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The performance of the input-output linearization controller fo a doubly-fed induction machine

Abstract.*The objective of this paper is to study the dynamic behavior of the generator of a wind turbine based on a dual-fed machine (DFIG) connected to the grid. The stator of the DFIG is directly connected to the grid. In this paper, a nonlinear controller is presented for the doubly-fed induction machine (DFIM). The nonlinear controller is designed on the basis of input-output linearization control technique ,this technique will be given good performance and dynamics at our machine than indirect vector control method of . The paper discusses the operating principles of the active and reactive power generation scheme . The simulation results show that the proven input-output linearization control, perfect tracking of the generated active and reactive power and its robustness to active and reactive power variations.*

Streszczenie. *Celem niniejszej pracy jest zbadanie dynamicznego zachowania generatora turbiny wiatrowej opartej na maszynie o podwójnym zasilaniu (DFIG) podłączonej do sieci. Stojan DFIG jest bezpośrednio podłączony do sieci. W niniejszym artykule przedstawiono nieliniowy regulator dla maszyny indukcyjnej z podwójnym zasilaniem (DFIM). Sterownik nieliniowy został zaprojektowany na podstawie techniki sterowania linearyzacją wejścia-wyjścia, która zapewnia dobrą wydajność i dynamikę maszyny w porównaniu z pośrednią metodą sterowania wektorowego. W artykule omówiono zasady działania schematu generowania mocy czynnej i biernej. Wyniki symulacji pokazują, że sprawdzone sterowanie linearyzacją wejścia-wyjścia zapewnia doskonałe śledzenie generowanej mocy czynnej i biernej oraz jest odporne na zmiany mocy czynnej i biernej. (**Działanie regulatora linearyzacji wejście-wyjście do maszyny indukcyjnej dwustronnie zasilanej**)*

Keywords: Wind; Doubly-Fed Induction Generator (DFIG); Input-Output linearization; Indirect vector control.
Słowa kluczowe: generator DFIG, elektrownia wiatrowa, linearyzacja

Introduction

The first use of wind power was to sail ships in the Nile some 5000 years ago. Today, it is one of the most important sources of renewable energy in the world; it knew an extraordinary growth during the last decade, because this energy is recognized to be ecological and economic to produce electricity. At the same time, there was a fast development relating to the wind turbine technology. [1]

Additionally the development of recent technology returns the conversion of this increasingly worthwhile electricity and economically aggressive, in the worldwide scales, wind power maintains a growth of 30% in keeping with annum for the remaining decade. Because of the unique blessings of the DFIG, it is turning into the main configuration of wind power technology. The vector control approach is used to study the generator, and the DFIG rotor is connected to an alternating excitation whose frequency, section and importance can be tailored [2]. With the DFIG,generation can be accomplished in variable velocity starting from sub synchronous pace to superb synchronous pace ((±30%) around the synchronous pace [3, 4]. DFIG is widely used for the variable-speed generation, and it is one of the most important generators for the wind-energy conversion systems [5]. DFIG-based wind turbines have many advantages over the fixed speed induction generators or variable speed synchronous generators with full-scale power converters, including variable speed operation for maximum power tracking, decoupled active and reactive power control,lower converter cost, and reduced power loss [6]. A main advantage of the doubly fed induction machine is the accessibility of its both armatures from which the power flow control can be easily occurred between machine and grid [7]. In the DFIG concept, the stator is usually directly connected to the three-phase grid.The stator is also connected to the grid, but via a transformer and two back-to-back converters (figure 1).

Both the grid-connected and stand-alone operation are feasible through an AC/DC/AC frequency converter [5].

The input-output linearizing command is a command which generalizes the vector-ensuring decoupling and linearization of the relationship between inputs and outputs. Assuming that all of the state vector is measurable, it is possible to design a nonlinear state feedback which ensures the stability of the closed loop system [3].

This paper concentrates on the design and implementation of DFIG control strategies which are based on the simplifiedinput-output linearizing and decoupling control to provideimproved decoupled performance and parameter insusceptivecontrol. The general concept of input-output linearizing controlis presented initially. The pertinent controllers are thendescribed.

Description system

This paper presents a comparative analysis of a simplified input-output linearization control with an indirect vector control while maintaining the stability and positive influence of parametric variations for the doubly-fed induction wind power conversion system. (WECS) with doubly fed. Theoretical analysis, modelling and simulation results are provided. A control strategy A control strategy is developed to control the active and reactive power in order to maximise the wind energy production. Figure 1 shows the structure of the DFIG wind energy conversion system.

