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A New Robust H_∞ Control Power

Samir Abdelmalek[1], Hocine Belmili[1], Linda Barazane[2], Larabi Abdelkader[2]
[1]Unité de Développement des Equipements Solaires, UDES/Centre de Développement des Energies Renouvelables, CDER, Bou Ismail, 42415, W. Tipaza, Algérie
samir_aut@yahoo.fr, belmilih@yahoo.fr
[2]Industrial and Electrical Systems Laboratory, Faculty of Electronics and Computer, University of Sciences and Technology Houari Boumediene, B. P. 32 El - Alia, 16111, Bab –Ezzouar, Algeria
lbarazane@yahoo.fr, larabiabdelkader@yahoo.fr

***Abstract*–This paper focuses on the problem H_∞ control design of the power flowing between the stator of the Doubly-Fed Induction Generator (DFIG) and the grid. $H\infty$ controller design is formulated as a mixed-sensitivity problem. A mathematical model of the DFIG written in an appropriate d-q reference frame is established to investigate simulations. Control power is elaborated and tested by the proposed approach and Proportional-Integral (PI) controller.The simulation results included by using MATLAB tool, based on frequency and time domain,show that the validity of the proposed approach, leading to an effective control power than classical PI controller.**

***Keywords*– Doubly Fed Induction Generator (DFIG), Vector Control, H_∞, Reactive and Active Powers, Robust performance and stability.**

I. INTRODUCTION

DUE to depletion of fossil fuels and increase of polluted emissions, renewable energy production is rapidly growing. Wind energy is one of the most promising renewable energy sources due to its availability and low cost and due to the fact that it is more efficient and advanced in technology [1]-[2]. It has several advantages, such as: is the most environment-friendly, energy-efficient, cost-efficient and 100% clean energy resource, and hence wind energy has begun to beusedas the panacea for solving global warming.

Energy of the wind is user for more than thousand years for water pumping, grinding grain, and other low-power applications. There were several early attempts to build large-scale wind powered systems to generate the electrical energy [3].

One of the main types of wind generators is the Doubly Fed Induction Generator (DFIG)[4]-[5]. Wind generators play an important role among all possible renewable energy resources, they considered as the most promising in terms of competitiveness in electrical power production. DFIG-based wind turbine has been widely used for large-scale wind power generation systems due to its many advantages, such as: variable speed operation, of its good performance, controllable power factor, improved system efficiency and, most importantly, the possibility of active and reactive power control, reduced converter rating, which is typically 30% of the generator rating and, therefore, decreases the cost and power loss [6]-[7]-[8].

DFIG controlled by vector control technique, have been widely used in industrial applications for their low cost, high reliability, power efficiency and easy maintenance. The DFIG are difficult to control for several reasons:

- Non-linear dynamics system;
- Multivariable system;
- Unmeasurable states variables.

In many motion control applications, using PI-controller presents suitable performances. However, when the machine parameters variations are registered, due especially to the natural phenomena machine effects (saturation, temperature, and skin effect), the PI control performances may be seriously deteriorated [9].

In order to eliminate the previous cited problems, the robust H_∞ approach, being developed in the last two decades and still an active research area, has been shown to be an effective and efficient robust design method to control complex systems [10]-[11].

Fig. 1 shows a synoptic diagram of the proposed power control system. The stator of the DFIG is directly connected to the electrical grid, while the rotor is fed from a back-to-back converter via slip rings. The converter rating will be only a fraction of the total power of the system, reducing the cost of the power electronics. The back-to-back converter consists of a rectifier connected to the rotor windings; namely the rotor side converter (RSC) and an inverter connected to the power grid; the so-called grid side converter (GSC) [12]-[13]-[14].

