i from (10).

Taking into account the mathematical study detailed in the above sections, the control system block diagram of the considered WECS can be presented by Fig. 6. In the considred WECS we use speed limitation and pitch control systems as we can see in Figure bellow.

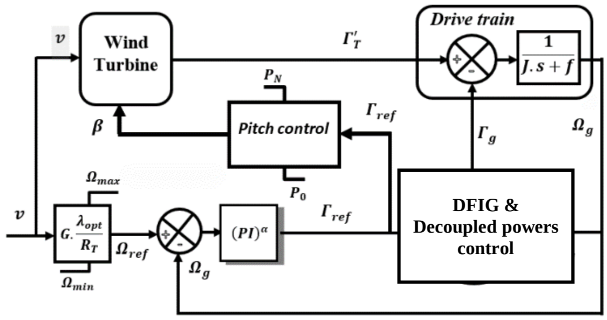

Fig. 6: Proposed fractional order control block diagram

V. SIMULATION AND DISCUSSION

Simulation results presented in this section are obtained by applying the proposed fractional order control presented in Fig. 6 on a WECS with parameters given in the table below.

TABLE I. WECSPARAMETERS

Parameter	*symbol*	*Value*
Rated power	P_n	**300 kW**
Rated stator voltage	V_n	**690 V**
Stator resistance	R_s	**54 mΩ**
Rotor resistance	R_r	**46 mΩ**
Stator inductance	L_s	**12.9 mH**
Rotor inductance	L_r	**12.7 mH**
Magnetizing inductance	M	**12.5 mH**
Nominal stator frequency	f	**50 Hz**
Number of pole pairs	P	**2**
Blade radius	R_T	**28 m**
Number of turbine blades	///	**3**
Total inertia	J	**42.9 kg.m^2**
Gearbox ratio	G	**1 : 30**

Fractional order controllers used are tuned using the proposed analytical design method.

TABLE II. FRACTIONAL ORDER CONTROLLER PARAMETERS

Parameter	*symbol*	*Powers controllers*	*Speed controller*
Proportional gain	K_p	**786.3**	**73**
Integration gain	K_i	**1844**	**144**
Integration order	α	**0.588**	**0.88**

All the operating regions are covered considering a wind profile with a variable wind speed between 6 m/s and 17 m/s.