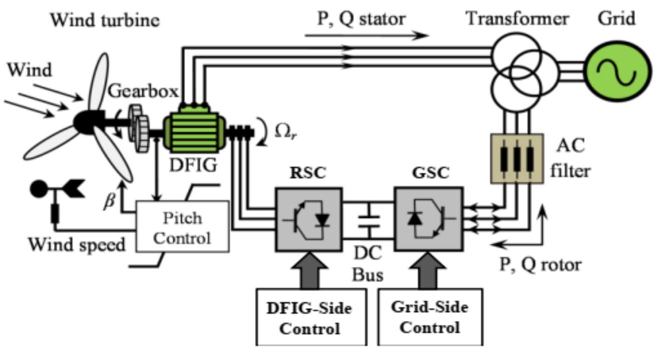

Fig.1. Wind energy conversion system based a DFIG

1. Modelling of the Wind Turbine

The mechanical power put into play on the shaft of theturbine, noted Pt, is expressed by :

(1) $$P_t = \frac{1}{2} C_p(\lambda,\beta)\rho\, \pi\, R^2 V^3$$

where *ρ* is the air density, *R* is the radius of the wind turbine, *V* is the speed of the wind, *Cp* (*λ*,*β*) is the power coefficient, *β* is the blade pitch angle, and *λ* is the tip speed ratio of the rotor blade tip speed to the wind speed and is defined by:

(2) $$\lambda = \frac{\Omega_t R}{V}$$

The expression of the turbine torque:

(3) $$C_t = \frac{1}{2} C_p(\lambda,\beta)\rho\, \pi\, R^3 V^2$$

where, $C_p(\lambda,\beta)$ is the power factor that characterizes the aerodynamic efficiency of the turbine (Figure 2). It depends on the dimensions of the blade, the angle of orientation of the blade β, and the ratio of th e speed λ, and expressed as :

(4)
$$(C_p(\lambda,\beta) = (0,5 - 0.0167(\beta-2).\sin(A) \text{ - } 0,00184(\lambda-3)(\beta-2)$$
$$A = \frac{\pi(\lambda+0.1)}{18,5-0,3(\beta-2)}$$

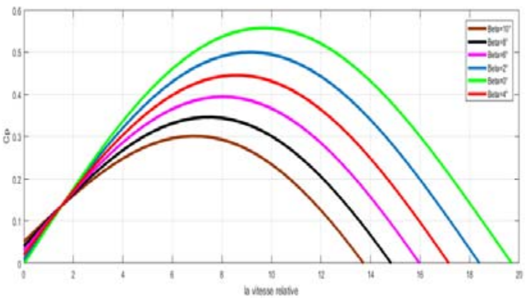

Fig.2.Coefficient of the pair C_p, as a function of λ, for different β

2. Doubly-fed induction machine model control strategy of the indirect vector control

Keep the same assumptions. By combining the different equations above, we can express the voltages based on the powers. and include :

Under assumption of linear magnetic circuits and a balanced operating condition, the equivalent two-phase model of a symmetrical DFIM with a stator connected to the line, represented in a fixed stator d-q reference frame is

(5) $$\begin{cases} V_{ds} = R_s I_{ds} + \dfrac{d\varphi_{ds}}{dt} - \omega_s \varphi_{qs} \\ V_{qs} = R_s I_{qs} + \dfrac{d\varphi_{qs}}{dt} + \omega_s \varphi_{ds} \end{cases}$$

Rotor voltage components:

(6) $$\begin{cases} V_{dr} = R_r I_{dr} + \dfrac{d\varphi_{dr}}{dt} - \omega_g \varphi_{qr} \\ V_{qr} = R_r I_{qr} + \dfrac{d\varphi_{qr}}{dt} + \omega_g \varphi_{dr} \end{cases}$$

Stator flux components:

(7) $$\begin{cases} \varphi_{ds} = L_s I_{ds} + M I_{dr} \\ \varphi_{qs} = L_s I_{qs} + M I_{qr} \end{cases}$$

Rotor flux components:

(8) $$\begin{cases} \varphi_{dr} = L_r I_{dr} + M I_{ds} \\ \varphi_{qs} = Lr I_{qs} + M I_{qs} \end{cases}$$

DFIG electromagnetic torque:

(9) $$T_{em} = P\frac{M}{L_s}(\varphi_{qs} \mathrm{I}_{dr} \text{-} \varphi_{ds} \mathrm{I}_{qr})$$

Mechanical equation:

(10) $$\frac{J}{p}\frac{d(\omega)}{dt} = T_{em} - C_t - f\,\omega$$

The control of the GADA must allow independent control of control of active and reactive power by the rotor voltages generated by an inverter.

