Robust Control $H\infty$ Fuzzy of a Doubly Fed Induction Generator Integrated to Wind Power System

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Received: May 2109 Revised: August 2019 Accepted: October 2019

ABSTRACT:
This paper proposes a $H\infty$ Fuzzy robust controller for Doubly Fed Induction Generator (DFIG) based wind turbines. The power exchange between the machine stator and the grid is carried out by acting on the rotor via a bidirectional converter. The control objective is to regulate the stator active and reactive power generated from the DFIG by means of two kinds of controllers named $H\infty$ PI and $H\infty$ Fuzzy. Comparison study between the proposed controllers considering reference tracking and robustness to parameter variations is discussed. Simulation results illustrate the effectiveness of the $H\infty$ Fuzzy controller compared with the other one for time-varying reference tracking and parameters variations, which improves quality and quantity of generated power.

KEYWORDS: DFIG Generator, Wind Turbine, Robust Control, $H\infty$ Fuzzy Controller, Weighing Function.

1. INTRODUCTION
Recently, the importance of wind power generation has led people to conduct extensive researches. These research objectives are to improve the efficiency and quality of the wind system and the produced power respectively, by selecting an optimal system architecture and developing a robust control able to compensate the effects of the parameter variations and the external disturbances [1].

Most of the wind turbines installed today are equipped with a Doubly Fed Induction Generator (DFIG). This configuration is adopted for variable energy conversion. The DFIG rotor winding is fed by two static converters separated by a continuous bus. This is the most known configuration in recent years, because it has many technical and economic advantages, especially when it is compared with the other configurations based on cage asynchronous machine or synchronous machine. This configuration allows to operate over a wide range of wind speeds, and to get the maximum power from variable wind speed [1], [2], [7].

In the industrial wind system, the conventional controllers are widely used such as Proportion-Integral (PI), Proportion-Integral-Derivative (PID) [5], [14]; due to their simple configuration. These controllers are highly depended on control system parameters and they do not guarantee the system stability. Control structures based on these conventional controllers are not able to ensure the desired performances. For context, the concept of robustness appears as an essential characteristic that must be taken into account in the synthesis of controllers [2], [3].

A robust control law aims to obtain acceptable operation of a real system under different conditions and modes of use, ensuring the stable dynamics of the controlled process. In this sense, advanced controllers also called robust controllers are proposed as alternative method to solve the control problem mentioned above. One of them is $H\infty$ approach where the automation engineer introduces the mathematical model of the controlled system with structured or unstructured uncertainties in additive or multiplicative form [8]. An optimization algorithm is then mounted seeking to maximize the stability of the closed-loop system taking into account these uncertainties. In addition, performance objectives can be added as an objective of the optimization algorithm [1].

Because of the disturbances, the development of robust controller is very important. Fuzzy logic control is one of the important branches of strategies artificial intelligence that is able to reproduce human reasoning and occupies a large place in modern research fields [13]. This technique becomes very dominant in several industrial fields. The fuzzy logic setting does not deal with a well-defined mathematical relationship, but uses inferences with multiple rules; based on linguistic
variables. Thus, it is possible to take into account the experiences acquired by the technical process operators [14]. The integration of fuzzy logic into the $H_{\infty}$ approach presents a strong solution to ensure optimal regulation that meets the requirements of the user even in a difficult and variable environment [13].

Marouane E, Hassane M, Chafik E. [2] have proposed an algorithm which could the nonlinear Backstepping approach while the field orientation is applied to control the DFIG. They have found that this combining presents the performances in terms of set point tracking, stability, but does not eliminate oscillations completely. Doumi M, Aissaoui A. [3] have examined the decoupling control of active and reactive powers by Nonlinear Backstepping control of a DFIG which shows superiority over PI during the robustness, but this method had a slow response time.

Swagat P, Swati S. [5] have used stator-flux oriented vector control scheme which is used in machine-side converter by which decouple control of active and reactive of DFIG is achieved, but this control had oscillations, exceeding, and the decoupling is not fully maintained.

