Sensorless Control of Brushless Doubly-fed Generator Using Luenberger Observer Based Wind Energy Conversion Systems

Hicham Serhoud, Djilani Benattous
Department of Electrical Engineering, University of EL-Oued, Algeria

ABSTRACT
This paper investigates the use of Luenberger observer for sensorless power control of brushless double fed induction machine (BDFM) in wind energy conversion systems, the control strategy for flexible power flow control is developed by applying flux-oriented vector control (technique). In order to estimate the rotor speed, an adaptive algorithm based on Lyapunov stability theory will be design. Finally, the analyzed and simulation results in MATLAB/ Simulink platform confirmed the good dynamic performance of this new sensorless control for BDFG based variable speed wind turbines.

1. INTRODUCTION
In recent years, the electrical machine has expanded considerably with the development of power electronics and data processing, in this way a many researchers developed the difference observation, for estimating the rotor speed and parameters identification of electrical machine. The Brushless double fed induction motor is one of the most important ac machines used because of its low cost and high reliability [1].

Sensorless control has been successfully applied to the BDFG based on an extended Kalman filter observer [2]. The rotor speed estimator is designed by a phase locked loop ignoring the power winding resistance [3], and MRAS observer scheme based on the stator current of the control winding (CW) yessed the a phase locked loop (PLL) is proposed by [3].

The Luenberger observer is a well-known method for the sensorless control of cage induction machines, there are few reports related to the use of Luenberger observer for sensorless control of DFIG [4-6], when has been proved to be a good compromise between accuracy and complexity, and is able to work at wide speed range [7].

This paper discussed of a novel sensorless vector control of BDFG using Luenberger observer (LO), the error between the observed value and the true value considered the rotor speed, based on Lypunov's stability theory. General scheme of Luenberger observer is shown in Figure 1.
2. THE MATHEMATICAL MODE OF BDFM

The BDFM is normally operated in the synchronous mode and the natural synchronous speed equal to:

\[ \omega_s = \frac{\omega_p \pm \omega_c}{P_p + P_c} \]  

(1)

\( \omega_p \) and \( \omega_c \) are the angular frequency of power winding and control winding and \( P_p \) and \( P_c \) are the number of pole pairs of power winding and control winding.

The mathematical model of BDFG with d-q reference (PW) is able to be expressed as [1], [8], [9]:

\[ V_p = R_p i_p + \frac{d\psi_p}{dt} + j\omega_p \psi_p \]  

(2)

\[ V_c = R_c i_c + \frac{d\psi_c}{dt} + j(\omega_p - (P_p + P_c)\omega_c)\psi_c \]  

(3)

\[ V_i = R_i i_i + \frac{d\psi_i}{dt} + j(\omega_p - P_c\omega_c)\psi_i \]  

(4)

And the flux equations are given as:

\[ \psi_p = L_p i_p + M_p i_e \]  

(5)

\[ \psi_c = L_c i_c + M_c i_i \]  

(6)

\[ \psi_i = L_i i_i + M_e i_c + M_p i_p \]  

(7)

The electromagnetic torque of BDFG is expressed as [3]:

\[ T_e = \frac{3}{2} P_p M_p \left( i_{qp} i_{uu} - i_{qp} i_{up} \right) - \frac{3}{2} P_c M_c \left( i_{qc} i_{uu} - i_{qc} i_{up} \right) \]  

(8)

The active and reactive powers of BDFM are as follows:

\[ P_p = \frac{3}{2} (V_{qp} i_{qp} + V_{up} i_{up}) \]  

(9)

\[ Q_p = \frac{3}{2} (V_{qp} i_{qp} - V_{up} i_{up}) \]  

(10)
3. VECTOR CONTROL DESIGN FOR BDFG

In this section, the vector control of BDFM will be presented, to achieve regulation of the active and reactive power between the BDFG and the grid [9], [10]. The vector control of BDFM is similar to the principle of classical vector control of DFIM, which it based on annulled the quadrature component of the PW flux, and suppose the $R_p$ is neglected, the Equations (2) and (5) can be written as follow:

$$\begin{align*}
V_{dp} &= 0 \\
V_{qp} &= V_p = \omega_p \psi_p \\
\psi_p &= L_p i_{dp} + M_p i_{dr} \\
0 &= L_p i_{qp} + M_p i_{qr}
\end{align*}$$

(11)

(12)

The rotor currents can be described using the power stator current:

$$\begin{align*}
i_{qr} &= \frac{\psi_p}{M_p} - \frac{L_{dq}}{M_p} i_{dp} \\
i_{dp} &= -\frac{L_{dq}}{M_p} i_{qp}
\end{align*}$$

(13)