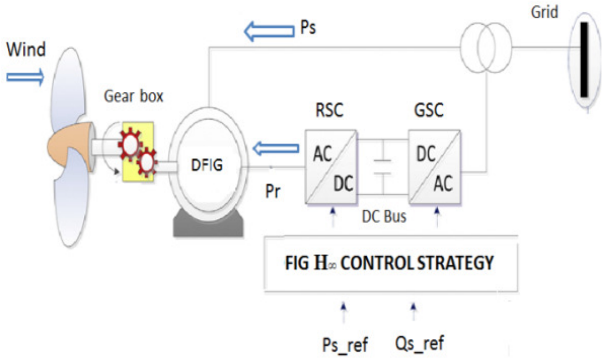

Fig. 1. DFIG-based wind turbine control proposed scheme.

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In this paper, we have been discussed the methodology to design a robust H_∞ controller to control the electrical power exchanged between the DFIG stator and the grid power by controlling independently the active and the reactive power is presented. The proposed controller allows the combination of both required objectives: can give improved tracking response and good robustness against the machine's parameters variations. The simulation results, demonstrates the effectiveness of the proposed control approach (H_∞) than classical Proportional- Integral (PI) controller.

This paper is structured as follows. In second section, we have modeled the complete wind turbine generation system. We modeled in the first step the Wind Profile modeling, in the second step the aerodynamic system and DFIG in the final step. In third section, we have presented a theory of vector control approach. The fourth section is deals to the design H∞ controller. In the last section, some simulation results are shown interesting obtained control performances of the DFIG in terms of the reference tracking power stability and the robustness against machines' parameters variations.

II. DFIG-BASED WIND TURBINE

This section is devoted to the modeling of the wind profile, modeling mechanical system of a 1.5 MW wind turbine, electrical modeling, and state space representation.

II.1 Wind Profile Modeling

Wind speed can be modeled by a sum of some harmony:

$$V_v(t) = V + \sum_{n=1}^{i} (a_n \cdot \sin(b_n \cdot \omega \cdot t)) \quad (1)$$

Where, a_n is constant and b_n, ω are respectively the amplitude and the pulse of sample wind. Fig.2 shows the wind speed profile of the wind turbine.

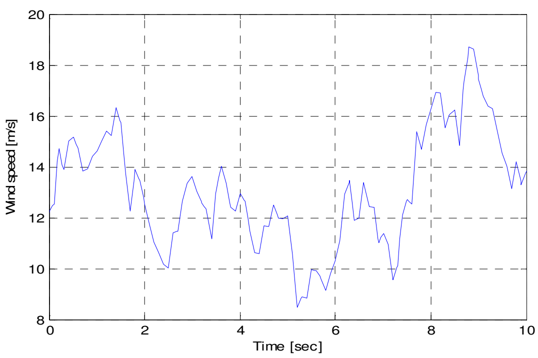

Fig.2 The profile of wind speed

II.2. Aerodynamics modelling [14]-[15]-[16]:

Theaerodynamic power captured by the aeroturbinerotor is given by:

$$P_m = 0.5 C_p(\lambda, \beta) \rho \pi R^2 V^3 \quad (2)$$

The power coefficient C_p is given as:

$$C_p = 0.22\left(\frac{116}{\lambda_i} - 0.4\beta_p - 5\right)e^{-12.5/\lambda_i} \quad (3)$$

$$\lambda_i = \left(\frac{1}{\lambda + 0.08\beta_p} - \frac{0.035}{\beta_p^{\,3} + 1}\right)^{-1} \quad (4)$$

$$\lambda = \Omega_r R / V \quad (5)$$

Where Cp is the power coefficient, β is the pitch angle, V is the wind speed, Ω_r is the turbine rotational speed on the low-speed side ofthe gearbox, R is the rotor-plane radius; ρ is the air density, and λ isthe tip speed ratio (TSR).