In the two-phase reference frame, the stator active and reactive powers of an asynchronous generator can be written as :

(11) $$\begin{cases} P_s = V_{ds} I_{ds} + V_{qs} I_{qs} \\ Q_s = V_{qs} I_{ds} + V_{ds} I_{qs} \end{cases}$$

To decouple the DFIG control, we express the machine model in adqreference frame and we apply a stator-flux vector control. Thus, the flux will be on hold on the $d$axis and the stator voltage vector on the $q$axis[15]. The DFIG final simplified model is given as .

The rotor voltages, which are the control vectors of the DFIG, are given by.

2.1Stator flux orientation :

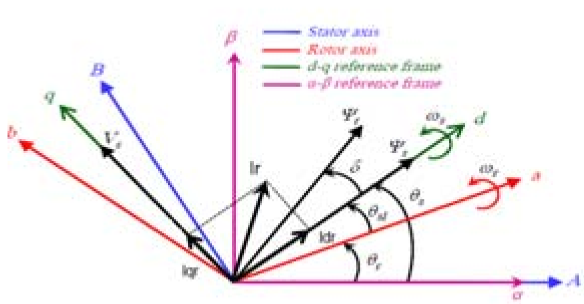

Fig. 3. Stator field-oriented control technique

(12) $$\begin{cases} \varphi_{sd} = \varphi_s = V_s / w_s \\ \varphi_{sq} = 0 \end{cases}$$

(13) $$\begin{cases} V_{sd} = 0 \\ V_{sq} = \omega_s \varphi_s = V_s \end{cases}$$

Substituting (12) into (7) yields:

(14)
$$\begin{cases} I_{sq} = -\dfrac{M}{L_s} I_{rq} \\ I_{sd} = \dfrac{\varphi_s}{L_s} - \dfrac{M}{L_s} I_{rd} \end{cases}$$

According to (14),(12) and (6) into (7), we get the so the state aquations hold:

(15)
$$\begin{cases} V_{dr} = R_r I_{dr} + \sigma L_r \dfrac{dI_{dr}}{dt} - \omega_g \sigma L_r I_{qr} \\ V_{qr} = R_r I_{qr} + \sigma L_r \dfrac{dI_{qr}}{dt} + \omega_g \sigma L_r I_{dr} + \omega_g \dfrac{MVs}{\omega_s L_s} \end{cases}$$

The stator active and reactive power which are controlled by the action at the rotor currents, are given by:

(16)
$$\begin{cases} P_s = -V_s \dfrac{M}{L_s} I_{qr} \\ Q_s = -V_s \dfrac{M}{L_s} I_{dr} + \dfrac{V^2{}_s}{w_s L_s} \end{cases}$$

The DFIG electromagnetic torque is giving as:

(17)
$$T_{em} = -P \frac{M}{L_s} \varphi_s \mathrm{I}_{qr}$$

From equations (8), (9) and (12), a block diagram block diagram with rotor voltages as inputs and stator active and reactive and the stator active and reactive powers as outputs is established in figure 3.

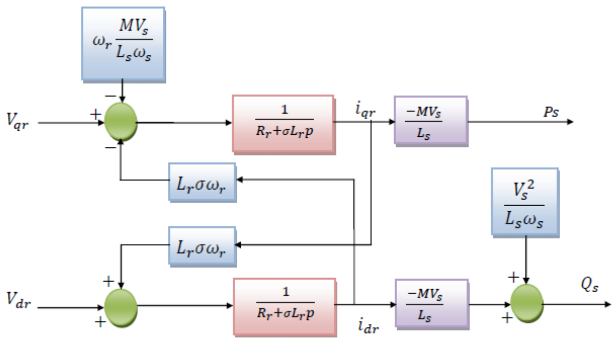

Fig. 4. Internal diagram of the DFIG

The block diagram of the indirect power control of the double-fed asynchronous machine is shown in Figure 5