3.1. The PW currents regulation

The mathematical mode of BDFG in the steady state given by [11],

$$\begin{align*}
V_{dp} &= R_p i_{dp} - \omega_p L_p i_{dq} - \omega_p M_p i_{qr} \\
V_{qp} &= R_p i_{dq} + \omega_p L_p i_{dp} + \omega_p M_p i_{dr}
\end{align*}$$

(14)

$$\begin{align*}
\frac{s_2}{s_1} V_{dc} &= \frac{s_2}{s_1} R_c i_{dc} - \omega_p L_c i_{qc} - \omega_p M_c i_{qr} \\
\frac{s_2}{s_1} V_{qc} &= \frac{s_2}{s_1} R_c i_{qc} + \omega_p L_c i_{dc} + \omega_p M_c i_{dr}
\end{align*}$$

(15)

$$\begin{align*}
0 &= \frac{1}{s_1} R_c i_{dr} - \omega_p L_c i_{qr} - \omega_p M_c i_{qc} - \omega_p M_p i_{qr} \\
0 &= \frac{1}{s_1} R_c i_{qr} + \omega_p L_c i_{dr} + \omega_p M_c i_{dc} + \omega_p M_p i_{dp}
\end{align*}$$

(16)

$s_1$, $s_2$ are the slips, which can be expressed as:

$$s_1 = \frac{\omega_p - \omega}{\omega_p}, \quad s_2 = \frac{\omega_p - \omega}{\omega_c}$$

(17)

Used (14), (15), (16), (11), (13), The control winding can be expressed as:

$$\begin{align*}
i_{dc} &= \left(\frac{L_p L_p - M_p}{M_p M_c}\right) i_{dp} - \frac{\psi_p L_p}{M_p \omega_p M_c} i_{qp} + \frac{R_p L_p}{M_p M_c \omega_p s_1} i_{qp} \\
i_{qc} &= \left(\frac{L_p L_p - M_p}{M_p M_c}\right) i_{qp} + \frac{R_p \psi_p}{M_p M_c \omega_p s_1} - \frac{R_p L_p}{M_p M_c \omega_p s_1} i_{qp}
\end{align*}$$

(18)

(19)
3.2. The CW currents regulation

Used the Equations (3), (6), (18), (19), the CW voltage can be regulation by the CW currents as:

\[ V_{dc} = R_c i_{dc} + \left( \frac{M_s^2}{L_c} \right) \frac{di_{dc}}{dt} - \frac{M_p R_p L_p}{\omega_p L_p s M_p} \frac{di_{ip}}{dt} - \frac{M_p M_p}{L_c} \frac{di_{ip}}{dt} \]

\[ + (\omega_p - (p_p + p_q) \omega_o)(L_c i_{qc} + M_c \left( \frac{L_{qp}}{M_p} i_{qp} \right)) \]

\[ V_{qc} = R_c i_{qc} + \left( \frac{M_s^2}{L_c} \right) \frac{di_{qc}}{dt} - \frac{M_p R_p L_p}{\omega_p L_p s M_p} \frac{di_{ip}}{dt} - \frac{M_p M_p}{L_c} \frac{di_{ip}}{dt} \]

\[ - (\omega_p - (p_p + p_q) \omega_o)(L_c i_{dc} + M_c \left( \frac{L_{qp}}{M_p} i_{qp} \right)) \]  

The third term: \(- (\omega_p - (p_p + p_q) \omega_o)(L_c i_{dc} + M_c \left( \frac{L_{qp}}{M_p} i_{qp} \right))\) shows another cross and the general block control diagram is shown in Figure 2.

![Figure 2. Control scheme for BDFM](image)

4. THE LUENBERGER OBSERVER

Using the six-order model of the Brushless doubly-fed induction machine in fixed stator d-q axis reference frame with PW current, CW current and rotor current components as state variables.

The dynamic model of the BDFM is given in (d-q) reference frame that is used in LO for state observation, the model is given [12-18]:

\[
\begin{bmatrix}
X = AX + Bu \\
Y = CX
\end{bmatrix}
\]

\[ u = \begin{bmatrix} V_{pd} & V_{pq} & V_{cd} & V_{cq} & 0 & 0 \end{bmatrix}^T \]

The state vector is

\[ X = \begin{bmatrix} i_{pd} & i_{pq} & i_{cd} & i_{cq} & i_{id} & i_{iq} \end{bmatrix}^T \]

