Nonlinear Backstepping controller Design for Recovering the Available Maximum Wind Power by a Wind Energy Conversion System at its Partial Load

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Abstract

This article aims to model the entities of a Wind Energy Conversion System (WECS) based on Doubly Fed Induction Generator (DFIG), to design and then to synthesize the regulators using the base technique of Backstepping. The first one will make it possible to extract the maximum of the available wind energy taking into account the variation of the air density, and the second will control the transit of the active and reactive powers exchanged with the Grid utility. We will then present the results of the simulations of the set under the Matlab-Simulink environment.

Keywords: WECS based on DFIG; MPPT by Optimal Torque; Backstepping Technique; Rotor Side Converter (RSC); Air Density in WECS.

1. Introduction

Renewable energy sources such as solar, wind, hydro, geothermal, tidal, and wave have emerged as a new paradigm to fulfill the energy needs of our civilization. In contrast to fossil fuels, renewable energy sources are clean, abundant, naturally replenished, available over wide geographical areas, and have less or no impact on the environment. Renewable energy sources are primarily used for electricity generation, heating, transportation fuels, and rural energy supply. Electricity production from renewable energy sources has come under growing attention in recent decades. All types of renewable energy sources compensate approximately 22% of global electricity consumption. Driven by technological innovations, cost reduction, government incentive programs, and public demand for clean energy, wind energy is increasingly becoming mainstream, competing with not only other renewable energy sources but also with conventional fossil fuel-based power generation units [1]. At the end of 2014, global cumulative wind power capacity reached 370 Gigawatts (GWs), which accounts for approximately 4% of the world’s net electricity production [2–4].
In order to generate electricity from the Aero-Generator (AG) more efficiently and reliably, numerous improvements have been made to the design of mechanical and electrical equipment for AGs. The wind turbine using the Doubly Fed Induction Generator (DFIG) remains the most installed in the world. Its low manufacturing cost, its variable-speed operation capability and the design of its Back-To-Back converters, reduce the third of the power injected into the network, and remain among its main motivations [4].

The main objective of this paper is the design and the implementation of a nonlinear control strategy such as Backstepping technique allowing to extract the maximum available wind power and controlling the transit of powers (active and reactive) exchanged with the utility grid. Figure 1 presents the components of the subject AG.

![Figure 1. Wind Turbine Generator controlled by Backstepping technique](image)

The paper will be organized as follows: the modelling of the assembly Turbine - DFIG and Rotor Side Converter (RSC) is presented in section 2. The concept of the BackStepping technique (BS) is described in section 3. The fourth section is reserved to design the controller of the RSC and the MPPT regulator. The validation, through interpreted simulations, of the regulator will be verified in section 5. Finally a conclusion in the sixth section.

2. Dynamical Modeling of the WECS

The diagram of the wind turbine based on a DFIG connected to the network, including the different mechanical and electrical quantities used to model the electromechanical conversion chain, is illustrated in Figure 1. At first, we present the aerodynamic model of the turbine, and the model of the mechanical transmission. Then we model the DFIG in the Park marker. Finally, the model of RSC is described for the purpose of his order.

2.1. Model of the Turbine

The wind velocity \( v \), applied to the blades of the wind turbine, causes its rotation and creates a mechanical power on the shaft of the turbine, noted \( P_t \), expressed by
Where \( \lambda \) is defined by:
\[
\lambda = \frac{R \cdot \Omega_t}{v}
\]  

With:
- \( \lambda \): Tip Speed Ratio (TSR) representing the ratio between the linear velocity at the end of the blades of the wind turbine and the wind speed,
- \( \rho \): the air’s density (~1.225 kg/m\(^3\)),
- \( S \): the surface swept by the turbine
- \( \Omega_t \): la vitesse de rotation de la turbine,
- \( R \): the radius of the turbine or the length of a blade.
- \( C_p \): the aerodynamic efficiency of the turbine.