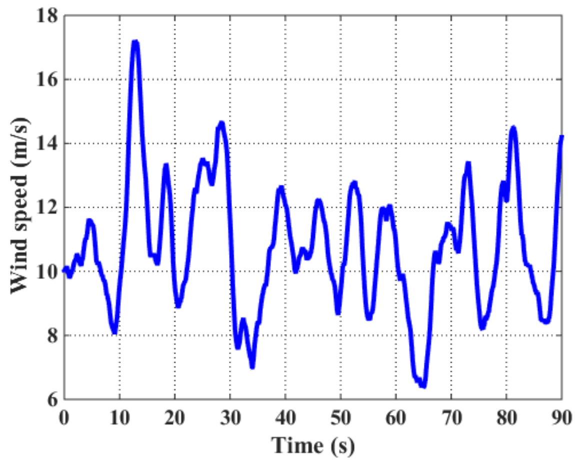

Fig. 7: Wind speed profile

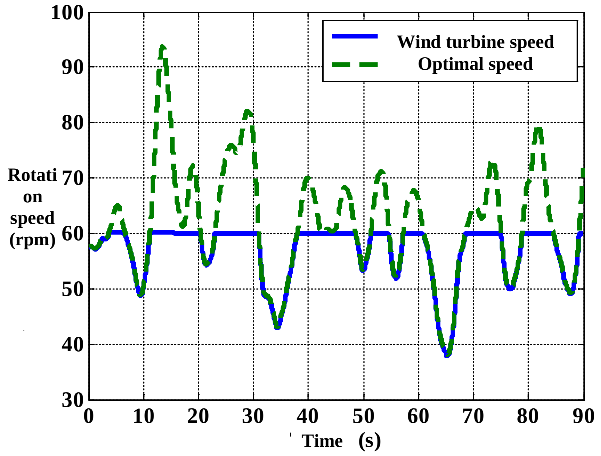

Fig. 8: Wind turbine speed

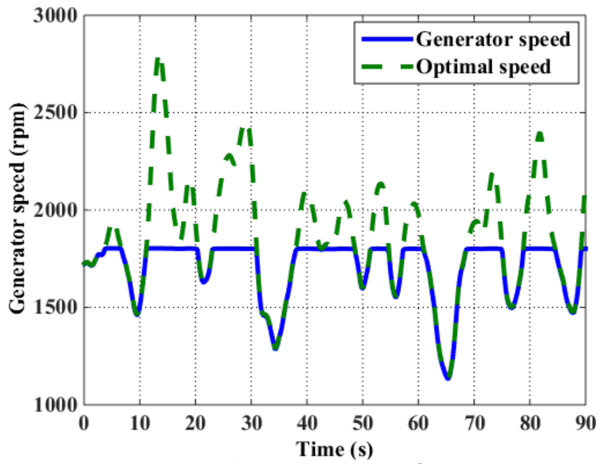

Fig. 9: Generator speed

Figures 8 and 9 show that for wind speeds below 11m/s, the rotational speed of the wind turbine and generator speed follow the reference speed very well. We therefore note that control objectives in subregion I of the second operating region is the maximum power point tracking which is confirmed by the result presented on Fig. 10. However, for wind speeds greater than 11m/s, rotation speed of the wind turbine as well as the rotation speed of the electric generator are limited to 60 rpm and 1800 rpm respectively thanks to the speed limitation system. Speed limitation in the second subregion of region II is very important due to mechanical and acoustic constraints.