The system matrix A, the input matrix B and the output matrix C are given as:

\[ C = \begin{bmatrix}
1 & 0 \\
0 & 1 \\
0 & 0 \\
0 & 0 \\
0 & 0 \\
0 & 0
\end{bmatrix}, \quad B = \begin{bmatrix} \text{inv(AL)} \end{bmatrix}, \quad A = \begin{bmatrix} \text{inv(AL)} \ A \end{bmatrix} \]
Where:
\[
\begin{bmatrix}
L_p & 0 & 0 & M_p & 0 \\
0 & L_p & 0 & 0 & M_p \\
0 & 0 & L_c & 0 & M_c \\
0 & 0 & 0 & L_c & 0 \\
M_p & 0 & M_c & 0 & L_r \\
0 & M_p & 0 & M_c & 0 \\
\end{bmatrix}
\]

\[
\begin{bmatrix}
R_p & -\omega_0 L_p & 0 & 0 & 0 & -\omega_0 M_p \\
\omega_0 L_p & R_p & 0 & 0 & \omega_0 M_p & 0 \\
0 & 0 & R_c & -\omega_0 L_c & 0 & -\omega_2 M_c \\
0 & 0 & \omega_2 L_c & R_c & \omega_2 M_c & 0 \\
0 & -\omega_3 M_p & 0 & -\omega_3 M_c & R_r & -\omega_1 L_r \\
\omega_3 M_p & 0 & \omega_3 M_c & 0 & \omega_3 L_r & R_r \\
\end{bmatrix}
\]

Where:
\[
\begin{align*}
\omega_2 &= \omega_p - \left(\frac{P_p}{P_r}\right)\omega_f \\
\omega_3 &= \omega_p - P_p \omega_f
\end{align*}
\]

The Luenberger observer which estimates the all stator currents will be designed using the BDFM model.

\[
\hat{\mathbf{x}} = A \hat{\mathbf{x}} + B \mathbf{u} + L(\mathbf{y} - C \hat{\mathbf{x}})
\]

\(L\): is the observer gain matrix

\[
\hat{\mathbf{x}} = \left( A - LC \right) \hat{\mathbf{x}} + B \mathbf{u} + L \mathbf{y}
\]

The Luenberger matrix gain \(L\) is chosen so that the poles of the characteristic matrix \(AL = A + LC\) to be stable. So, all eigenvalues of \(AL\) should have negative real parts.

The poles can be placed by solving the differential equation, thus the matrix gain \(L\) can be calculated by the function (PLACE) Pole placement technique in MATLAB.

4.1. Estimation of the rotor speed

The estimation error of the state variable giving by:

\[
\Delta \mathbf{A} = (A - \hat{A}) \mathbf{X}
\]

\[
\Delta \mathbf{A} = (A - \hat{A}) \mathbf{X}
\]

\[
\Delta \mathbf{A} = (A - \hat{A})
\]

Assuming that \(\Delta \omega_r = \omega_r - \hat{\omega}_r\)
The elements of matric are showed in the appendix. 

The speed observer can be constructed based on Lyapunov’s stability theory. Assuming that the Lyapunov function is defined as:

\[
V = E^T E + \frac{1}{kL} \Delta \omega r^2
\]

(27)

Where:

\[
E = \begin{bmatrix}
i_{pd} - \hat{i}_{pd} \\
i_{dq} - \hat{i}_{dq} \\
0 \\
0 \\
0 \\
0 \\
\end{bmatrix}
\]

The application of the general adaptation mechanism

\[
\hat{\omega} r = k \int E^T \Delta A X dt
\]

(28)

Where:

\[
\hat{\omega} r = k \int e_{pq} (-a1 \hat{i}_{pq} + a2 \hat{i}_{iq} + a3 \hat{i}_{dq}) + e_{pq} (a1 \hat{i}_{pd} - a2 \hat{i}_{qd} - a3 \hat{i}_{dq}) dt
\]

(29)

Which means:

\[
\hat{\omega} r = k \int a2 (e_{pq} \hat{i}_{iq} - e_{pq} \hat{i}_{id}) + a1 (e_{pq} \hat{i}_{dp} - e_{pq} \hat{i}_{dp}) + a3 (e_{pq} \hat{i}_{dq} - e_{pq} \hat{i}_{dq}) dt
\]

(30)

We can neglect the values of \(-a1, a3\) because its low values compared to \(a2\), the adaptation mechanism becomes:

\[
\hat{\omega} r = k \int a2 (e_{pq} \hat{i}_{iq} - e_{pq} \hat{i}_{id}) dt
\]

(31)

Where \(k\) is a positive constant.