The values of the power coefficient \( C_p \) are obtained from the experimental tests and generally provided by the manufacturers. Several analytical forms are used in the literature for its approximation [5-6]. As part of this work, the power factor \( C_p \) is approximated by:
\[
C_p(\lambda, \beta) = 0.5 \left( \frac{116}{\lambda_i} - 0.4\beta - 5 \right) e^{-\frac{21}{\lambda_i}}
\]

With:
\[
\lambda_i = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{1 + \beta^2}
\]

Knowing the speed of rotation of the turbine, the mechanical torque \( C_t \) available on the slow shaft of the turbine can therefore be expressed by:
\[
C_t = \frac{P_t}{\Omega_t} = 0.5 \cdot \frac{\pi}{\lambda} \cdot \rho \cdot R^3 \cdot v^2 \cdot C_p(\lambda, \beta)
\]

Figure 2 illustrates the evolution of the coefficient \( C_p \) as a function of the pitch angle \( \beta \) and the TSR.

![Figure 2: Evolution of the \( C_p \) for different \( \beta \) and TSR](image-url)
2.2. Model of the mechanical part

The mechanical part of the turbine comprises three steerable blades of length R. They are fixed on a drive shaft rotating at a rotation speed $\Omega_t$, connected to a gain multiplier $G$. This multiplier drives the electric generator. The three blades are considered identical. In addition, we consider a uniform distribution of the wind speed on all blades and therefore equality of all thrust forces. Thus, we can model all three blades as one and the same mechanical system characterized by the sum of all the mechanical characteristics. Due to the aerodynamic design of the blades, we consider that their coefficient of friction with respect to the air is very low and can be neglected. Likewise, the speed of the turbine being very low, the losses by friction will be negligible in the case of friction losses on the generator side. On the basis of these assumptions, we obtain a mechanical model consisting of two masses as shown in Figure 3 whose validity, compared to the complete model of the turbine, has already been verified [7].

\[
\begin{align*}
J_t & : \text{the moment of inertia of the turbine equivalent to the inertia of the three blades of the wind turbine,} \\
J_m & : \text{the moment of inertia of the DFIG,} \\
f_v & : \text{the coefficient due to the viscous friction of the DFIG,} \\
C_m & : \text{the mechanical torque on the DFIG shaft,} \\
\Omega_m & : \text{the speed of rotation of the DFIG.}
\end{align*}
\]

The multiplier adapts the rotational speed of the turbine (slow shaft) to the speed of rotation of the DFIG (fast shaft). Considering that the multiplier is ideal, that is to say that the mechanical losses are negligible, it is then modelled by the following two equations:

\[
\begin{align*}
C_m &= \frac{C_t}{G} \quad (6) \\
\Omega_m &= G \cdot \Omega_t \quad (7)
\end{align*}
\]

From Figure 3, we can write the fundamental equation of the dynamics of the system brought back to the shaft of the DFIG by:

\[
C_m = \left(\frac{J_t}{G^2} + J_m \right) \cdot \frac{d\Omega_m}{dt} + f_v \cdot \Omega_m + C_{em} \quad (8)
\]

With, $C_{em}$ is the electromagnetic torque of the DFIG.

The block diagram of Figure 4 corresponds to the aerodynamic and mechanical models of the wind turbine. It shows that the rotation speed $\Omega_m$ of the DFIG, and therefore of the turbine, can be
controlled by acting either on the pitch angle $\beta$ (pitch control) or on the electromagnetic torque $C_{em}$ (MPPT method) of the DFIG. Wind speed $v$ is considered a disturbing input to the system.

2.3. DFIG’s Model

In order to establish the command of the DFIG, we recall here its modeling in the Park marker. The model is based on the following simplifying assumptions: constant air gap, effect of notches neglected, sinusoidal spatial distribution of magnetomotive air gap forces, influences of skin effect and heating not taken into account, and unsaturated magnetic circuit with constant permeability. These choices mean, among other things, that the fluxes are additive, that the inherent inductances are constant and that there is a sinusoidal variation of the mutual inductances between the stator and rotor windings as a function of the electric angle of their magnetic axes.

