An Efficient Nonlinear Backstepping Controller Approach of a Wind Power Generation System Based on a DFIG

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Abstract-In this paper; we present an efficient and robust nonlinear control model for wind energy conversion system based on a doubly fed induction generator (DFIG). The aim of this work is to develop a model, which combines the vector control and the nonlinear Backstepping approach to control the currents rotor and the mechanical rotor speed of the generator in order to extract the maximum of the power produced. The robustness and performance of the system are tested and compared with classical PI controller in terms of reference tracking whatever generator parameters variations. Simulation results were evaluated and presented under MATLAB/SIMULINK Software.

Keywords DFIG, Wind turbine, MPPT, Backstepping Controller, Lyapunov function.

1. Introduction

At the beginning of the 21st century, the exploitation and development of renewable energy resources, especially wind turbine, becomes the priority of several countries. The reasons for this interest in wind conversion system technologies are the bulk availability of this resource without any cost and it’s the most environmental means to get electricity from an inexhaustible source [1-2].

Various researches have focused in the study of wind power generation systems using doubly fed induction generator (DFIG) from an endless source [2-6]. The most used machine in the wind farms is the doubly fed induction generator, the stator of the generator is connected directly to a phase grid and the rotor is connected to the utility grid via a two power converters linked by a DC bus (Fig.1) [7-8]. This structure has several advantages such as; allows operation at over a large range of wind speeds of about ± 30% around the synchronous speed which allows to better exploit the resources wind turbines, and the power converters are sized to use a fraction (25%-30%) of the total power produced by the generator to achieve full control of the system. Consequently, the reduction of losses in power electronics components [7], [9].

The Control of the doubly fed induction generator is more difficult than the control of a standard induction machine. Various control methods have been developed in the literature [10-13]. The classical control for DFIG used PI controller is the most applied in industrial applications for his good reliability, easy maintenance and low cost, but when the internal parameters of the system are subject to changes caused by physical phenomena the classical PI controller performances may be changed [14].

These recent decades, many studies have focused on the nonlinear controller such us Backstepping control which has
enjoyed perfect success for his robustness against disturbance and simplicity of implementation [15].

Fig.1.Diagram of the wind energy system based on the DFIG.

The purpose of this work is to advance an efficient nonlinear control design which combines the Backstepping method and the vector control for controlling the DFIG, in order to vary the mechanical speed of the generator for each wind speed to provide the maximum of the electrical power produced. To show the importance of this study, the proposed control strategy was compared with the classical PI controller used in each to improve the system robustness and stability. The results obtained by simulation under Matlab/Simulink environment prove the robustness of the control model in terms of stability, dynamic performance, effectiveness and the reference tracking against parameter variations of the generator.

This paper is presented as follows; the second section is devoted to the mathematical model of the wind turbine and the principle of MPPT control (Maximum Power Point Tracking). In the third section we introduce the modeling of the generator in the Park reference (d-q). The description of mathematical development of the proposed nonlinear approach is detailed in Section 4. In the fifth section, we present numerical simulation results, we discuss and we compare with those of the PI controller for illustrating the control effectiveness and the performance of our study. Finally, we provide some conclusions.

2. Modelling of the Wind Turbine

The extracted power from the wind turbine is written as follows:

\[ P_v = \frac{\rho \cdot S \cdot v^3}{2} \]  
(1)

Wind turbines transform the mechanical energy generated by the wind to the electrical energy. The aerodynamic power available on the rotor is expressed as follows [17-20]:

\[ P_{aer} = C_p(\lambda, \beta) \cdot P_v \]  
(2)

\[ P_{aer} = C_p(\lambda, \beta) \cdot \frac{\rho \cdot S \cdot v^3}{2} \]  
(3)

Where \( \rho \), \( S \), \( v \), \( C_p \), \( \lambda \) et \( \beta \) are the air density (\( \rho = 1.22 \) kg/m\(^3\)), the circular surface swept by the turbine, the wind speed, the power coefficient, speed ratio and the pitch angle of the blade, respectively.

The expression \( C_p(\lambda, \beta) \) defines the aerodynamic efficiency of the wind turbine; it depends on the blade pitch angle \( \beta \) and the speed ratio \( \lambda \), which is defined as [21-22]:

\[ \lambda = \frac{R \cdot \Omega}{v} \]  
(4)

The aerodynamic torque is given by:

\[ T_{aer} = \frac{P_{aer}}{\Omega} = C_p(\lambda, \beta) \cdot \frac{\rho \cdot S \cdot v^3}{2 \cdot \Omega_i} \]  
(5)

The power coefficient \( C_p(\lambda, \beta) \) can be described as follows [23]:

\[ C_p(\lambda, \beta) = 0.5176 \times \frac{116}{\lambda^2} - 0.4 \beta - 5 \times e^{-\frac{21}{\lambda^2}} + 0.0068 \lambda \]  
(6)

\[ \lambda_i = \frac{1}{\lambda + 0.008 \beta - 0.035}{\beta^3} + 1 \]  
(7)

The characteristics of \( C_p(\lambda, \beta) \) depending of \( \lambda \) for different values of \( \beta \) are presented in the Fig.2.