Sebastian K, Yusuke M. [6] proposed a new $H_{\infty}$ robust control strategy for DFIG to improve transient stability during uncertainties and grid faults, the performance of the proposed $H_{\infty}$ control approach is more effective than that of the conventional PI control, but it can also be extended to $H_{\infty}$ design problems for decentralized control systems and descriptor systems.

Wang, Y; Wu, Q. [7] proposed an $H_{\infty}$ robust controller which was designed for the DFIG rotor current regulation in order to improve the robustness and harmonic suppression performance subject to grid voltage distortions and generator parameter perturbation.

The aim of the work performed by Hamane B, Benghanem M. [16] is to apply and compare the dynamic performances of two types of controllers (namely, classical PI and Fuzzy-PI) for the WECS in terms of tracking and robustness with respect to the wind fluctuation as well as the impact on the quality of the energy produced. The performed work by Marouane E. [17] deals with the vector control based on fuzzy logic of active and reactive power of DFIG. For a comparative study, the independent control of active and reactive power is ensured in the first step by conventional controllers (PI) and the second step by the fuzzy controller. In addition, the performance and robustness are analyzed.

Zerzouri et al. [18] tried to improve the performance of WECS based DFIG, they decoupled the active and reactive power of the stator and they used a single PI in each control loop, but the oscillations were remained apparent.

The focus of this paper is on implementation of $H_{\infty}$ controller combined with fuzzy logic control for the adjustment of active and reactive power which is organized as following: the wind turbine characteristics are described in section II, modeling of the proposed system is introduced in section III, the $H_{\infty}$ approach and fuzzy logic controller are synthesized in section IV, simulation result is presented in section V, finally conclusions are stated.

2. MODELING OF THE WIND POWER SYSTEM

Fig. 1 shows the DFIG based wind turbine configuration. The DFIG stator is directly connected to the grid and the rotor is linked to the grid through a back-to-back converter based IGBT's (In-Gate Bipolar Transistor) controlled by Pulse Width Modulation (PWM). Back-to-back converter consists of two voltage converters (rotor side converter (RSC) and the grid side converter (GSC)) with a DC bus in common [1], [2].

We are interested in controlling the active and reactive powers of the DFIG through the RSC converter.

![Fig. 1. DFIG based wind turbine while system.](image_url)

2.1. Wind Turbine Modelling

It is assumed that the velocity $V$ of the wind passing through a surface $S$ is constant. The aerodynamic power $P_{aer}$ is given by the expression (1) [2], [4]:

$$
P_{aer} = 0.5 \rho A v^3 \lambda \eta$$

The power $P_T$ of the turbine according to Betz's theory is:

$$
P_T = 0.5 \rho A v^3 C_p(\lambda, \beta)$$

Where, $\rho$ (1.225 kg.m$^{-3}$) is the air density, $A = \pi R_1^2$ is the turbine blade sweep area (m$^2$), with $R_T$ (m) is the turbine radius, $v$ (m.s$^{-1}$) is the wind speed and $C_p(\lambda, \beta)$ is the power coefficient, which represents the
2.2. Mechanical Shaft Modeling

The mechanical system is represented by the following equation [3]:

\[
J_t \frac{d \Omega_t}{dt} = T_t - T_{em} - f \Omega_t
\]  

(7)

Where, \( J_t \) (kg.m²) is the total inertia which appears on the shaft of the generator, \( T_t \) (N.m) is the mechanical torque, \( T_{em} \) (N.m) is the electromagnetic torque applied to the DFIG rotor, and \( f \) (N.m.s.rad⁻¹) is a viscous friction coefficient.