The equations of the stator and rotor voltages of the DFIG in the Park coordinate system are defined by [4-5], [7-8] and [10]:

$$v_{sd} = R_s \cdot i_{sd} + \frac{d\varphi_{sd}}{dt} - \dot{\theta}_s \cdot \varphi_{sq}$$  \hspace{1cm} (9)

$$v_{sq} = R_s \cdot i_{sq} + \frac{d\varphi_{sq}}{dt} + \dot{\theta}_s \cdot \varphi_{sd}$$  \hspace{1cm} (10)

$$v_{rd} = R_r \cdot i_{rd} + \frac{d\varphi_{rd}}{dt} - \dot{\theta}_r \cdot \varphi_{rq}$$  \hspace{1cm} (11)

$$v_{rq} = R_s \cdot i_{rq} + \frac{d\varphi_{rq}}{dt} + \dot{\theta}_r \cdot \varphi_{rd}$$  \hspace{1cm} (12)

With:

- $v_{sd}, v_{sq}, v_{rd}, v_{rq}$ are the respective stator and rotor voltages in the Park landmark,
- $i_{sd}, i_{sq}, i_{rd}, i_{rq}$ are the respective stator and rotor currents in the Park landmark,
- $\varphi_{sd}, \varphi_{sq}, \varphi_{rd}, \varphi_{rq}$ are the respective stator and rotor fluxes in the Park landmark,
- $R_s, R_r$ are the respective resistances of the stator and rotor windings,
- $\theta_s, \theta_r$ are the respective Park angles of the stator and rotor quantities,

The stator and rotor fluxes are expressed by:

$$\varphi_{sd} = L_s \cdot i_{sd} + M_{sy} \cdot i_{rd}$$  \hspace{1cm} (13)

$$\varphi_{sq} = L_s \cdot i_{sq} + M_{sy} \cdot i_{rq}$$  \hspace{1cm} (14)
\( \varphi_{rd} = L_r \cdot i_{rd} + M_{sr} \cdot i_{sd} \)  \hspace{1cm} (15) \\
\( \varphi_{rq} = L_r \cdot i_{rq} + M_{sr} \cdot i_{sq} \)  \hspace{1cm} (16)

With:

- \( L_s, L_r \) are the respective cyclic inductances stator and rotor,
- \( M_{sr} \) : Mutual inductance between a stator phase and a rotor phase in the Park marker;

Park angles for stator and rotor quantities are related by:

\[ \theta_s = \theta_e + \theta_r \]  \hspace{1cm} (17)

Where, \( \theta_e \) is the electrical angle between the stator and rotor windings.

The active and reactive stator and rotor powers are expressed by:

\[ P_s = v_{sd} \cdot i_{sd} + v_{sq} \cdot i_{sq} \]  \hspace{1cm} (18) \\
\[ Q_s = v_{sq} \cdot i_{sd} - v_{sd} \cdot i_{sq} \]  \hspace{1cm} (19) \\
\[ P_r = v_{rd} \cdot i_{rd} + v_{rq} \cdot i_{rq} \]  \hspace{1cm} (20) \\
\[ Q_r = v_{rq} \cdot i_{rd} - v_{rd} \cdot i_{rq} \]  \hspace{1cm} (21)

The electromagnetic torque \( C_{em} \) can be expressed, from the stator fluxes and the rotor currents, by:

\[ C_{em} = p \frac{M_{sr}}{L_s} (\varphi_{sq} \cdot i_{rd} - \varphi_{sd} \cdot i_{rq}) \]  \hspace{1cm} (22)

### 2.4. Modeling of The Rotor Side Converter (RSC)

Figure 5 shows the topology 2L-VSC (two-Level Voltage Source Converter) chosen for the RSC.

![Figure 5. Two Levels-Voltage Source Converter (2L-VSC) Topology](image)

The relationship between the different parties involved in the 2L-VSC converter is given by:
This Converter can operate as inverter or rectifier.

3. **Backstepping technique concept**

Backstepping was developed by Kanellakopoulos et al. (1991) and inspired by the works of Feurer & Morse (1978) on the one hand and Tsinias (1989) and Kokotovit & Sussmann (1989) on the other. The arrival of this method has given new life to the adaptive control of non-linear systems [14].