From the Figure 2 we found that the maximum value of \( C_p \) is \( C_{p_{max}} = 0.48 \), which corresponds to the pitch angle of the blade \( \beta = 0^\circ \) and the optimum speed ratio \( \lambda_{opt} = 8.1 \). By setting \( \beta \) and \( \lambda \) respectively to their optimal values, the wind system will provide optimum electrical power.

The multiplier adjusts the slow speed of the rotation of the turbine to the high mechanical speed of the generator; this multiplier is modelled by a gain \( G \). The total inertia \( J \) depends on the inertia of the generator \( J_g \) on the fast axis and the inertia of the turbine \( J_s \) on the slow axis [18].

\[ J = \frac{J_i}{G^2} + J_g \]  
(8)
The fundamental equation of dynamics makes it possible to determine the evolution of the mechanical speed from the total mechanical torque $T_{mec}$ is given by [7]:

$$ J \frac{d\Omega_{mec}}{dt} = T_{mec} = T_g - T_{em} - C_f \Omega_{mec} \quad (9) $$

Where:

- $T_g$: The generator torque.
- $T_{em}$: The electromagnetic torque.
- $C_f \Omega_{mec}$: The torque of viscous friction.

3. MPPT Control

The aim of this control is to optimize the capture wind energy by tracking the optimal speed, to extract the maximum of the power produced from the wind turbine; we must always adjust the rotor speed of the generator to the wind speed [18]. In order to estimate the value of the wind speed which gives the maximum of the power we can fixed the speed ratio $\lambda$ to its optimum value $\lambda_{opt}$ that corresponds to the maximum power coefficient $C_{p_{max}}$ (Fig.3). According to equation 4 it's can be possible to deduce in real time the estimate value of the wind speed:

$$ v_{est} = \frac{R \Omega_{mec}}{\lambda_{opt}^2} \quad (10) $$

The expression of the reference electromagnetic torque as a function of the mechanical speed is expressed as [24]:

$$ T_{em,ref} = \frac{1}{2} C_{p_{max}} (\lambda, \beta) \frac{\rho R^3}{(G \omega_{opt})^2} \Omega_{mec}^2 \quad (11) $$

The block diagram in Fig.3 shows the model of the turbine and the MPPT control.

4. Modeling of the DFIG

4.1. Mathematical Model of the DFIG

The general mathematical model of the doubly fed induction generator in the Park reference (d-q) is given by the following equations [8], [15]:

$$ \begin{cases} V_{sd} = R_s I_{sd} + \frac{d\varphi_{sd}}{dt} - \varphi_{sq} \omega_s \\ V_{sq} = R_s I_{sq} + \frac{d\varphi_{sq}}{dt} + \varphi_{sd} \omega_s \\ V_{rd} = R_r I_{rd} + \frac{d\varphi_{rd}}{dt} - \varphi_{rq} \omega_r \\ V_{rq} = R_r I_{rq} + \frac{d\varphi_{rq}}{dt} + \varphi_{rd} \omega_r \\ \varphi_{sd} = L_s I_{sd} + L_m I_{rd} \\ \varphi_{sq} = L_s I_{sq} + L_m I_{rd} \\ \varphi_{rd} = L_r I_{rd} + L_m I_{sq} \\ \varphi_{rq} = L_r I_{rq} + L_m I_{sq} \end{cases} \quad (12) $$

Where $\omega_s$ is the pulsation of the currents stator and $\omega_r$ is the pulsation of the currents rotor, is given by:

$$ \omega_r = \omega_s - p \Omega \quad (14) $$

Where $p$ is the number of the pole pairs of an induction machine.