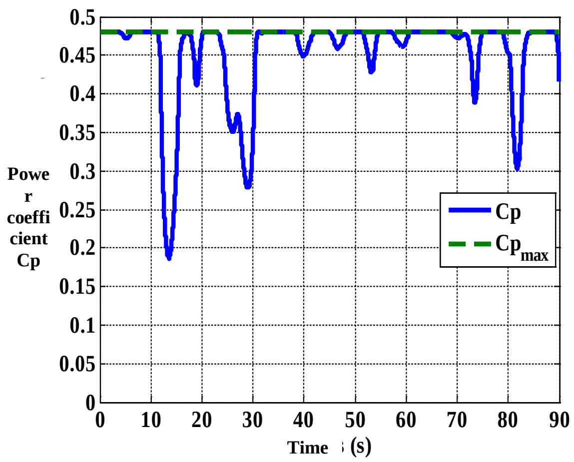

Fig. 10 : Power coefficient

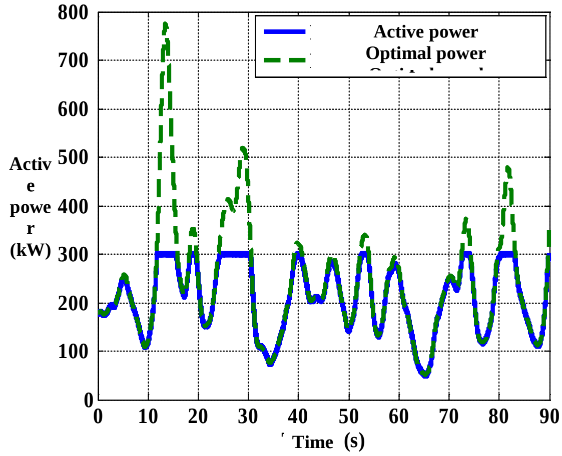

Fig. 11 : Active power variation

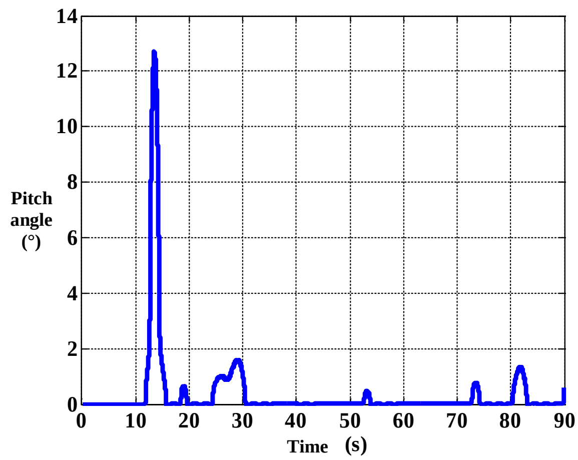

Fig. 12: Pitch angle

For wind speed that exceeds12m/s, the nominal power of the wind turbine is reached as we can see on Fig. 11. Therefore, the control objective will be to protect the wind turbine against overloads by adjusting turbine blades pitch angle in order to limit the converted power to the nominal power of the wind turbine which can be seen in Fig. 11 and Fig.12. In the light of the presented simulation results we can deduce an improved performance of the controlled system using the proposed non-integer order control.

In order to give a good view of the performance of the proposed fractional order control, we have introduced results presented in Fig. 13 on which we can distinguish easily operation regions of the wind turbine. Indeed, on Fig. 13 we can easily distinguish the operating region II, for wind speed lower than 11 m/s, where the control objective is the maximum power extraction which is affirmed by the follow-up of the active power to its reference curve. However, for wind speed higher than 11 m/s the control objective is no longer the maximum power extraction but rather the speed limitation which is confirmed by result presented on Fig. 14. Moreover, when wind speed reaches 12,5 m/s, the wind turbine is then at its nominal power, hence the operating objective becomes the protection of the wind turbine by limiting the extracted power to its nominal value using the pitch angle control system as presented in Fig. 13.

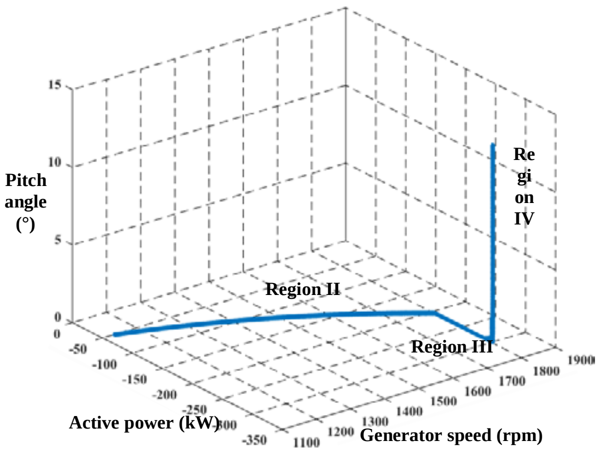

Fig. 13: Operating characteristics of WECS (P, Ω_g, β).

Finaly, performances of the WECS using the proposed fractional order control can be resumed by the results presented on Fig.13 on which all operation regions can be easily distinguished. In fact, the first region characterized by maximum power extraction which spreads out from 50 kW up to 200 kW on the power axis. Then region II in which the rotation speed is limited to 1800 rpm for mechanical and acoustic reasons and finally the third region where the converted power is limited by action on the blade pitch angle to protect the wind turbine from destruction.

VI. CONCLUSION

In present work, afractional order control is proposed. The used FOPI controllers are designed based on three specifications in frequency domain using a proposed analytic method. The WECS performance using the proposed non-integer control are presented with model simulation in Matlab. Indeed, the interest targets have been achieved as we ca see on the obtained results, which show a good performance of the considered WECS. The results also show effectiveness in the operation of the WECS in three regions of operation with satisfaction regarding references tracking and convergence. In fact, simulation results are very attractive and ensuring stability, quality and efficiency of WECS. Finaly, from the simulation results presented in this paper, it can be concluded that the proposed non-integer control has improved performances of the studied WECS.

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