Modelling and simulation of a wind system using variable wind regimes with Backstepping control of DFIG

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Abstract. Nowadays wind turbine power is considered as the most reliable solution for power generation to complement the other power sources. While the majority of the established wind turbines have a constant speed, the use of wind turbines equipped with a variable speed is increasing. The Asynchronous Generator is a machine that has shown a great performance and it is currently used in the wind turbine industry. In the present study we propose a model of wind system with doubly Fed Induction Generator using variable wind regimes modelling. We use Matlab / Simulink software to analyse the performance of this system.

Keywords: Wind-Turbine, wind modeling, spectral decomposition, asynchronous generator, Backstepping control, Matlab / Simulink.

1. Introduction

The intense industrialization in recent decades and the increase in the usage of household electrical devices lead to a considerable global electricity need. To cope with these problems, countries are turning progressively towards the use of clean energy such as renewable energy. Among these renewable energy sources, wind power shows the greatest energy potential. Currently, the wind power used in onshore wind farms is a system based on asynchronous generator.

The variation of the operating regime of an autonomous wind system is caused by two factors:

- The variation of the system load
- The variation of the wind speed

That is why it is important to analyze wind speed properties.

There are two major families of wind turbines: the vertical and the horizontal axis wind turbines. Due to economical reasons that are related to their manufacture and installation, the horizontal axis wind turbines have been widely used compared to vertical axis wind turbines. It has been shown that the doubly Fed Induction Generator (DFIG) is a machine that has excellent performance and is commonly used in the wind turbine industry [1].
There are several advantages to using a DFIG for a variable speed wind turbine, including minimal exhaustion on mechanical parts, noise reduction and the possibility to control active and reactive power [2].

The performance and energy production depend not only on the GADA generator, but also on way of which the both parts of "back-to-back" converter are controlled.

In order to control the speed of DFIG with a specific detection model, we have designed a nonlinear Backstepping control schematic. The asymptotic stability of the resulting closed loop system is guaranteed upon the use of the Lyapunov stability theorem. Due to the complexity and the diversity of the electric control devices, it is difficult to define a general structure for such systems. However, if we consider the elements most commonly encountered in these systems, it is possible to define a general structure of an electric control device.

![Figure 1. Architecture of the control](image)

2. Wind model

One of the necessary conditions to ensure the feasibility of a wind project is that the average power developed by the wind turbines is at least equal to the power demanded by the local network, including the sum of the powers of the receivers supplied with priority.

Therefore, the energy demands imposed on the site, to ensure the feasibility of a project, refer to:

- The wind power density;
- The behavior of the system during random high frequency variations, given by the turbulence component of the wind speed.

The evolution of the wind speed can be modeled from the model established by Van Der Hoven. It contains the spectral components of the long-term and medium-term variations, as well as those due to the turbulence component [3].

We obtain the model of wind speed:
We reduce the temporal scale of wind variation for the smooth running of the simulation. We get the wind speed shown in the figure 2:

![Wind Speed Time Scale Reduced](image)

**Figure 2.** Wind speed time scale reduced

### 3. Wind Turbine Model

We build the model of turbine from the following system of equations [2]:

\[
P_{\text{incident}} = \frac{1}{2} \rho S v^3
\]

\[
P_{\text{extracted}} = \frac{1}{2} \rho S C_p(\lambda, \beta) v^3
\]

\[
\lambda = \frac{\Omega t R}{v}
\]

\[
C_p^{\text{max}}(\lambda, \beta) = \frac{16}{27} = 0.593
\]

\[
C_p(\lambda, \beta) = c_1\left(c_2 + \frac{1}{A} - c_3 \beta - c_4 e^{-\frac{1}{\lambda}} + c_6 \lambda \right)
\]

\[
\frac{1}{A} = \frac{1}{\lambda + 0.08 \beta} = \frac{0.035}{1 + \beta^3}
\]

\[
C_a = \frac{P_{\text{col}}}{\Omega_t} = \frac{1}{2} \rho S C_p(\lambda, \beta) v^3 \cdot \frac{1}{\Omega_t}
\]

\[
J = J_{\text{tur}} + J_{\text{g}}
\]

\[
J \frac{d\Omega_{\text{mech}}}{dt} = C_{\text{mech}} = C_{\text{ar}} - C_{\text{em}} - f \Omega_{\text{mech}}
\]

S: the area swept by the pales of the turbine \([m^2]\)

\(\rho\): the density of the air \((\rho = 1.225 \text{kg/m}^3)\) at atmospheric pressure.