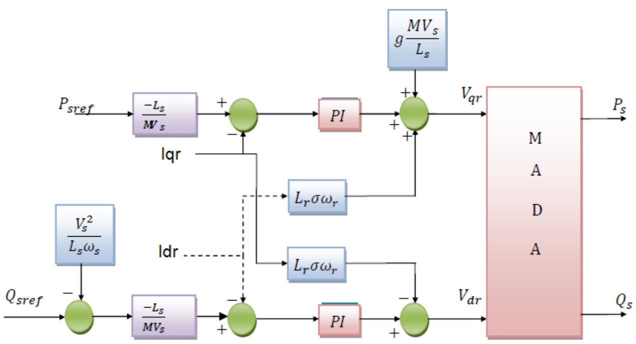

Fig.5. Block diagram of the indirect control without loops of the GADA

3. principle of the input-output technique linearization control

The concept of linearisation in the input-output sense is now well known. Several references describing how to apply it are now available. [9, 10] The decoupling phase consists of looping the system into independent monovariable systems[ref kada]. We will show how to obtain a linear relationship between the output y and a new input v, by making a good choice of the linearisation law. Since the equivalent model is linear, it can be given a stable dynamic based on the linear methods .[11, 12]

After that, a desired dynamics can be imposed on the system by adding a new control input.

Consider a non-linear system with inputs and outputs (MIMO) [13, 14]

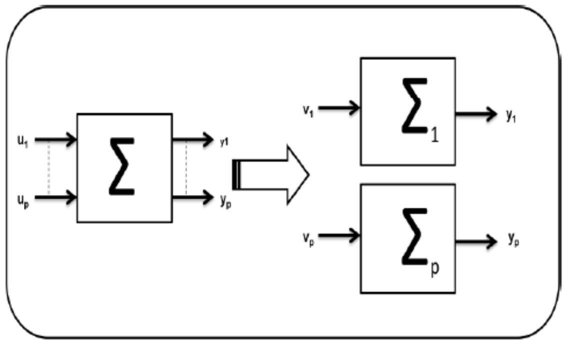

Fig. 6 diagram of principle of linearising control.

Equivalent model is linear, we can impose a stable dynamics on it based on the classical linear methods.

(18)
$$\dot{x} = f(x) + \sum_{i=1}^{p} g(x).u_i$$

(19)
$$y_i = h_i(x)$$

$$\text{Or } \; x = \left[x_1, x_2, x_3, ...x_p\right]^T \; \textit{is the state vector}$$

$$u = \left[u_1, u_2, u_3, ...u_p\right]^T \; \textit{is the vector of controls}$$

$$y = \left[y_1, y_2, y_3, ...y_p\right]^T \; \textit{is the vector of outputs}$$

$$f, g_i : \textit{are fields of smooth vectors and}$$

$$h_i : \textit{the smooth function.}$$

Consider the non-linear model of the following form:

(20)
$$\begin{cases} \dot{x} = f(x) + g(x).u \\ y = h(x) \end{cases} \quad with \begin{cases} x \in R^n \\ y \in R^m \\ u \in R^p \end{cases}$$

Deriving the output y gives the following equation

(21)
$$\dot{y} = A(x) + B(x)u$$

3.1. Definition: The relative degree r of the output yi is the smalleat derivation order k such that us:

(22)
$$\begin{cases} y_p^{(k)} = A_{(K,p)}(x) + B_{(K,p)}(x)u \\ \text{with} \quad B_{(K,p)}(x) \neq 0 \end{cases}$$

A system that is defined by (20) is decoupled by static looping if and only if :

(23) $$rang\left(\frac{\left(y_1^{r1}..........y_p^{rp}\right)}{\left(u_1............u_m\right)}\right)=p$$

The problem is to find a linear relationship between the input and the output by deriving the output until at least one input appears using the expression :

(24) $$\begin{cases} y_j^{(rj)} = L_j^{rj}h_j(x) + \sum_{i=l}^{p} L_{gi}(L_f^{rj-1}h_j(x))u_i \\ \text{with} \quad \text{J=1,2,3..........p} \end{cases}$$

Which can be expressed in a matrix form :

(25) $$\begin{bmatrix} y_1^{r_1} & . & . & . & y_p^{r_p} \end{bmatrix}^T = A_0(x) + B_0(x).U$$

with

(26) $$A_0(x) = \begin{bmatrix} L_f^{r_1}h_1(x) \\ .... \\ L_f^{r_p}h_p(x) \end{bmatrix}$$

and

(27) $$B_0(x) = \begin{bmatrix} L_{g1}L_f^{r1-1}h_1(x) & ... & & L_{gm}L_f^{rm-1}h_1(x) \\ ... & ... & & ... \\ ... & ... & ... & ... \\ L_{g1}L_f^{rm-1}h_m(x) & ... & ... & L_{gm}L_f^{rm-1}h_m(x) \end{bmatrix}$$

The linearization law is therefore given in the form :

(28) $$u = B_0(x)^{-1}\left[-A_0(x)+V\right]$$

$B_0(x)$ has to be invertible matrix.