The aerodynamic torque on the wind turbine rotor can be obtainedusing the following relationships:

$$T_r = 0.5 \cdot C_p(\lambda_{opt}, \beta) \rho \pi R^2 V^3 / \Omega_r \quad (6)$$

A typical C_{p_λ} curve for different values of β is shown in Fig. 3. If $C_{p\_max} = 0.48$, the maximum value of C_p is achieved for $\beta = 0^0$ and a particular value of λ is defined as the optimal value of TSR (λ_{opt}). Thus the maximum power captured from the wind is given by:

$$P_{m\_max} = 0.5 \cdot C_{p\_max}(\lambda_{opt}, \beta) \rho \pi R^2 V^3 \quad (7)$$

Normally, a variable-speed wind turbine follows the C_{p_max} to capture the maximum power up to the rated speed by varying the rotor speed at Ω_{opt} to keep the TSR at λ_{opt}, T_r is then given by:

$T_r = K_{opt} \Omega_r^2$ (8)

Where, $K_{opt} = 0.5 C_{p\_max} \rho \pi R^5 / \lambda_{opt}^2$

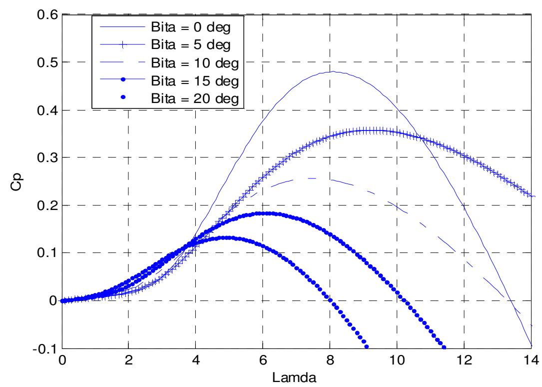

Fig. 3.Power coefficient Cp versus Lamda.

II.3. DFIG modelling [17]-[18]-[19]:

The DFIG is described in the Park (d-q) frame by the well-known following set of equations:

$$\vec{V}_d = R_s \cdot \vec{I}_s + j \cdot \omega_s \vec{\psi}_s + p \cdot \vec{\psi}_s \quad (9)$$

$$\vec{V}_r = R_r \cdot \vec{I}_r + j \cdot (\omega_s - \omega_r) \vec{\psi}_r + p \cdot \vec{\psi}_r \quad (10)$$

As the d and q axis are magnetically decoupled, the flux are given by:

$$\vec{\psi}_s = L_s \cdot \vec{I}_s + L_m \cdot \vec{I}_r \quad (11)$$

$$\vec{\psi}_r = L_r \cdot \vec{I}_r + L_m \cdot \vec{I}_s \quad (12)$$

The active powers of the stator are defined as:

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$$P_s = V_{ds} \cdot I_{ds} + V_{qs} \cdot I_{dr} \quad (13)$$

$$Q_s = V_{qs} \cdot I_{ds} - V_{qs} \cdot I_{dr} \quad (14)$$

The reactive powers of the rotor are defined as:

$$P_r = V_{dr} \cdot I_{dr} + V_{qr} \cdot I_{qr} \quad (15)$$

$$Q_r = V_{dr} \cdot I_{dr} - V_{qr} \cdot I_{dr} \quad (16)$$

And the electromagnetic torque C_{em} is defined by:

$$C_{em} = P \cdot (\Phi_{ds} \cdot I_{qs} - \Phi_{qs} \cdot I_{ds}) \quad (17)$$

III. VECTOR CONTROL STRATEGY

For the DFIG control, classical techniques as vector control were extensively used. For this purpose, several kinds of assumptions can be found in the literature (for more details see references [22]-[23]-[24] and [25]).The rotor-side converter is controlled in a synchronously rotating d–q axis frame, with the d-axis oriented along the stator flux vector position [26]-[27]. In this approach, decoupled control between the stator active and reactive powers is obtained.