- $R_s, R_r$: The stator and rotor resistance
- $L_s, L_r$: The cyclic stator and rotor inductance
- $L_m$: The mutual inductance

The electromagnetic torque of the DFIG is expressed as:

$$ T_{em} = \frac{3}{2} p L_m (\varphi_{sq} I_{rd} - \varphi_{rd} I_{sq}) \quad (15) $$

The stator and rotor active and reactive powers of the DFIG are expressed as follows [18]:

$$ \begin{cases} P_s = V_{sd} I_{sd} + V_{sq} I_{sq} \\ Q_s = V_{sq} I_{sd} - V_{sd} I_{sq} \\ P_r = V_{rd} I_{rd} + V_{rq} I_{rq} \\ Q_r = V_{rq} I_{rd} - V_{rd} I_{rq} \end{cases} \quad (16) $$

4.2. Vector control

The use of the asynchronous machine can adopt several types of control such as vector control, which is ensures decoupling between his variables and making it similar to a DC generator [25].

In our study, we chose a park reference (d-q) linked to the rotating field. Assuming that the flux stator is constant and oriented along the axis d of the rotating reference frame and the stator resistance $R_s$ is neglected [7], the equations of
The stator voltages and flux can be simplified as follow [18], [26]:

\[
\begin{align*}
\psi_{sd} &= L_s I_{sd} + L_m I_{id} = \psi_s \\
\psi_{sq} &= L_s I_{sq} + L_m I_{iq} = 0 \\
V_{sd} &= R_s I_{sd} + \frac{d\psi_{sd}}{dt} - \psi_{sq} \omega_s = 0 \\
V_{sq} &= R_s I_{sq} + \frac{d\psi_{sq}}{dt} + \psi_{sq} \omega_s = \psi_s \omega_s \\
V_{rd} &= R_r I_{rd} + (L_r - \frac{L_m^2}{L_s}) \frac{dI_{rd}}{dt} - \omega_r (L_r - \frac{L_m^2}{L_s}) I_{rd} \\
V_{rq} &= R_r I_{rq} + (L_r - \frac{L_m^2}{L_s}) \frac{dI_{rq}}{dt} + \omega_r (L_r - \frac{L_m^2}{L_s}) I_{rd} + \omega_r \frac{L_m}{L_s} \psi_s \\
\end{align*}
\]

(17)

The expression of the electromagnetic torque can be expressed:

\[
T_{em} = - \frac{3}{2} p \frac{L_m}{L_s} \psi_s I_{rq}
\]

(18)

The simplified expressions for the active and reactive powers of the stator are written as follows:

\[
\begin{align*}
P_s &= - \frac{V_s L_m}{L_s} I_{rq} \\
Q_s &= \frac{V_s \psi_s}{L_s} - \frac{V_s L_m}{L_s} I_{rd}
\end{align*}
\]

(19) (20)

The schematic diagram of the simplified model of the DFIG in Park reference (d-q) is shown in Fig.4.

The Backstepping approach is a recursive controller design for stabilizing highly nonlinear dynamic systems [27]. The principle of the Backstepping controller approach is the use of a virtual control to decompose a complex nonlinear design problem into various simpler design steps. The stability and performance of the system are achieved by using a Lyapunov function which is used to drive the virtual control [15].

According to equation (8), (16) and (17), the equations of the DFIG become:

\[
\begin{align*}
\frac{dI_{sd}}{dt} &= -b I_{rd} + \omega_r I_{rq} + a V_{rd} = g_1 + a V_{rd} \\
\frac{dI_{rq}}{dt} &= -b I_{rq} - \omega_r I_{rd} - c \psi_s \omega_s + a V_{rq} = g_2 + a V_{rq}
\end{align*}
\]

(21)

\[
\frac{d\Omega}{dt} = T_{ref} - \frac{c}{J} \Omega + \frac{d}{J} I_{rd}
\]

(22)

Where:

\[
\begin{align*}
g_1 &= -b I_{rd} + \omega_r I_{rq} \\
g_2 &= -b I_{rq} - \omega_r I_{rd} - c \psi_s \omega_s \\
\sigma &= 1 - \frac{L_m^2}{L_r L_i}; a = 1 - \frac{1}{\sigma L_r}; b = a R_r; c = a \frac{L_m}{L_r}; d = \frac{3}{2} p \frac{L_m}{L_s} \psi_s
\end{align*}
\]

(23)

According to Eq. (21) and Eq. (22), we concluded that \(V_{rd}\) and \(V_{rq}\) are the variables of the rotor voltages to impose on the machine in order to achieve the currents rotor and the mechanical speed desired. The scheme presented in Fig.5 is the proposed model control of the DFIG by the Backstepping controller.