\(v\): wind speed \([\text{m/s}]\).

\(C_p(\lambda, \beta)\) is the power coefficient.

\(\lambda\): the specific speed.
β: the angle of orientation of the blades

$P_{\text{extracted}}$: the power extracted of the turbine.

$\Omega_t$: Rotational speed of the turbine

$C_{\text{ad}}$: Torque on the slow axis (turbine side)

$J_{\text{tr}}$: turbine inertia

$J_g$: inertia of the generator.

$\Omega_m$: Mechanical speed of DFIG

$C_{\text{ar}}$: Aerodynamic torque on the fast axis of the turbine

$c_1=0.5872, c_2=116, c_3=0.4, c_4=5, c_5=12.5, c_6=0.0085$

4. DFIG Model

We choose a dual feed asynchronous machine in order to allow an optimal production of electricity whatever the conditions of wind and speed of the wind turbine [4].

Using the d-q reference The Power equations DFIG can be written as follows [2]:

\[
\begin{cases}
\dot{v}_{ds} = R_s i_{ds} + \frac{d}{dt} \phi_{ds} - \omega_r \phi_{qs} \\
\dot{v}_{qs} = R_s i_{qs} + \frac{d}{dt} \phi_{qs} + \omega_r \phi_{ds} \\
\dot{v}_{dr} = R_s i_{dr} + \frac{d}{dt} \phi_{dr} - \omega_r \phi_{qr} \\
\dot{v}_{qr} = R_s i_{qr} + \frac{d}{dt} \phi_{qr} + \omega_r \phi_{dr}
\end{cases}
\]

\[\omega_r = \omega_m - P \Omega \]

With

\[
\begin{align*}
\phi_{ds} &= L_s i_{ds} + M i_{dr} \\
\phi_{qs} &= L_s i_{qs} + M i_{qr} \\
\phi_{dr} &= L_s i_{dr} + M i_{ds} \\
\phi_{qr} &= L_s i_{qr} + M i_{qs} \\
L_s &= l_s - M_r, \quad L_r = l_r - M_r
\end{align*}
\]

$L_s$, $L_r$: Cyclic inductances of stator and rotor phase;
\( l_s, l_r: \) Inductances of stator and rotor phase;
\( M_s, M_r: \) Mutual inductances between stator and rotor phases respectively;
\( M: \) Maximum mutual inductance between stator and rotor stage.

The electromagnetic torque of the DFIG is written as:

\[
C_{em} = P(\phi_{ds}i_{qs} - \phi_{qs}i_{ds})
\]  
(12)

\( P \) is the number of pole pairs of the DFIG.

The active and reactive powers stator and rotor of the DFIG are written as follows:

\[
\begin{align*}
P_s &= v_{ds}i_{ds} + v_{qr}i_{qs} \\
Q_s &= v_{qr}i_{ds} - v_{ds}i_{qs} \\
P_r &= v_{dr}i_{dr} + v_{qr}i_{qr} \\
Q_r &= v_{qr}i_{dr} - v_{dr}i_{qr}
\end{align*}
\]  
(13)

The active and reactive powers stator and rotor of the DFIG are written as follows:

\[
\begin{align*}
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Q_s &= v_{qr}i_{ds} - v_{ds}i_{qs} \\
P_r &= v_{dr}i_{dr} + v_{qr}i_{qr} \\
Q_r &= v_{qr}i_{dr} - v_{dr}i_{qr}
\end{align*}
\]

Figure 4. DFIG model

5. Backstepping control

The main objective of controlling the rotor side converter is to operate the wind turbine almost at the nominal power. For this, it is necessary to control the active and reactive powers of stator by calculating and controlling the rotor’s voltages. According to the electrical equation of the DFIG, we can calculate the following expressions of the instantaneous variations of the reactive and active powers of the stator [5]:

\[
\begin{align*}
\frac{dP_s}{dt} &= \frac{3}{2} \left[ \frac{dV_{ad}}{dt} I_{ad} + \frac{dI_{ad}}{dt} V_{ad} + \frac{dV_{sq}}{dt} I_{sq} + \frac{dI_{sq}}{dt} V_{sq} \right] \\
\frac{dQ_s}{dt} &= \frac{3}{2} \left[ \frac{dV_{ad}}{dt} I_{ad} + \frac{dI_{ad}}{dt} V_{ad} - \frac{dV_{sq}}{dt} I_{sq} - \frac{dI_{sq}}{dt} V_{sq} \right]
\end{align*}
\]  
(13)