For such a reference frame selection, the DFIG model can be derived as:

$$\begin{cases} V_{ds} = 0 \\ V_{qs} = V_s \end{cases} \quad (18)$$

And;

$$\begin{cases} \psi_{ds} = \Phi_s \\ \psi_{qs} = 0 \end{cases} \quad (19)$$

The stator active and reactive power can be written according to the rotor currents as:

$$\begin{pmatrix} P_r \\ Q_r \end{pmatrix} = \begin{pmatrix} -V_s \dfrac{L_m}{L_s} & 0 \\ 0 & -\dfrac{V_s L_m}{L_s} \end{pmatrix} \begin{pmatrix} I_{dr} \\ I_{qr} \end{pmatrix} + \begin{pmatrix} 0 \\ \dfrac{V_s^2}{\omega_s L_s} \end{pmatrix} \quad (20)$$

The rotor voltages can be written according to the rotor currents as:

$$\begin{pmatrix} V_{dr} \\ V_{dr} \end{pmatrix} = \begin{pmatrix} (R_r + \sigma s) & -g.\omega_s \sigma \\ +g.\omega_s \sigma & (R_r + \sigma s) \end{pmatrix} \begin{pmatrix} I_{dr} \\ I_{qr} \end{pmatrix} + \begin{pmatrix} 0 \\ g \dfrac{L_m.V_s}{L_s} \end{pmatrix} \quad (21)$$

With,

$$\begin{pmatrix} I_{dr} \\ I_{qr} \end{pmatrix} = \begin{pmatrix} -V_s \dfrac{L_m}{L_s} & 0 \\ 0 & -\dfrac{V_s L_m}{L_s} \end{pmatrix}^{-1} \left(\begin{pmatrix} P \\ Q \end{pmatrix} - \begin{pmatrix} 0 \\ \dfrac{V_s^2}{\omega_s L_s} \end{pmatrix} \right) \quad (22)$$

Where,
$g = (\omega_s - \omega)/\omega_s$ is defined as the generator's slip, and σ is the dispersion factor, $\sigma = 1 - (L_m * L_m / L_s * L_r)$.

IV. ROBUST $H\infty$ CONTROL APPROACH

In the last three decades, the H∞ control problem has been studied extensively [28]. Typical applications for robust control include systems that have high requirements for robustness to parameter variations and high requirements performances. The controllers that result from this algorithm are robust.

A- H_∞ Controller Design:

Consider the feedback control system as in Fig. 2, in which $G(s)$ is the nominal plant, $\Delta(s)$ is represented a multiplicative uncertainty. It is assumed that system $\Delta(s)$ is stable with its maximum singular value bounded. As in (1);

$$\sigma_{\max}[\Delta(j\omega)] < \sigma_{\max}[W_3^{-1}], \forall \omega \in [\omega_{\min} \quad \omega_{\max}] \quad (23)$$

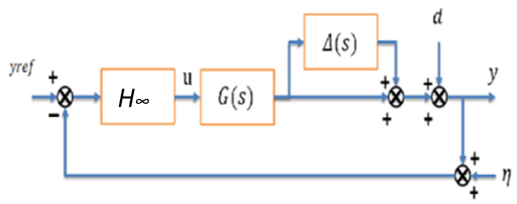

Fig. 2 A feedback controlled system parameters variations.

Where, the transfer functions from set point y_{ref} to control error e , or from disturbance d to e and η noise. The design of robust H_∞ control should be sets the following characteristics as possible:

- A stable closed loop system, T should be made small in frequency regions where the model uncertainty is large ($T = (I - S)$, as small as $\omega \to \infty$).
- The sensitivity function S is a performance indicator: the lower the sensitivity function, the lower the tracking error and hence, the better the performance.
- Guard against instability from parameter variations. This is achieved by minimizing $K(s)S(s)$.

B- A mixed sensitivity problem:

The controller is designed based on H∞ control theory and the solving process of controller is usually transformed into the standard design problem. The choice of the weighting functions is shown below [29]-[30].