2.3. DFIG Modeling

The DFIG is a classic machine where its rotor is accessible and identical to the stator. Therefore, it has the same model as the cage asynchronous machine, with the exception of rotor voltages which are not zero [3], [4]. The equations of the electrical voltages that govern the DFIG are:

\[
\begin{align*}
\nu_{ds} &= R_s \cdot i_{ds} + \frac{d \varphi_{ds}}{dt} - \omega_s \cdot \varphi_{qs} \\
\nu_{qs} &= R_s \cdot i_{qs} + \frac{d \varphi_{qs}}{dt} + \omega_s \cdot \varphi_{ds} \\
\nu_{dr} &= R_r \cdot i_{dr} + \frac{d \varphi_{dr}}{dt} - (\omega_s - \omega_r) \cdot \varphi_{qr} \\
\nu_{qr} &= R_r \cdot i_{qr} + \frac{d \varphi_{qr}}{dt} - (\omega_s - \omega_r) \cdot \varphi_{dr}
\end{align*}
\]  

(8)

The magnetic flux equations that govern DFIG are:

\[
\begin{align*}
\varphi_{ds} &= l_s \cdot i_{ds} + l_m \cdot i_{dr} \\
\varphi_{qs} &= l_s \cdot i_{qs} + l_m \cdot i_{qr} \\
\varphi_{dr} &= l_r \cdot i_{dr} + l_m \cdot i_{qs} \\
\varphi_{qr} &= l_r \cdot i_{qr} + l_m \cdot i_{qs}
\end{align*}
\]  

(9)

Where, \( l_s \) and \( l_r \) are respectively the stator and the rotor inductances, \( l_m \) is the mutual inductance, \( i_d \) and \( i_q \) are the equivalent current of \( d \) and \( q \) axis; \( R_s \) and \( R_r \) are respectively the stator and the rotor resistance; \( \Omega_t \) is the electrical angular speed, \( \Omega_t = \omega \cdot p \) is the number of pole pairs; \( \varphi_q \cdot \varphi_d \) are respectively direct and quadrature flux; \( \nu_d \) and \( \nu_q \) are direct and quadratic voltages respectively.

The electromagnetic torque expression is given as:

\[
T_{em} = p \cdot l_m \cdot (i_{ds} \cdot i_{qr} - i_{dq} \cdot i_{qs})
\]  

(10)

The active \( (P_s) \) and reactive \( (Q_s) \) stator power are [3], [4]:

\[
\begin{align*}
P_s &= (\nu_{ds} \cdot i_{ds} + \nu_{qs} \cdot i_{qs}) \\
Q_s &= (\nu_{qs} \cdot i_{ds} - \nu_{ds} \cdot i_{qs})
\end{align*}
\]  

(11)

Using Field Oriented Control (FOC) strategy [3], [18], the DFIG control scheme is given as [6], [18]:

Fig. 3. Global control structure of the wind generator with DFIG.
According to Fig. 3, there are four regulators (two power regulators and two regulators for currents). We make a combination between the $H_\infty$ controller and the fuzzy logic controller on each axis d and q, where the $H_\infty$ is used to control the DFIG stator powers and the fuzzy logic controller is installed to control the DFIG rotor currents.

3. ROBUST $H_\infty$ CONTROL APPROACH

The robustness of enslaved systems is important. Industrial applications are submitted to external disturbances and measurement noise, in addition, the mathematical model of the controlled system does not always describe the full system dynamics such as parametric uncertainties and unmodeled dynamics. The robust control $H_\infty$ is an interesting solution for system uncertainties [8], [12].

3.1. General Control Configuration with Uncertainty

The standard configuration of $H_\infty$ controller $K(s)$ with the plant $P_M(s)$ and the uncertainties $W_\eta$ is shown in Fig. 4 [6], [7], and [10].

\[\begin{align*}
\dot{x}(t) &= A_x x(t) + B_1(t). w(t) + B_2(t). u(t) \\
z(t) &= C_x x(t) + D_{11}. w(t) + D_{12}. u(t) \\
y(t) &= C_2 x(t) + D_{21}. w(t)
\end{align*}\]  

(12)

With;
- $x(t)$: Controlled outputs vector;
- $z(t)$: Measured outputs vector;
- $y(t)$: Inputs vector of criterion $H_\infty$;
- $u(t)$: Inputs vector of control;
- $A, B_1, B_2, C_1, D_{11}, D_{12}, C_2, D_{21}$ Are matrices with corresponding dimensions and $W_\eta(s)$ is the weighting function.