Usually the following proportional and integral adaptation mechanism, in order to improve the response of the rotor speed estimation.

\[
\hat{\omega} r = Kp (e_{pq} \hat{i}_{iq} - e_{pq} \hat{i}_{id}) + Ki \int (e_{pq} \hat{i}_{iq} - e_{pq} \hat{i}_{id})
\]

(32)

5. WIND TURBINE MODEL

In this work a horizontal axis wind turbine is used, which the mechanical power of the wind can be derived as:
\[ P = \frac{\pi}{2} C_p R^2 \rho v^3 \]  

(33)

Where \( \rho \) = air density, \( R \) = radius of Blades, \( v \) = wind speed and \( C_p \) = power coefficient which can be derived as:

\[ C_p(\lambda, \beta) = 0.5176 \left( \frac{116}{\lambda_i} - 0.4 \beta - 5\right)e^{\frac{21}{\lambda_i}} + 0.0068 \lambda \]  

(34)

Where:

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

(35)

The power conversion coefficient defined as:

\[ \lambda = \frac{\omega R}{v} \]  

(36)

Where \( \omega \) = the turbine rotor speed.

The wind turbine is normally characterized between \( C_p \) and \( \gamma \) for the given values of pitch angle \( (\beta) \) is as illustrated in Figure 3.

![Figure 3. Wind turbine generator \( C_p - \lambda \) characteristics](image)

5.1. Pitch angle controller design

The advantage of pitch angle control is more efficiency in low wind, small variation in the pitch angle can give strongly influenced by the blade respect to the direction of the wind or to the plane of rotation.

Used the wind velocity \( v \), the reference rotor speed for extracting the MPPT is obtained by:

\[ \omega_m = \frac{G_{\text{opt}} v}{R} \]  

(37)

The gearboxes in a typical wind turbine increase the speed of the generator by the relation

\[ \omega_m = G_0 \omega_i \]  

(38)

The pitch controller is employed to regulation the rotor speed at the maximum used the rotor speed measure and the reference speed, which can find by the Equation (36).

A simple proportional-integral (PI) controller is used to regulation, this regulator followed by limitation to fixing the angle to between the maximum and the minimum angle as shown in Figure 4.
6. SIMULATION RESULTS

The senseless control developed has been implemented in a MATLAB 7.0 simulation. The BDFM used in this simulation model is 3Y-3Y connected and its stator winding is 2-6 poles. The machine parameters presented by J. Poza [3] are used in this simulation as showed in table 1.

To verify the state estimation performance extensive simulation tests were carried out to compare the senseless control under different wind speed.

A step change in wind speed is simulated in Figure 6, the wind speed is start at 5m/S, at 7second, the wind speed suddenly become 7m/S.
Figure 10. Power winding active power

Figure 11. Phase power winding current

Figure 12. Phase power winding current

Figure 13. Phase control winding current

Figure 14. DC voltage

Figure 15. Blade pitch angle

Figure 16. Power coefficient Cp variation

Figure 17. Power coefficient Cp variation

Figure 18. Zoom of phase PW current and voltage

Figure 19. Power coefficient Cp variation
7. CONCLUSION

In this study we presented in detail sensorless control strategy for (BDFG) in variable wind turbine generators used Luenberger observer, a vector control strategy using power winding flux-oriented scheme is proposed to assess the decoupage of active and the reactive power, the observer gains are selected by the pole placement method and the stability of the observer is analyzed using the Lyapunov theory. The simulation results show effectiveness of the optimal power sensorless operating methods in low and high wind speed, we can conclude the MPPT senseless operating methods proposed only by measuring phase voltages and currents therefore it can improve the control system dependability and energy conversion competence efficiency.

Appendix

Table 1 The Electrical Parameter of BDFG

| Parameter          | PW   | CW   | Rotor |
|--------------------|------|------|-------|
| Resistance (Ω)     | $\rho_R = 1.732$ | $\rho_C = 1.079$ | $\rho_L = 0.473$ |
| self-inductance (mH) | $L_R = 714.8$ | $L_C = 121.7$ | $L_L = 132.6$ |
| Mutual inductance (mH) | $M_{PW} = 242.1$ | $M_{CW} = 59.8$ |

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BIOGRAPHIES OF AUTHORS

Hicham Serhoud was born on Mar. 30, 1983 in El Oued Algeria. He received Master’s degree in electrical engineering from Batna University, Algeria, in 2009. He received the PhD degree in electrical engineering from Mohamed Kheider University of Biskra (Algeria), in 2015. He is currently associate professor at El Oued University Algeria in Electrical Engineering. His fields of interest are control of Brushless doubly fed induction machines, and double fed induction machines, modelling and control of wind turbines, sensorless control of electrical machine and the control technology of photovoltaic system.

Djilani Benattous was born on May 24, 1959 in El Oued Algeria. He received his Engineer degree in Electrotechnics from Polytechnic National Institute Algiers Algeria in 1984. He got Msc degree in Power Systems from UMIST England in 1987. In 2000, he received his doctorat d'état (PHD from Batna university Algeria). He is currently associate professor at El Oued university Algeria in Electrical Engineering. His research interests in Planning and Economic of Electric Energy System, Optimization Theory and its applications and he also investigated questions related with Electrical Drives and Process Control.