Backstepping is based on the second method of Lyapunov, which combines the choice of the function with that of the laws of control and adaptation. This allows him, in addition to the task for which the controller is designed (tracking and / or regulation), to guarantee, at all times, the overall stability of the compensated system.[14-16]

The basic version of Backstepping is non-adaptive feedback control, in the absence of uncertainties. This very special case will be used to expose the recursive design procedure. [18]

In order to illustrate the principle of the Backstepping method, we consider the case of nonlinear systems of the form: [17-18]

\[
\begin{align*}
\dot{x}_1 &= \varphi_1(x_1)^T \theta + \theta_1(x_1)x_2 \\
\dot{x}_2 &= \varphi_2(x_1, x_2)^T \theta + \theta_2(x_1, x_2)u \\
y &= x_1
\end{align*}
\]  

The vector of the parameters \( \theta \) is assumed to be known. It is desired to forward at the output \( y \) the reference signal \( y_r \) where \( \dot{y}_r \) and \( \ddot{y}_r \) are assumed to be known and uniformly bounded. The system being second-rate, the design is done in two stages.

**Step 1** - We consider first equation (24) where the state variable \( x_2 \) is treated as a virtual command and we define the first desired value \((x_1)_d \equiv \alpha_0 = y_r \)

The first error variable is defined by:

\[
\varepsilon_1 = x_1 - \alpha_0
\]

With these variables, the system (24) is written

\[
\begin{align*}
\dot{\varepsilon}_1 &= \dot{x}_1 - \dot{\alpha}_0 = \varphi_1^T \theta + \theta_1 x_2 - \dot{\alpha}_0
\end{align*}
\]  

For such a system, the quadratic function \( V_1(\varepsilon_1) = \frac{1}{2} \varepsilon_1^2 \) is a good choice of the Lyapunov control function (lcf). Its derivative, along the solution of (28), is given by:
A judicious choice of $x_2$ would make $\dot{V}_1$ negative and ensure the stability of the origin of the subsystem described by (24). Let us take the value of $x_2$ as the function $\alpha_1$ as

$$\dot{\varphi}_1^T \theta + \vartheta_1 \alpha_1 - \dot{\alpha}_0 = -k_1 \varepsilon_1$$  \hspace{1cm} (30)

Where, $k_1 > 0$ is a design parameter. This gives

$$(x_2)_d \triangleq \alpha_1 = \frac{1}{\vartheta_1} [-k_1 \varepsilon_1 - \varphi_1^T \theta + \dot{\alpha}_0]$$  \hspace{1cm} (31)

**Step 2** - We consider the subsystem (24) - (25) and we define the new error variable

$$\varepsilon_2 = x_2 - \alpha_1$$  \hspace{1cm} (32)

Due to the fact that $x_2$ can’t be forced to instantly take a desired value, in this case the error $\varepsilon_2$ is not, instantaneously, zero. The design in this step consists, then, in forcing it to cancel itself with a certain dynamic, chosen beforehand.

The equations of the system to be controlled, in space$(\varepsilon_1, \varepsilon_2)$, are written

$$\dot{\varepsilon}_1 = \varphi_1^T \theta - \dot{\alpha}_0 + \vartheta_1 (\varepsilon_2 + \alpha_1)$$  \hspace{1cm} (33)

$$\dot{\varepsilon}_2 = \varphi_2^T \theta - \dot{\alpha}_1 + \vartheta_2 u$$  \hspace{1cm} (34)

for which one chooses as function of Lyapunov

$$V_2(\varepsilon_1, \varepsilon_2) = \frac{1}{2} \varepsilon_1^2 + \frac{1}{2} \varepsilon_2^2$$  \hspace{1cm} (35)

The latter has as a derivative, along the solution of (33) and (34).

$$\dot{V}_2 = -k_1 \varepsilon_1^2 + \varepsilon_2 \{\varphi_2^T \theta + \vartheta_1 \varepsilon_1 + \vartheta_2 u - \dot{\alpha}_1\}$$  \hspace{1cm} (36)

Now, we are in the presence of the real command $u$. A good choice of this one is given by:

$$u = \frac{1}{\vartheta_2} [-\varphi_2^T \theta - \vartheta_1 \varepsilon_1 - k_2 \varepsilon_2 + \dot{\alpha}_1]$$  \hspace{1cm} (37)
Where $k_2 > 0$ is a second design parameter.