The transfer matrix $P_M(s)$ describes a system comprising two inputs and two outputs with [6], [8], [9]:

\[\begin{bmatrix} w \\ z \end{bmatrix} = [W_\eta]. [z] \]  

(13)

\[\begin{bmatrix} z(s) \\ y(s) \end{bmatrix} = P_M. \begin{bmatrix} w(s) \\ u(s) \end{bmatrix} \]  

(14)

If $P_M(s)$ and plant uncertainty $W$ are combined to give $P_W(s)$, we get:

\[\begin{bmatrix} z(s) \\ y(s) \end{bmatrix} = \begin{bmatrix} W_1(s). S(s) & W_3(s). S(s). G(s) \\
W_2(s). K(s) & W_2(s). K(s) \end{bmatrix}. \begin{bmatrix} w(s) \\ u(s) \end{bmatrix} \]  

(15)

with $s$ Laplace operator.

The standard problem of the $H_\infty$ control is to find a $K(s)$ controller, which internally stabilizes the closed-loop as in Fig. 4, and minimizes the $H_\infty$ norm of the transfer function from the input to the output, such that it [7], [9]:

\[\| [W_1.S & W_3.S.G] \|_\infty ^{\gamma} \leq \gamma \]  

(16)

\[\| T_{zw} \|_\infty \leq \gamma \min \gamma > 0 \]  

(17)

Where, $T_{zw}$ is the transfer matrix of the input signal to the output signal, and $\gamma$ is a positive constant value called optimization level.

\[z(s) = [P_{11} + P_{12}. W. K. (I - P_{22}. W)^{-1}]. P_{21}. w \]  

(18)

\[y(s) = P_{W}. u = [P_{22} + P_{21}. W. K. (I - P_{11}. W)^{-1}]. P_{12}. u \]  

(19)

From Fig. 4 we have:

\[u = K(s). y(s) \]  

(20)

The robust controller $K(s)$ can be given by:

\[K(s) = [P_{22} + P_{21}. W. (I - P_{11}. W)^{-1}]. P_{12} \] \(^{-1}\)  

\[= F(SI - P_{22})^{-1} \]  

(21)

3.2. Synthesis of the Robust Controller by the Method of Mixed Sensitivity

In this subsection, the mathematical tools necessary for the development of a robust $H_\infty$ controller is presented.

The system augmented by the weighting functions is shown in Fig. 5 [8], [9], [11].
must satisfy the following condition [9][10]:

\[ ||W_2.K.S||_\infty \leq \gamma \iff \forall \omega \in \mathbb{R} \ s.t \ |KS(j\omega)| \leq \frac{\gamma}{||W_2(j\omega)||} \]  

(26)

W_2(s) : written in the form: 

\[ W_2(s) = \frac{s+\omega_n/M_u}{s.x_u+\omega_h} \]

The choice of \( \omega_n \) at a low value ensures the attenuation of \( K.S(s) \) at high frequencies and consequently leads to the rejection of measurement errors and the limitation of the control energy. The pulsation \( \omega_h \) limits the amplification range of the measurement noises. This pulsation is chosen sufficiently far from the desired proper pulsation for closed-loop control. The value of \( M_u \) limits the maximum of the frequency response of \( K.S(s) \) [8].

To control \( Z_1, Z_2, Z_3 \), we can write [11]:

\[ Z_1 = W_1(s) \left[ \frac{Q_{ref} - Q}{P_{ref} - P} \right] \]  

(22)

\[ Z_2 = W_2(s).u(s) \]  

(23)

\[ Z_3 = W_3(s) \left[ \frac{Q}{P} \right] \]  

(24)

with the error \( E_Q = Q_{ref} - Q \) and \( E_P = P_{ref} - P \) is weighted by the filter \( W_1(s) \), the command \( u \) by \( W_2(s) \) and the output \( y \) by \( W_3(s) \). In the mixed sensitivity problem shown in Fig. 5, the computation of the robust controller \( K(s) \) stabilizing the looped system passes through the choice of the weighting functions \( W_1, W_2 \) and \( W_3 \), where it must check the condition in (16).