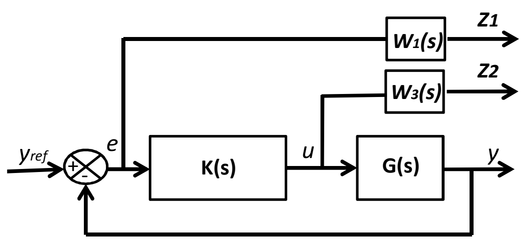

Fig.3. Mixed S/KS problem.

- $W_1(s)$ is used to limit the sensitivity function S(s), and ensure the performance index of the closed-loop system achieved the requirement. $W_1(s)$ must satisfy:

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$$\| S(jw)W_1(jw)\|_\infty \leq 1 \quad (24)$$

- $W_3(s)$ is used to limit the complementary sensitivity function T(s) and ensure the system stable when the system exist uncertainty. $W_3(s)$ is satisfied by:

$$\| T(jw)W_3(jw)\|_\infty \leq 1 \quad (25)$$

The performance and stability robustness specifications (24) and (25) can be combined into a single infinity norm specification of the form:

$$\left\| \begin{matrix} S(jw)W_1(jw) \\ T(jw)W_3(jw) \end{matrix} \right\|_\infty \leq 1 \quad (26)$$

Where, $S=(1+GK)^{-1}$, and $T=GK(1+GK)^{-1}$.
It is worth noting that, S and T are just the sensitivity function and complementary sensitivity function of the system, respectively.The cost function in (26),can also be interpreted as the design objectives of nominal performance, good tracking or disturbance attenuation, and robust stabilisation.

V. SIMULATION RESULTS

The proposed DFIG control has been evaluated via simulation tests through Matlab/Simulink software. The parameters of a 1.5 MW DFIG used in the simulation are presented in the Appendix. The performance of the designed H∞ controller is tested and compared with classical PI controller, in terms of power reference tracking (reactive and active powers) response and the robustness against the machine's parameters variations.

1. Reference tracking:

The first test investigated to compare both controllers (PI and H∞ controller) is reference tracking by applying stator active and reactive power steps to the DFIG, while the machine's speed is maintained constant at 1500 rpm. The machine is consideredas working over ideal conditions (no parameters variations and no perturbations and), the results are presented in Fig. 4 and Fig. 5.

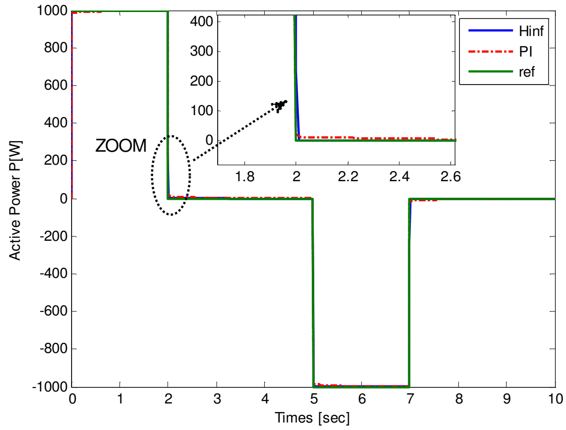

Fig.4. Dynamics of tracking active power reference, with PI and H∞ controllers.

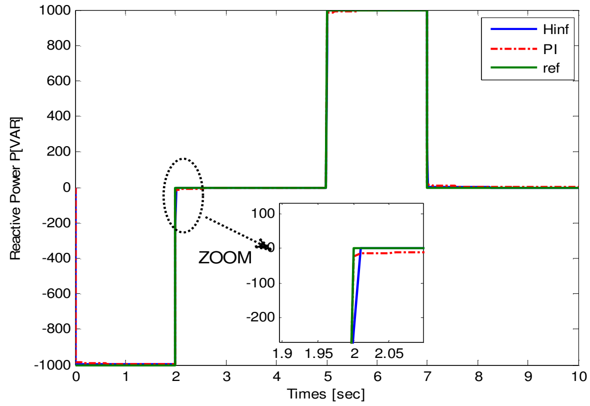

Fig.5. Dynamics of tracking reactive power reference, with PI and H∞ controllers.