The V vector represents the new orders designed to impose a new dynamic.

(29) $$V = \left[V_1, V_2, ...V_p\right]$$

The block diagram of the linearized system is given in Figure 4

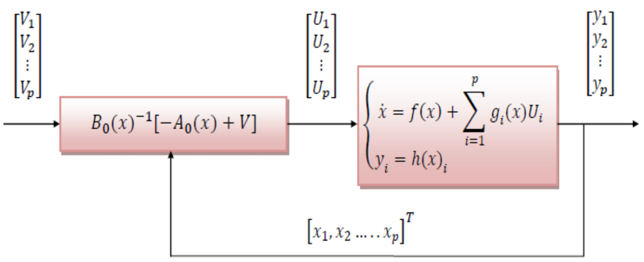

Fig. 7. Block diagram of linearised system.

4. Input-output linearizing control of the DFIG

By applying the linearisation technique with input-output decoupling to the DFIG model, it is possible to control the stator active and reactive power separately. With this control technique, the machine model is composed of two independent monovariable linear systems. Each subsystem represents an independent control loop for a given variable.

4.1 Non-linear DFIG model

For a voltage control of the MADA, the corresponding complete model is obtained by considering the state vector. According (15) the direct and quadrature components of stator and rotor currents are linear dependent respectively, thus wechooses state vectors of the DFIG as follows. [5, 6]

(30) $$x = \left[x_1 \;\; x_2\right]^T = \left[I_{rd} \;\; I_{rq}\right]^T$$

The Input variable are the rotor voltages:

(31) $$u = \left[u_1 \;\; u_2\right]^T = \left[V_{rd} \;\; V_{rq}\right]^T$$

The output variables are the active and reactive stator powers:

(32) $$u = \begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} h_1(x) \\ h_2(x) \end{bmatrix} = \begin{bmatrix} P_s \\ Q_s \end{bmatrix}$$

The expressions of active and reactive power are:

(33) $$\begin{cases} y_1 = h_1(x) = -\dfrac{M}{L_s}V_sI_{qr} \\ y_2 = h_2(x) = -\dfrac{M}{L_s}V_sI_{dr} + \left(\dfrac{V_s^{\;2}}{L_s.w_s}\right) \end{cases}$$

Differentiating (35) until an input appears:

(34) $$\begin{cases} \dot{y}_1 = \dot{h}_1(x) = -\dfrac{3}{2}\dfrac{M}{L_s}V_s\dot{I}_{qr} \\ \dot{y}_2 = \dot{h}_2(x) = -\dfrac{3}{2}\dfrac{M}{L_s}V_s\dot{I}_{dr} \end{cases}$$

By replacing (15), the following equation hold:

Where: $\omega_g = g.\omega_s$ and $g = \dfrac{\omega_g}{\omega_s}$

(35) $$\begin{cases} V_{dr} = R_rI_{dr} + \sigma L_r\dfrac{dI_{dr}}{dt} - g\omega_s\sigma L_rI_{qr} \\ V_{qr} = R_rI_{qr} + \sigma L_r\dfrac{dI_{qr}}{dt} + g\omega_s\sigma L_rI_{dr} + \dfrac{gMVs}{L_s} \end{cases}$$

Arranging (35) in the form of (14) as following :

(36) $$\begin{cases} \dfrac{dI_{dr}}{dt} = -\dfrac{1}{\sigma T_r}I_{dr} + g\omega_sI_{qr} + \dfrac{V_{dr}}{\sigma L_r} \\ \dfrac{dI_{qr}}{dt} = -g\omega_sI_{dr} - \dfrac{1}{\sigma T_r}I_{qr} - \dfrac{gMVs}{\sigma L_rL_s} + \dfrac{V_{qr}}{\sigma L_r} \end{cases}$$

Where:

(37) $$\begin{cases} \dot{y}_1 = \dot{h}_1(x) = -\dfrac{3}{2}\dfrac{M}{L_s}V_s\dot{I}_{qr} \\ \dot{y}_2 = \dot{h}_2(x) = -\dfrac{3}{2}\dfrac{M}{L_s}V_s\dot{I}_{dr} \end{cases}$$

From (37), we have :

$$(38)\quad \begin{cases} f_1(x) = -\dfrac{1}{\sigma T_r} I_{dr} + g\omega_s I_{qr} \\ f_2(x) = -g\omega_s I_{dr} - \dfrac{1}{\sigma T_r} I_{qr} - \dfrac{gMVs}{\sigma L_r L_s} \end{cases}$$