3.3. Weighting Functions Design

According to the stability condition in (16), it is clear that the frequency response of the functions \( S(s), S.K(s), S.G(s) \) and \( K.S.G(s) \) is constrained by a range which depends on the filters \( W_1, W_2, W_3 \) chosen. Figs. 6, 7 show the typical look you choose for ranges [8], [9], [10].

To limit the sensitivity function \( S(s) \) we use \( W_1(s) \) and must satisfy the condition:

\[ ||W_1.S||_\infty \leq \gamma \ \forall \ \omega \in \mathbb{R} \ s.t \ |S(j\omega)| \leq \frac{\gamma}{||W_1(j\omega)||} \]  

(25)

\( W_1(s) \) : written in the form: 

\[ W_1 = \frac{s+\omega_1}{s+M_0+\omega_1} \]

For good choice of the weighting function \( W_1(s) \), we set \( \epsilon \) to a low value at basses frequencies. This choice gives rise to an almost integral action within the regulator, which implies a minimization of \( S(s) \) and ensures a good precision in steady state. The pulsation \( \omega_1 \) for which the range intersects the 0 dB axis can be interpreted as the minimum bandwidth required for the control. The \( M_0 \) value limits the maximum, in high frequencies, of the frequency response of the sensitivity function \( S(s) \) [8].

To limit the function \( K.S(s) \), we use \( W_2(s) \) and ensure system stability when there is uncertainty. \( W_2(s) \) must satisfy the following condition [9][10]:

\[ ||W_2.K.S||_\infty \leq \gamma \iff \forall \ \omega \in \mathbb{R} \ s.t \ |K.S.G(j\omega)| \leq \frac{\gamma}{||W_2(j\omega)||} \]  

(27)

In some cases, it is sufficient to take \( W_2(s) \) constant, which allows to adjust attenuation at low frequencies. However, \( W_2(s) \) also allows to modify the behavior of \( S.G(s) \) in medium frequencies, which proves obtaining a correct transient behavior in presence of disturbance.

The range on \( S.G(s) \) depends on the two filters \( W_1(s) \) and \( W_3(s) \) to ensure the stability of our system it is [9], [10]:

\[ ||W_1, S.G.W_3||_\infty \leq \gamma \iff \forall \ \omega \in \mathbb{R} \ s.t \ |S.G(j\omega)| \leq \frac{\gamma}{||W_1.W_3(j\omega)||} \]  

(28)

However, in some cases it may be preferable to adjust by \( W_2(s) \) the template on \( K.S.G(s) \) rather than range on \( S.G(s) \), for example to satisfy an attenuation template ensuring robustness to neglected dynamics [9].
Weighting functions are not necessarily first order functions. They can be constant or order superior according to the constraints of the specifications and the needs of the designer for the realization of the controller.

\[
W_2 = \begin{bmatrix}
\frac{s+\omega_h}{s+\omega_h + \omega_1} & 0 \\
\frac{s+\omega_h + \omega_1}{s+\omega_h + \omega_1}
\end{bmatrix}
\]  
(31)

\[
W_3 = \begin{bmatrix}
0.42 & 0 \\
0 & 0.021
\end{bmatrix}
\]  
(32)

We obtain \(\gamma = 0.4249\), and the controller \(H_\infty\) of the reactive power of order 3 whose transfer function is given as follows:

\[
K_Q(s) = \frac{1.63e04 \ s^2 + 5.109e07 \ s + 3.53e09}{s^3 + 1.094e06 \ s^2 + 3.341e09 \ s + 4.469e06}
\]  
(33)

We obtain \(\gamma = 0.5067\), and the controller \(H_\infty\) of the active power of order 3 whose transfer function is given as follows:

\[
K_P(s) = \frac{7.094e02 + 1.414e05 \ s + 9.928e06}{s^3 + 1.775e05 \ s^2 + 3.141e09 \ s + 3.141e09}
\]  
(34)

To improve the performance of our system, we can solve the problem of the parameter variations and disturbances on the control, which have consequences on system performances and stability. In this part, we will focus on the replacement of the classical PI regulator by a fuzzy controller where the regulator adapts to the operating conditions of the system. As mentioned in Fig. 3.