5. Backstepping Controller

5.1. The Calculation of the Reference Current Rotor \(I_{r q}\)

The mechanical speed tracking error \(e_1\) is defined by:

\[
e_1 = \Omega_{ref} - \Omega
\]

(24)

The derivative of the equation (24) gives:

\[
\dot{e}_1 = \dot{\Omega}_{ref} - \dot{\Omega}
\]

(25)

Using Eq. (21) the previous equation becomes as the following form:
\[ \dot{e}_1 = \Omega_{\text{ref}} - \frac{T_g}{J} - \frac{C_f}{J} \Omega + \frac{d}{J} I_{rq} \]  
\[ v_1 = \frac{1}{2} e_1^2 \]

To reduce the tracking error, we use the following first Lyapunov function [23]:

\[ v_1 = \frac{1}{2} e_1^2 \]

Using the equation (26) and (27) the derivative of the first Lyapunov function \( v_1 \) is given by:

\[ \dot{v}_1 = e_1 \dot{e}_1 + e_1 \left( \frac{T_g}{J} - \frac{C_f}{J} \Omega + \frac{d}{J} I_{rq} \right) = -k_1 e_1^2 \]

In order to guarantee a stable tracking, \( k_1 \) should be a positive parameter [14]. From Eq. (28), the expression of the control variable \( I_{rq} \) can be rewritten as:

\[ I_{rq\text{ref}} = \frac{J}{d} \left( \Omega_{\text{ref}} + k_1 e_1 \right) + \frac{1}{d} \left( C_f \Omega - T_g \right) \]

5.2. The calculation of the reference rotor voltages \( V_{rd} \) and \( V_{rq} \)

The currents rotor tracking errors \( e_2 \) and \( e_3 \) are defined by:

\[ \begin{cases} 
  e_2 = I_{rd\text{ref}} - I_{rd} \\
  e_3 = I_{rq\text{ref}} - I_{rq} 
\end{cases} \]

The derivative of equation (29) gives:

\[ \begin{cases} 
  \dot{e}_2 = I_{rd\text{ref}} - \dot{I}_{rd} \\
  \dot{e}_3 = I_{rq\text{ref}} - \dot{I}_{rq} 
\end{cases} \]

Using equation (21), (22) and (31), we get:

\[ \begin{align*}
  \dot{e}_2 &= I_{rd\text{ref}} - (g_1 + a V_{rd}) \\
  \dot{e}_3 &= I_{rq\text{ref}} - (g_2 + a V_{rq}) = \frac{J}{d} \left( \Omega_{\text{ref}} + k_1 e_1 \right) + \frac{1}{d} \left( C_f \Omega - T_g \right) - (g_2 + a V_{rq}) 
\end{align*} \]

To reduce the tracking error, we use a new Lyapunov candidate function, such that [23]:

\[ v_2 = e_1^2 + e_2^2 + e_3^2 \]

Using the equation (32) and (33), the derivative of \( v_2 \) is given by:

\[ \dot{v}_2 = e_1 \dot{e}_1 + e_2 \dot{e}_2 + e_3 \dot{e}_3 \]

\[ \dot{v}_2 = -k_2 e_2^2 - k_3 e_3^2 + e_2 (k_2 e_2 + I_{rd\text{ref}} - g_1 + a V_{rd}) + e_3 (k_3 e_3 + \frac{J}{d} \Omega_{\text{ref}} + k_1 e_1) + \frac{1}{d} \left( C_f \Omega - T_g \right) - g_2 + a V_{rq} \]

Where \( k_2 \) and \( k_3 \) should be positive in order to guarantee a good and stable tracking [14]. Using the Eq. (26) and (35) the expressions of the control variables \( V_{rd} \) and \( V_{rq} \) are expressed by:

\[ \begin{cases} 
  V_{rd\text{ref}} = \frac{I_{rd\text{ref}} - g_1 + k_2 e_2}{a} \\
  V_{rq\text{ref}} = \frac{\mu - k_1 I_{rq\text{ref}} - g_2 + k_3 e_3}{a} 
\end{cases} \]

With:

\[ \mu = \frac{1}{d} \left( J \Omega_{\text{ref}} + k_1 (J \Omega_{\text{ref}} - T_g + C_f \Omega) + C_f \Omega - T_g \right) \]

That ensure \( v_2 \leq 0 \). The performance and the stability the of the system are giving by a good choice of \( k_1, k_2 \) and \( k_3 \).