And :

$$(39)\quad g = \begin{bmatrix} g_1(x) & 0 \\ 0 & g_2(x) \end{bmatrix} = \begin{bmatrix} \dfrac{1}{\sigma L_r} & 0 \\ 0 & \dfrac{1}{\sigma L_r} \end{bmatrix}$$

We replace (38) in (34) and then we dind

$$(40)\quad \begin{cases} \dot{y}_1 = \dot{h}_1(x) = -\dfrac{M}{L_s} V_s (f_2 + \dfrac{V_{qr}}{\sigma L_r}) \\ \dot{y}_2 = \dot{h}_2(x) = -\dfrac{M}{L_s} V_s (f_1 + \dfrac{V_{dr}}{\sigma L_r}) \end{cases}$$

We can rewrite (41) in the form:

$$(41)\quad \begin{bmatrix} \dot{y}_1 \\ \dot{y}_2 \end{bmatrix} = A(x) + D(x) \begin{bmatrix} u_2 \\ u_1 \end{bmatrix}$$

Where:

$$(42)\quad A(x) = -\begin{bmatrix} V_s \dfrac{M}{L_s} f_2(x) \\ V_s \dfrac{M}{L_s} f_1(x) \end{bmatrix}$$

$$(43)\quad D(x) = -\begin{bmatrix} 0 & \dfrac{M}{\sigma L_s L_r} V_s \\ \dfrac{M}{\sigma L_s L_r} V_s & 0 \end{bmatrix}$$

Since the decoupling matrix D(x) is nonsingular, the control law is given as:

$$(44)\quad \begin{bmatrix} V_{dr} \\ V_{qr} \end{bmatrix} = D^{-1}(x) \left[-A(x) + \begin{bmatrix} v_2 \\ v_1 \end{bmatrix} \right]$$

The Proportional Integral (PI) controller achieves the tracking of the stator powers.Hence,the new input ''v'' is given by :

$$(45)\quad \begin{bmatrix} V_1 \\ V_1 \end{bmatrix} = \begin{bmatrix} \dot{y}_1^{*} - k_{p1} e_1 - k_{i1} \int e_1 dt \\ \dot{y}_2^{*} - k_{p2} e_2 - k_{i2} \int e_2 dt \end{bmatrix}$$

Where e1 is the error between the desired and the measured active power,and e2 is that relates to the reactive power:

$$(46)\quad \begin{cases} e_1 = y_1^* - y_1 = P_s^* - P_s \\ e_2 = y_2^* - y_2 = Q_s^* - Q_s \end{cases}$$

The block diagram of the input output linearizing control of the DFIG is represented by the Fig.8

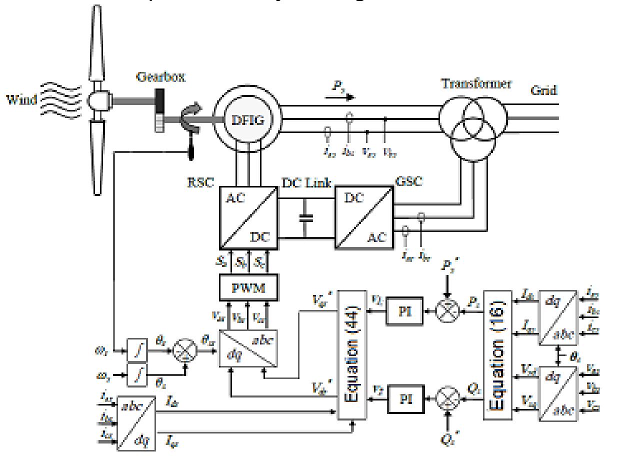

Fig.8. Block diagram of the input output linearizing control of the DFIG

5. Simulation resultats and discussions

In this section, the input-output linearisation control of the DFIG is tested by simulation under Matlab/Simulink. Three types of tests have been applied to the wind energy conversion system to observe the behaviour of its control:

1- Reference tracking test at fixed wind speed.

2- Robustness test against DFIG parameters variations at fixed wind speed.

3- Comparative study between indirect vector control and non-linear control.

Some illustrations will now be introduced to show the dynamic performance of the proposed control system. The controllers are tested for reference tracking and robustness to parameter variations. Our simulations are performed on a 4 KW generator connected to a 230V/50 Hz grid.

The DFIG parameters are:

Rs = 1.2 Ω, *Ls* = 0.1554 H, *Rr* =1.8 Ω, *Lr* = 0.1568 H, *Lm* = 0.15 H, *F* = 0.001 Nm/s, *J* = 0.2 kg. m² **.**

5.1. Pursuit test

The simulation is carried out using Matlab/Simulink software. We have therefore subjected this system to
to active and reactive power steps in order to observe the behaviour of its regulation.