4. FUZZY LOGIC CONTROL

Fuzzy logic allows doing the link between numerical and linguistic modeling, which has allowed spectacular industrial developments from very simple algorithms for the translation of symbolic knowledge into a digital entity and vice versa. Fuzzy set theory has also given rise to an original treatment of uncertainty, based on the idea of order, which formalizes the treatment of partial ignorance and inconsistency in information systems advances [13, 14, 17, and 19].

Fuzzy sets have an impact on automatic classification techniques, and have contributed to some renewal of existing approaches to decision support.

4.1. Structure of a Fuzzy Regulator with Five Assemblies

The design of a fuzzy system consists of three main steps: converting inputs to fuzzy values, evaluating the rules, and converting the result of the rules to a digital output value. The first step is fuzzification uses; to transform the physical quantities (entries) into linguistic value (sub-set fuzzy). The second step is the inference module, which consists of two blocks, the inference engine and the rule base. Finally, the step of defuzzification which makes it possible to infer a net value (precise) [16].
Fig. 9. The proposed fuzzy controller to regulate the active and reactive power of DFIG through the control of $i_{rd}, i_{rq}$.

As illustrated in Fig. 9, we note:

$E_r$: The error, it is defined by:

$$\begin{align*}
E_{rd}(k) &= i_{rd}^*(k) - i_{rd}(k) \\
E_{rq}(k) &= i_{rq}^*(k) - i_{rq}(k)
\end{align*}$$ (35)

$dE$: The derivative of the error, it is approximated by:

$$dE_{rd,q}(k) = \frac{E_{rd,q}(k) - E_{rd,q}(k-1)}{T_s}$$ (36)

$T_s$: The sampling period.

The output of the regulator is given by:

$$\begin{align*}
\nu_{rd,fc}^*(k) &= \nu_{rd,fc}^*(k-1) + d\nu_{rd,fc}^*(k) \\
\nu_{rq,fc}^*(k) &= \nu_{rq,fc}^*(k-1) + d\nu_{rq,fc}^*(k) \\
\nu_{rd}(k) &= \nu_{rd,fc}^*(k) - \left(\omega_0 l_r \sigma_1 i_{qr}\right) \\
\nu_{rq}(k) &= \nu_{rq,fc}^*(k) + g_0 l_r \sigma_1 i_{dr} + g_0 m_{ps} i_{ls}
\end{align*}$$ (37)

4.2. Fuzzification

It consists of transforming the physical quantities into linguistic variables (fuzzy variables) represented by the fuzzy sets of the variables $E_{rd}(k), dE_{rd}(k),$ and $\nu_{rd,fc}^*(k)$ and their membership functions which can be processed by the mechanism of inference. We have chosen to each variable the triangular shapes as shown in the following Figs [13, 14, 17]:

Fig. 10. Input and output membership functions of current controller.

The linguistic variables are noted as follows: NB for negative big, NS for negative small, EZ for approximately zero, PS for positive small, and PG for positive big.

4.3. The Base Rules

It is the rule collection that binds fuzzy input and output variables, they have the form: "if ….then", they can be written verbatim using inputs and outputs and they are given by experts in a direct numerical manner or by terms or linguistic variables through membership functions [16], [19].

4.4. Inference

It calculates the fuzzy set associated with the command and is done by fuzzy inference operations and rule aggregation. Table 1 illustrates the inference matrix of the fuzzy regulator at five sets [14].