6. Simulation Results and Discussions

The simulation of the whole system is performed using the MATLAB/Simulink Software. The values of the system parameters are given respectively in the appendix. The Table 1. present the Backstepping controller parameters are chosen to satisfy the convergence conditions.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( k_1 )</td>
<td>0.002</td>
</tr>
<tr>
<td>( k_2 )</td>
<td>100</td>
</tr>
<tr>
<td>( k_3 )</td>
<td>200</td>
</tr>
</tbody>
</table>

6.1. Reference Tracking and Control

We apply a random wind profile, which varies between 8 m/s and 11 m/s. It shows clearly in Fig.6. From Fig.7 that, the mechanical speed extracting from the MPPT controller varies in the same shape as the wind speed.
Furthermore, comparing Fig.8 with Fig.9, we notice that the rotor currents $I_{rd}$ and $I_{rq}$ follow perfectly their reference values and the decoupling between them is well assured. The rotor current $I_{rd}$ shown in Fig.8 is kept a constant value to have a unity power factor on the stator side to optimize the quality of the energy produced [18]. The response of the current rotor $I_{rq}$ that controls the mechanical speed of the generator is shown in Fig.9. The variation of $I_{rq}$ is following the wind speed variation in order to extract the maximum of the electrical power generated. The tracking profile is depicted in Fig.10 shows the rotor speed varies in accordance with its reference speed. It is seen that the Backstepping control lead to good tracking performance.

From the Fig.11, it can be seen that the stator active power is negative $P_s<0$ and it varies between $-4000$ W and $-10$ KW, although of this change, the power coefficient $C_p$ keeps at its maximum value $C_{p_{max}} = 0.48$ (show Fig.12), which confirm the robustness of the MPPT control. Scanning the simulation results, we concluded that MPPT control and Backstepping approach are efficient and robust.
6.2. Robustness Test

The internal parameters of the DFIG are subject to variations caused by different physical phenomena such as the temperature increase, saturation and skin effect, so our controller must provide good results whatever generator parameters variations.

The robustness of the Backstepping controller is proved by comparing the results with those of PI controller in terms of reference tracking when we varied the internal generator parameters.

Figures 13 and 14 illustrate the evolution of the current rotor $I_{rq}$ after the variation of rotor resistance and inductance from $R_r$ to $2R_r$ and $L_r$ to $2L_r$ respectively. This variation has almost no influence on Backstepping controller and the tracking of the set point is always ensured. However by using the PI controller, with the same performance, this variation shows more undesirable responses.

7. Conclusion

This paper describes an efficient and robust control of DFIG applied in a wind system by using the nonlinear Backstepping controller, MPPT strategy. After modeling the generator in the Park reference (d-q), we have adopted a vector control of the DFIG based on stator flux oriented to decouple the control of direct and quadrature currents rotor. In addition, we are interested in modeling of various components of wind system. To validate the proposed control model of the system, we have performed a simulation in Matlab/Simulink. Finally, we have compared our model to the classical PI controller in terms of reference tracking when we change the DFIG internal parameters.

According to the simulation results, the Backstepping approach ensured with better efficiency and robustness the control of the mechanical rotor speed and the currents rotor of the generator, which allows operation of the wind energy system at the maximum of the electrical power produced to the network.
Appendix: Characteristics and Parameters

Table 2. DFIG Parameters

<table>
<thead>
<tr>
<th>Denotation</th>
<th>Numerical value of parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Power</td>
<td>$P = 10KW$</td>
</tr>
<tr>
<td>Nominal frequency</td>
<td>$f = 50Hz$</td>
</tr>
<tr>
<td>Number of pole pair</td>
<td>$p = 2$</td>
</tr>
<tr>
<td>Stator resistance</td>
<td>$R_s = 0.455 \Omega$</td>
</tr>
<tr>
<td>Rotor resistance</td>
<td>$R_r = 0.62 \Omega$</td>
</tr>
<tr>
<td>Stator inductance</td>
<td>$L_s = 0.084 H$</td>
</tr>
<tr>
<td>Rotor inductance</td>
<td>$L_r = 0.085 H$</td>
</tr>
<tr>
<td>Mutual inductance</td>
<td>$L_m = 0.078 H$</td>
</tr>
</tbody>
</table>

Table 3. Wind Turbine Parameters

<table>
<thead>
<tr>
<th>Denotation</th>
<th>Numerical value of parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius of the turbine</td>
<td>$R = 3m$</td>
</tr>
<tr>
<td>Gain multiplier</td>
<td>$G = 5.4$</td>
</tr>
<tr>
<td>Inertia total moment</td>
<td>$J = 0.2kg.m^2$</td>
</tr>
<tr>
<td>Coefficient of viscous friction</td>
<td>$C_f = 0.0024m/s$</td>
</tr>
<tr>
<td>Optimal tip speed ratio</td>
<td>$\lambda_{opt} = 8.1$</td>
</tr>
<tr>
<td>Maximal power ratio</td>
<td>$C_{p,max} = 0.48$</td>
</tr>
</tbody>
</table>

References