The instantaneous stator current variations can be expressed with the following equations:
\[
\begin{align*}
\frac{dV_{sd}}{dt} &= w_s V_s \cos (w_s t) = w_s V_{ssd} \\
\frac{dV_{sq}}{dt} &= -w_s V_s \sin (w_s t) = -w_s V_{ssq}
\end{align*}
\]

With:
\[
\begin{align*}
V_{sd} &= V_s \sin (w_s t) \\
V_{sq} &= V_s \cos (w_s t + \pi/2) = V_s \cos (w_s t)
\end{align*}
\]

So, the study of stability of the system is characterized by the state vector \([X]\) and the control variable \([U]\):
\[
[X] = [P_r, Q_r, \Omega]^T : \text{The state vector.} \\
[U] = [v_{sd}, v_{sq}]^T : \text{The control variable.}
\]

The Lyapunov function is dividing in two steps, one for the control of the speed and the other for the control of the powers.

- Backstepping controller speed

The first step of the Backstepping control defines the error of the state variable by the following calculation:
\[
e_\Omega = \Omega_{\text{ref}} - \Omega
\]

Its derivative gives:
\[
\dot{e}_\Omega = \frac{de_\Omega}{dt} = \dot{\Omega}_{\text{ref}} - \dot{\Omega}
\]

It results:
\[
\dot{\Omega} = \Omega_{\text{ref}} - \frac{p}{J V_s} \phi_{\text{sd}} P_r + \frac{p}{J V_s} \phi_{\text{sq}} Q_r - \frac{1}{J} T_w
\]

Subsequently, we define the Lyapunov function by the form:
\[
V_i = \frac{1}{2} (e_\Omega^2)
\]

Its derivative gives:
\[
\dot{V}_i = e_\Omega \dot{e}_\Omega = e_\Omega \dot{\Omega}_{\text{ref}} - \frac{p}{J V_s} \phi_{\text{sd}} \dot{P}_r + \frac{p}{J V_s} \phi_{\text{sq}} \dot{Q}_r - \frac{1}{J} \dot{T}_w
\]

We use the Backstepping design method to ensure the stability of the sub-system. For this, we need to make the equation (13) negative, we consider the active and reactive powers as virtual inputs of our system and we define the following equations as:
\[
\begin{align*}
\dot{P}_{\text{ref}} &= \frac{1}{p} \left( K_{\Omega} e_\Omega + \frac{p}{J V_s} \phi_{\text{sd}} \Omega_{\text{ref}} - \frac{1}{J} \Omega \right) \\
\dot{Q}_{\text{ref}} &= \frac{1}{p} \left( K_{\Omega} e_\Omega + \frac{p}{J V_s} \phi_{\text{sq}} \Omega_{\text{ref}} - \frac{1}{J} \Omega \right)
\end{align*}
\]

With: \(K_{\Omega} > 0\).

We substitute equation (15) in the derivative of the Lyapunov function equation \(V_i\) and we assume that \(\Omega_{\text{ref}}\) is constant. As a result, we have the negativity of the function:
\[
\dot{V}_i = -K_{\Omega} e_\Omega^2 \leq 0
\]

- Backstepping Controller power

The objective of the section is to control the active and reactive powers of stator by calculating and controlling the rotor’s voltages. For this, we define the following errors:
\[
\begin{align*}
\epsilon_P &= P_{\text{ref}} - P_r \\
\epsilon_Q &= Q_{\text{ref}} - Q_r
\end{align*}
\]

their derivatives are:
\[
\begin{align*}
\dot{\epsilon}_P &= \dot{P}_{\text{ref}} - \dot{P}_r \\
\dot{\epsilon}_Q &= \dot{Q}_{\text{ref}} - \dot{Q}_r
\end{align*}
\]
The control’s laws of real machine are $V_{rd}$ and $V_{rq}$. To analyze the stability of this system, we define a new Lyapunov function final $V_2$ given by the following form:

$$V_2 = \frac{1}{2}(e_\alpha^2 + e_\beta^2 + e_\vartheta^2)$$  \hspace{1cm} (26)