Figures (Fig.9) and (Fig.10) represent respectively the simulation results of the indirect control of the doubly-fed induction generator.

Figures (Fig.11) and (Fig.12) show the non-linear input-output control of the doubly-fed Induction generator.

5.2.Robustness test

Fig. 14 shows the active and reactive powers responses of DFIG for the input-output linearization control, whose the wind turbine is driven at fixed wind speed of 12 m/sec.
Simulation results in Fig. 13 show the robustness of the proposed control strategy against parameters variations
of the DFIG, contrary to the vector control strategy (FOC) based PI (Proportional-Integral) controllers.

5.3.Comparative test

Fig.15 the power curves at variation show significant oscillations of the oscillations of the indirect vector control system, while they are The power curves at variation show large oscillations of the indirect vector control system, while they are almost negligible for the non-linear input-output or control system. Here, there are no variations and the power variations are very small. This result is interesting for wind power applications, as it helps to ensure stability and quality of production. to ensure the stability and quality of the power generated.

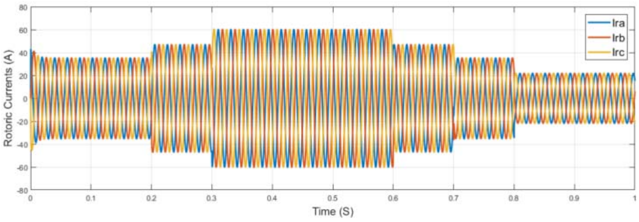

Fig.9.Three-phase Rotor Current for indirect vector control.

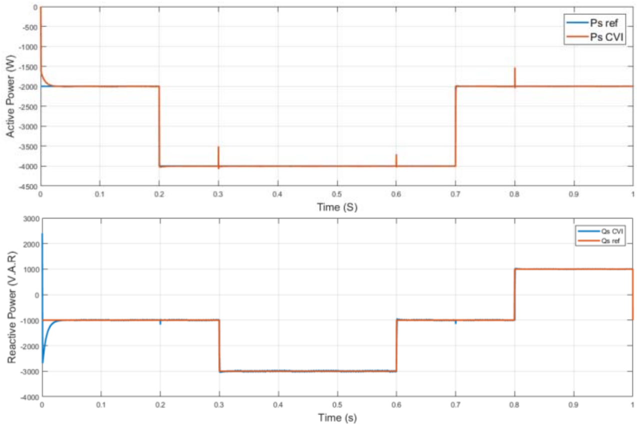

Fig.10. Decoupling of Active and Reactive power for indirect vector control.

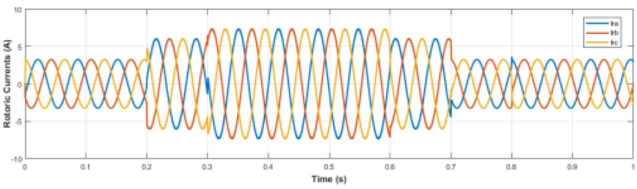

Fig.11.Three-phase Rotor Current for Non-Linear control.

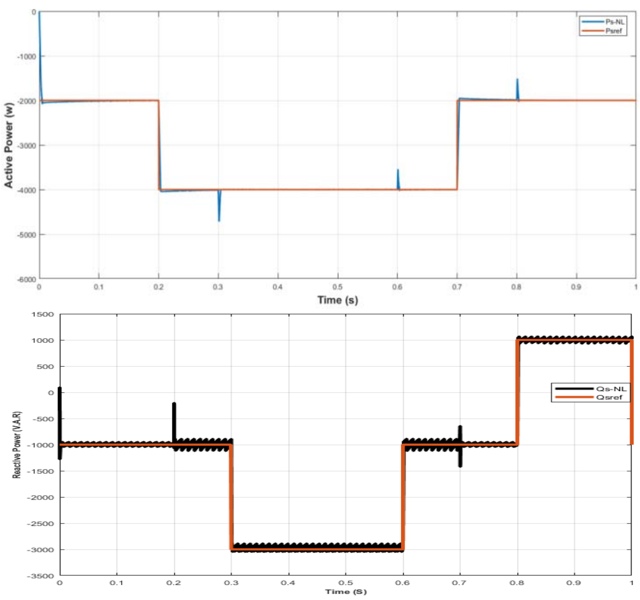

Fig.12. Decoupling of active and reactive power for Non-Linear Control.