With this choice, we have $\dot{V}_2 = -k_1 e_1^2 - k_4 e_2^2 \leq 0$.

Hence the asymptotic stability of the origin of (33) - (34). This results in the closed-loop stability of the original system (24) - (25) and the zero-tracking of the tracking error $y - y_r$. The two main objectives of the design are then achieved.

**Note**- Design parameters $k_i$ are directly related to pole position of the closed loop. Their choice makes it possible to make a placement of the poles, thus fixing the dynamics in regulation of this loop.

4. **Controllers design**

4.1. **MPPT Algorithm**

With the random nature of wind speed $v$, the peak power extraction is important in VS-WECS (Variable-speed WECS) because it increases energy conversion efficiency. For a given $v$ value, the MPPT control attempts to obtain the maximum possible power from the wind. The working region of the MPPT control corresponds to the wind speeds lower than the nominal wind speed. Various MPPT control techniques have been developed in literature and applied in the wind energy industry [5],[8]. These techniques determine the reference speed $\Omega_{y^*}$ (OTSR-Optimal TSR), reference electromagnetic torque $T_{em^*}$ (OT-Optimal Torque) or reference power $P_s^*$ (PSF-Power Signal Feedback). The interested reader will find a comparative between these techniques at [5]. It's indicates that OT Control combines the simplicity of its structure and the good performance of control.

In this algorithm, the torque of the generator is controlled to obtain optimum torque reference curve according to maximum power of the wind turbine at a given wind speed.

From Eqs. (1), (2), (6) and (8) the mechanical torque of the DFIG can be written as:

$$C_{em^*} = K_{opt}^{OT} \rho \Omega_m^2$$

Where,

$$K_{opt}^{OT} = \frac{0.5 \pi R^5 C_{p,max}}{\lambda_{opt}^3 G^3}$$

The block diagram in Figure 6 illustrates a MPPT algorithm by OT technique.
This algorithm requires information on the air density and the mechanical parameters of the turbines, which vary according to the system. Moreover, the empirical curve OT, presented in figure 7, will change with the aging of the system [9-13]. This will also affect the effectiveness of the MPPT.

![Figure 7. Turbine power versus turbine speed for different wind speeds](image)

**Figure 7.** Turbine power versus turbine speed for different wind speeds

### 4.2. Regulators driving the RSC

- **Dynamics of the system in the canonical form of the Backstepping**

For the description of nonlinear systems, the state representation is defined by:

\[
\begin{align*}
\dot{x} &= f(x) + g(u) \\
y &= h(u)
\end{align*}
\]  

(40)

Where \( x \) is the state vector, \( u \) the command vector, and \( y \) the output vector.

Since the state representation is not unique for a given system, several choices for the state vector depend on the objective being plotted. As part of this work, a voltage control of the DFIG is envisaged with a vector control by orientation of the stator flux SVOC (Stator Voltage-Oriented Control), in this respect the following choices have been preferred:

For state variables:
For command variables:
\[ u = [v_{rd} \ v_{rq}]^T \]  \hspace{1cm} (42)

Considering the choice of the dq mark linked to the stator rotating field SVOC and neglecting the resistance of the stator windings, and from equations (9) to (22). The state representation chosen for the rotor side control is:
\[ \dot{i}_{rd} = \frac{1}{\sigma L_r} (v_{rd} - R_r i_{rd} + \sigma L_r \omega_r i_{rq}) \]  \hspace{1cm} (43)
\[ \dot{i}_{rq} = \frac{1}{\sigma L_r} (v_{rq} - R_r i_{rq} - \sigma L_r \omega_r i_{rd} - \omega_r \frac{M_{sr}}{L_s} \phi_s) \]  \hspace{1cm} (44)

The setpoints of these currents are deduced from the setpoints of the active power (or electromagnetic torque) and the reactive power as follows:
\[ C_{em}^* = -p \frac{M_{sr}}{L_s} \phi_{sd} \cdot i_{rq}^* \]  \hspace{1cm} (45)
\[ Q_s^* = \frac{v_{sq}^2}{L_s w_s} - v_{sq} \cdot \frac{M_{sr}}{L_s} \cdot i_{rd}^* \]  \hspace{1cm} (46)

- **RSC controller design**

Consider the system (43) and (44).