<table>
<thead>
<tr>
<th>dE/E</th>
<th>NB</th>
<th>NS</th>
<th>EZ</th>
<th>PS</th>
<th>PB</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB</td>
<td>NB</td>
<td>NB</td>
<td>NB</td>
<td>NS</td>
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<tr>
<td>NS</td>
<td>NB</td>
<td>NS</td>
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<td>EZ</td>
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<td>PB</td>
<td>EZ</td>
<td>PS</td>
<td>PB</td>
<td>PB</td>
<td>PB</td>
</tr>
</tbody>
</table>

There are three main and common methods; Max-Min, Max-Product and Sum-Product, and the method we used in this work is the Max-Min method (Mamdani implication).
4.5. Defuzzification
This step consists of performing the inverse operation of the fuzzification, which is to say, obtaining a physical value of the output from the surface obtained. Several methods of défuzzification exist, we are interested in the center method of gravity because of its simplicity of calculations and its unique output [13].

Fig. 11. Fuzzy rule surface for the proposed fuzzy controller with five assemblies.

Three-dimensional representation of the function $dC_{i=q} = f(E, dE)$ in normalized coordinates is shown in Fig. 11 and the surface related to the fuzzy controller is smooth and has good symmetry.

Fig. 12 gives the global control scheme for a DFIG based wind turbine with the $H\infty$ Fuzzy Logic controller.

Fig. 12. General diagram of control the stator powers (active and reactive) by $H\infty$ Fuzzy Logic Controller.

5. SIMULATION RESULTS
The proposed DFIG control has been evaluated via simulation tests through MATLAB/Simulink. The nominal power of DFIG used in the simulation is 1.5 MW.

Fig. 13. The profile of wind speed.

Fig. 14. Rotor speed of DFIG.

Fig. 15. Dynamics of tracking active power reference, with $H\infty$ PI and $H\infty$ Fuzzy controllers.
is negligible in the cases of corrector $H_\infty$ Fuzzy, but it is important in the case of the corrector $H_\infty$ PI. It is possible to explain that the $H_\infty$ PI controller has no mechanism for ensuring the cancellation of the static error as in the $H_\infty$ fuzzy. In addition, for the transient regime, and for both controller, a peak in active and reactive power dynamics is provoked, such as a high amplitude pack appears in the stator active and reactive power controlled by $H_\infty$ PI at $t=0.75s$, $2s$ and $3s$, caused by active power reference changing, while a less peak amplitude for the active and reactive power controlled by $H_\infty$ Fuzzy controller.

As the conclusion for this test, the $H_\infty$ Fuzzy controller shows a good tracking performance even in presence of variable power reference.

5.1. Robustness Test

The robustness test consists of varying the parameters of the DFIG electric parameters used; these parameters are subject to variations driven by different physical phenomena (saturation of the inductances, heating of the resistors, etc.).
The purpose of these controllers is to control the active and reactive power exchange between the stator of the DFIG and the grid by modifying the amplitude and the frequency of the rotor voltages, also the performances of the regulators were evaluated by several tests of simulations. For this purpose, the differences between the two regulators are significant with respect to the set-point tracking, although the $H_\infty$ PI regulator seems to have a bad precision which can be improved by a judicious choice of the template on the sensitivity function.

For robustness, the controller based on $H_\infty$ Fuzzy presents high performances to parameter variations and noise rejection; these tests have shown the effectiveness of the $H_\infty$ Fuzzy controller compared to the $H_\infty$ PI regulator.

REFERENCES


6. CONCLUSION

This paper enables us to compare the performance of two controllers which are applied to wind turbine system based on DFIG: $H_\infty$ PI controller based on the minimization of the $H_\infty$ standard, using frequency concepts and $H_\infty$ Fuzzy regulator to improve the performance and robustness of $H_\infty$ PI controller.

Parameter variations (resistance, inductance) significantly increase the deviation and response time of $H_\infty$ PI controller, as illustrated in Figs. 19, 20, we note that the variation of the rotor resistance causes a difference which exceeds twice the active power and 3 times the reactive power for a similar test without variation of the resistance for the corrector $H_\infty$ PI. The $H_\infty$ Fuzzy controller has good performance for this test (almost invisible effect). In addition, $H_\infty$ PI controller has a better performance for variation of the inductances, two times better than normal condition, while the proposed controller has no effect to this disturbance.