The result of the derivative of the Lyapunov function is:

$$V'_2 = -K_\alpha e_\alpha - K_\beta e_\beta - K_\vartheta e_\vartheta + e_\alpha \left( K_\alpha e_\alpha - \frac{p}{J_{sv}} \varphi_\alpha P + \frac{p}{J_{sv}} \varphi_\beta Q - \frac{1}{J} L \right) +$$

$$+ e_\beta \left( K_\beta e_\beta - \frac{3}{2\alpha L_s L_{q}} \right) \left( \frac{3}{2} (R_s L_{q} + R_q L_s) |P| + \omega Q \right) + e_\vartheta \left( K_\vartheta e_\vartheta - \frac{3}{2\alpha L_s L_{q}} \right) \left( \frac{3}{2} (R_s L_{q} + R_q L_s) |Q| + \omega P \right)$$  \hspace{1cm} (27)

With: $K_\alpha > 0$, $K_\beta > 0$ and $K_\vartheta > 0$.

The expressions of the control voltages $V_{rq}$ and $V_{rd}$ are extracted from equation (21):

$$V_{rd} = -\frac{1}{V_{sw}} \left( M \left( -\frac{2}{3} \sigma L_s L_{q} \right) \left( K_\alpha e_\alpha - \omega Q \right) \right)$$  \hspace{1cm} (28)

$$V_{rq} = \frac{1}{V_{sw} M} \left( -\frac{2}{3} \sigma L_s L_{q} \right) \left( K_\beta e_\beta + \omega P \right)$$

Equation (29) implies the negativity of the Lyapunov function $V_2$ as following:

$$V'_2 = -K_\alpha e_\alpha - K_\beta e_\beta - K_\vartheta e_\vartheta \leq 0$$  \hspace{1cm} (29)

6. Simulation and Results

Applying the backstepping control, we obtain the following results:

![Figure 5. Statoric current of DFIG](image_url)
The results presented here were obtained from a modeling in MATLAB SIMULINK. In figure 5 we observe that the currents at the outputs of the system are purely sinusoidal with a constant frequency. We also observe in figure 6 that the active power is negative because it sent to the electrical grid, we notice that the reactive power sent to the grid is near zero in figure 7, the system is more robust.

7. Conclusion

In this work, we present a model and simulation of a wind turbine system using a variable wind regime. Simulations results are shown interesting obtained control performances of the DFIG. The simulation of the wind speed was developed with a modeling algorithm realized from measurement files. By breaking it down into a slow and turbulence component.
References:

[1] Mahmoudi H, El Ghamrasni M, Lagroui A and Bossoufi B 2015 *Journal of theoretical and applied information technology* **82** 321.

[2] Bossoufi B, Karim M, Lagrioui A, Taoussi M and Derouich A 2015 *Renewable Energy Journal* **81** 903.

[3] Ackermann T and Soder L 2002 *Renewable and Sustainable Energy Reviews* **6** 67.

[4] Ihedrane Y, El Bekkali C and Bossoffi B 2017 *International Journal of Power Electronics and Drive System* **8** 444.

[5] Bossoufi B, Ionita S, Alami Arroussi H, EL Ghamrasni M and Ihedrane Y 2017 *International Journal of Automation and Control* **11** 451.

[6] Lamnadi M, Trihi M, Bossoufi B and Boulezhar A 2016 *International Journal of Power Electronics and Drive System* **7** 241.

[7] Alami Aroussi H, Ziani El.M and Bossoufi B 2016 *Journal of Theoretical and Applied Information Technology* **83** 426.

[8] Yung-Tsai W 2016 *Journal of Elsevier of Renewable Energy* **94** 383.

[9] Bossoufi B, Karim M, Ionita S and Lagrioui A 2012 *Journal of Journal of Electrical Systems* **8** 236.

[10] Sarwar Kaloi G, Wanga J and Hussain Baloch M 2016 *Journal of Elsevier of Energy Reports* **2** 194.