The first error variable is defined by
\[ e_1 = i_{rq\text{ref}} - i_{rq} \]  \hspace{1cm} (47)

If we take as control function of Lyapunov (cfl)
\[ V_1(e_1) = \frac{1}{2} \varepsilon_1^2 \]  \hspace{1cm} (48)

Its derivative will be given by
\[ \dot{V}_1 = e_1^2 i_{rq}^* - \frac{1}{\sigma L_r} (v_{rq} - R_r i_{rq} - \sigma L_r \omega_r i_{rd} - \omega_r \frac{M_{sr}}{L_s} \phi_s) \]  \hspace{1cm} (49)

To make it negative, just take
\[ v_{rq} = \sigma L_r i_{rq}^* + \sigma L_r k_1 \varepsilon_1 + R_r i_{rq} + \sigma L_r \omega_r i_{rd} + \omega_r \frac{M_{sr}}{L_s} \phi_s \]  \hspace{1cm} (50)

Where \( k_1 > 0 \) is a design parameter

The second error variable is
If we take as control function of Lyapunov (cfl)

\[ V_2(e_2) = \frac{1}{2} e_2^2 \]  \hspace{1cm} (52)

Its derivative will be given by

\[ \dot{V}_2 = e_2 \left[ i_{rd}^* - \frac{1}{\sigma L_r} (v_{rd} - R_r i_{rd} + \sigma L_r \omega_r i_{rd}) \right] \]  \hspace{1cm} (53)

To make it negative, just take

\[ v_{rd} = \sigma L_r i_{rd}^* + \sigma L_r k_2 e_2 + R_r i_{rd} - \sigma L_r \omega_r i_{rd} \]  \hspace{1cm} (54)

Where \( k_2 > 0 \) is a design parameter

Figure 8 describes the entities of the control part by the Backstepping Algorithm of the RSC. The first significant entity is the PLL; it makes it possible to restore \( V_{sq} \) and \( \theta_s \) from the measurement of the stator tests of the DFIG. The second attractive block is the SVPWM (Space Vector Width Pulse); it’s a technique used in the final step of field oriented control (FOC) to determine the pulse-width modulated signals for the RSC switches in order to generate the desired 3-phase voltages to the rotor.

**Figure. 8.** Regulator Backstepping of the RSC
5. Results and Interpretations

The simulations were performed with Matlab Simulink. In order to validate the commands designed in last section. The different electrical and mechanical parameters of the wind system studied are shown in Table 1. Table 2 shows the different regulator setting parameters.

Table 1. Mechanical and electrical parameters of the studied wind system

<table>
<thead>
<tr>
<th>Entity</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbine</td>
<td>Number of blades: 3</td>
</tr>
<tr>
<td></td>
<td>R=45 m</td>
</tr>
<tr>
<td></td>
<td>( J_t = 1.4 \times 10^6 \text{ kg.m}^2 )</td>
</tr>
<tr>
<td></td>
<td>( v_{wn} = 13 \text{ m/s} )</td>
</tr>
<tr>
<td></td>
<td>( N_{in} = 19 \text{ tr/min} )</td>
</tr>
<tr>
<td>Gearbox</td>
<td>G = 100</td>
</tr>
<tr>
<td>DFIG</td>
<td>( P_n = 3 \text{ MW}, U_s = 690 \text{ V}, f = 50 \text{ Hz}, p=2 )</td>
</tr>
<tr>
<td></td>
<td>( R_s = 2.97 \text{ m}\Omega, R_c = 3.82 \text{ m}\Omega )</td>
</tr>
<tr>
<td></td>
<td>( L_s = 121 \text{ } \mu \text{H}, L_c = 57.8 \text{ } \mu \text{H}, L_s = 12.2 \text{ } \mu \text{H} )</td>
</tr>
<tr>
<td></td>
<td>( J_m = 114 \text{ kg.m}^2 )</td>
</tr>
<tr>
<td>Utility Grid</td>
<td>( U_s = 690 \text{V}, f = 50 \text{Hz} )</td>
</tr>
</tbody>
</table>