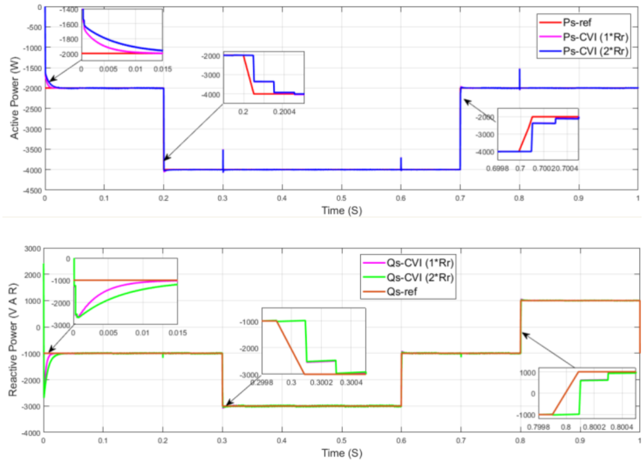

Fig.13. Robustness test for active and reactive power of the indirect vector control.

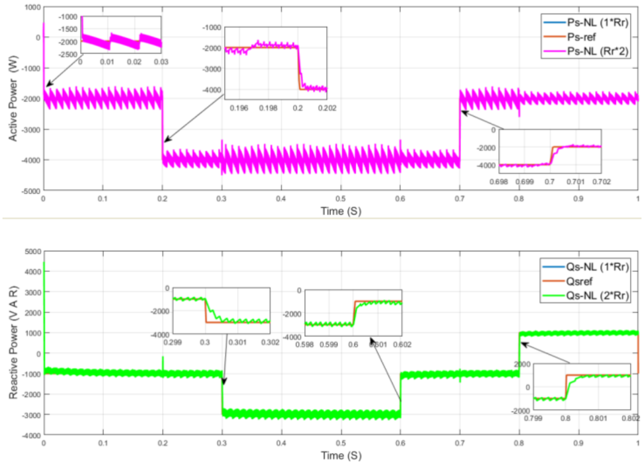

Fig.14. Robustness test for active and reactive power of the Non-Linear control.

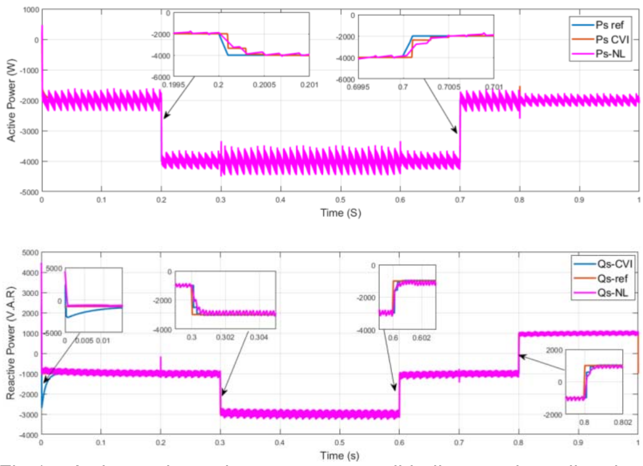

Fig.15. Active and reactive power vectoreil indirect and non lineaire controller

Conclusion

A simplified input-output linearization control applied to a DFIG turbine is proposed. A simulation study a simulation study is done to use it on the DFIG of a wind power conversion system. The performance of the controller this input-output linearization technique used in a wind power generation system is compared to that of indirect vector .

So while adjusting the parameters of our system was tuned more positively by the input-output technique and better suited to the transient and dynamic regimes, From the results the performance showed efficiency and robustness to the parameters of the control system. the simulation results offer us. The results are very consistent with the theoretical calculations and validate the accuracy of the presented simulation system.

Non-linear control has attracted many researchers who deal with the control of non-linear systems. This is the input-output linearisation control.

It has been shown that this control offers exact linearization and perfect decoupling between the active and reactive power of the doubly-fed induction generator. This allows the machine to operate in a wide range.

It has been found that the non-linear controller develops a better performance than the flow-oriented controller. The non-linear controller, on the other hand, maintains the same performance for as long as there are no uncertainties in the parameters.

The linearisation technique in the input-output sense is based on the idea of transforming a non-linear system into a linear system and then applying state feedback. It is well suited to trajectory tracking and stabilisation problems.

The main advantage of linearising control is that it is based on the knowledge of the exact model of the system. Indeed, in the majority of cases, the real model of the system cannot be known precisely.

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