The control mode based on the use of robust H∞ approach gives the best results for the DFIG control (a good reference tracking and small static error).

2. Robustness against machines' parameters variations:

The aim of this test is to analyse the influence of the DFIG parameters variations on the controller's performances. The machines' model parameters have been deliberatelymodifiedwithexcessive variations: the values of the rotor resistance R_r is multiplied by 10 of its nominal valueand the value of mutual inductance L_m is decreased by 10% of its nominal value. The obtained results are presented in Fig. 6 and Fig. 7.

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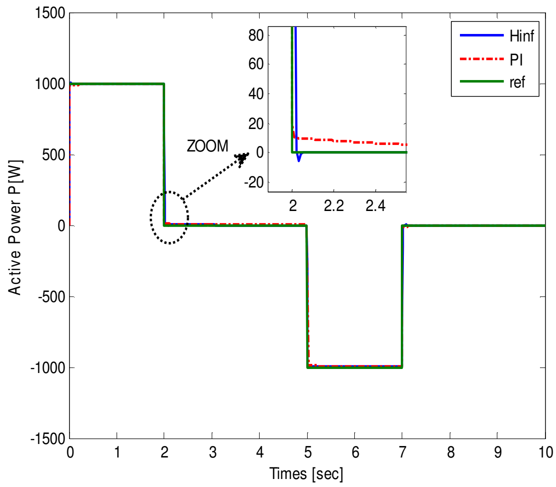

Fig.6. Dynamics of robustness (active power) against the machine's parameters variations, with PI and H∞ controllers.

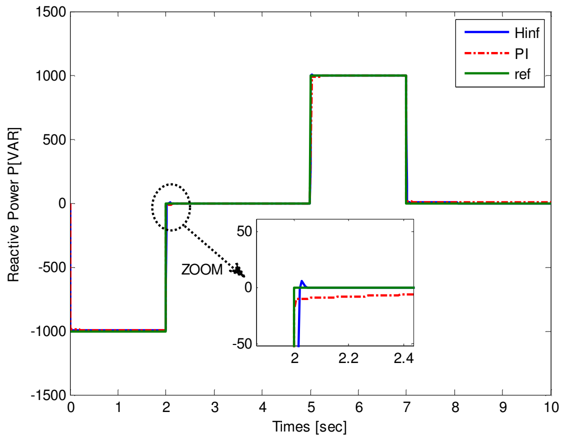

Fig.7. Dynamics of robustness (reactive power) against the machine's parameters variations, with PI and H∞ controllers.

These results show that parameters variations of the DFIG increase the time-response of the PI controller but not the H∞ controller, a static error on reactive power appears when the value of the active power is changed but it keeps reasonable values (no more than 5% for the proposed approach). The results illustrate the effectiveness of the robust H∞ approach than classical PI controller.

VI. Conclusion

In this paper, we have presented a comparative study in order to control stator active and reactive powers exchanged between the DFIG and the grid. Simulations results has been carried out using MATLAB show interesting performances of the proposed approach in terms of the reference tracking and the ability, the robustness against DFIG parameters variations and there are improvements in the dynamic response and stability of the generator system with the H∞ controller. Settling time in active and reactive power response is 0.1 sec in H∞ controller, where as in PI it is 0.4 sec.

Appendix

Rated voltage (Vs): 690 V; Frequency (f): 50 Hz; Rated speed (w_s): 1500 rpm; Number of pole pairs: 2; Stator resistance Rs: 1.2pu; Stator leakage inductance Ls: 0.1554pu; Rotor resistance R_r: 1.8 pu; Rotor leakage inductance L_r: 0.1568pu; Stator and rotor mutual inductance L_m: 0.15 pu.

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