Table 2. Regulator Adjustment Parameters

<table>
<thead>
<tr>
<th>Regulator of</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>( I_{rd} ) (ou ( Q_s ))</td>
<td>( k_1 = 100 )</td>
</tr>
<tr>
<td>( I_{ql} ) (ou ( P_s ))</td>
<td>( K_2 = 90 )</td>
</tr>
</tbody>
</table>

5.1. Results

The results obtained for the different simulation tests, are exposed on:

- Figure 9 for tracking and regulation tests for the three modes of hyposynchronous, synchronous and hypersynchronous operation;
- Figure 10 for robustness tests compared with regulators PI as to the variations of the inductance \( L_r \);
- Figure 11 to expose the impact of the change in air density on the technical MPPT

Wind Speed (m/s)

DFG Speed (Rpm)

Cp

Landa
(a) Results of aerodynamic and mechanical parts of WECS
Figure 9. Tracking and regulation test by Backstepping Algorithm

(b) Results of Electric parts of WECS
(a) Backstepping Algorithm

(b) PI Regulator

**Figure 10.** Robustness Test

**Figure 11.** MPPT taking into account the variation of the air density $\rho$
5.2. **Interpretations**

For the tracking test (Figure 9), the ordered quantities follow their reference trajectory, without exceeding and without static error in steady state. At startup, the three-phase stator current generated by the DFIG is sinusoidal at steady state with good harmonic distortion THD, also the voltage is sinusoidal frequency 50Hz and RMS value 690V. The frequency of the rotor currents depends on the slip and the frequency of the stator quantities. According to the slip profile, it should be noted that the DFIG will operate according to its 3 modes: Hypersynchronous ③, Hyposynchronous ① and Synchronous ② observed at the frequency of currents flowing in the rotor windings. The active power has the same shape as that of the wind speed.

For the control test (Figure 9), there is a low sensitivity to external disturbances due to abrupt changes in the speed of the wind turbine or variation of the reference of the reactive power. The three-phase stator currents are almost sinusoidal thanks to the good choice of control frequency of the Space Vector PWM and the parameters of the regulators Backstepping technique.

For the robustness tests, the variation of the inductance Lr (Figure 10) has very little influence on the response time and on the amplitude of transient and permanent oscillations for the BS regulators, but it has an impact observed in the case of PI controller whose control parameters are sensitive to internal disturbances (variation of Lr in our case).

Figure 11 shows the impact of air density (here depending on the temperature) on the MPPT algorithm. If the MPPT algorithm uses a constant value of $\rho = 1.225\, \text{Kg/m}^3$ (where $T = 15\, \text{°C}$), the maximum available power is not harvested in the case of temperatures below 15 °C. In addition, in the case where the temperature is greater than 15 °C, the reference torque imposed by the MPPT algorithm does not represent the true setpoint.

The results of the simulation clearly indicate that the DFIG based Wind Turbine Generator with the control scheme designed has a good command of the different quantities involved, and it has shown good behavior with respect to parametric variations compared to the conventional PI controller.

6. **Conclusion**

In this paper, we applied the non-linear algorithm Backstepping to control the transit of active and reactive powers stator with the utility grid, and to control the speed of the machine in order to extract the peak of available power in the wind. Then, we evaluated the performance of said control in tracking, regulation and robustness against parametric variations. The simulation results presented confirm the feasibility of the proposed approach. In addition to ensuring the stability of the system and the zero convergence of errors (tracking and / or regulation), Backstepping offers the means to improve the quality of the transient regime of this convergence.

Future works will be devoted to the design of a complete control scheme taking into account the GSC Grid Side Converter, and also evoking the behavior of this command in the case of a disturbed network.
References