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

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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.

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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.

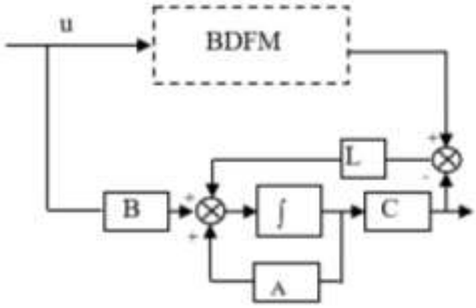

Figure 1. General scheme of Luenberger observer for speed estimation of BDFG

2. THE MATHEMATICAL MODE OF BDFM

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

$$\omega_r = \frac{\omega_p \pm \omega_c}{p_p + p_c} \quad (1)$$

ω_p and ω_c are the angular frequency of power winding and control winding and Pp and Pc 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]:

$$V_p = R_p.i_p + \frac{d\psi_p}{dt} + j\omega_p\psi_p \quad (2)$$

$$V_c = R_c.i_c + \frac{d\psi_c}{dt} + j(\omega_p - (P_p + P_c)\omega_r)\psi_c \quad (3)$$

$$V_r = R_r.i_r + \frac{d\psi_r}{dt} + j(\omega_p - P_p\omega_r)\psi_r \quad (4)$$

And the flux equations are given as:

$$\psi_p = L_p i_p + M_p i_r \quad (5)$$

$$\psi_c = L_c i_c + M_c i_r \quad (6)$$

$$\psi_r = L_r i_r + M_c i_c + M_p i_p \quad (7)$$

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

$$T_e = \frac{3}{2}P_p M_p (i_{qp} i_{dr} - i_{dp} i_{qr}) - \frac{3}{2}P_c M_c (i_{qc} i_{dr} - i_{dc} i_{qr}) \quad (8)$$

The active and reactive powers of BDFM are as follows:

$$P_p = \frac{3}{2}(V_{dp} i_{dp} + V_{qp} i_{qp}) \quad (9)$$

$$Q_p = \frac{3}{2}(V_{qp} i_{dp} - V_{dp} i_{dp}) \quad (10)$$

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 of the principle of classical vector control of DFIM, which it based of 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:

$$\begin{cases} V_{dp} = 0 \\ V_{qp} = V_P = \omega_p \psi_P \end{cases} \tag{11}$$

$$\begin{cases} \psi_P = L_p i_{dp} + M_p i_{dr} \\ 0 = L_p i_{qp} + M_p i_{qr} \end{cases} \tag{12}$$

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

$$\begin{cases} i_{dr} = \dfrac{\psi_P}{M_p} - \dfrac{L_{dp}}{M_p} i_{dp} \\ i_{qr} = -\dfrac{L_{qp}}{M_p} i_{qp} \end{cases} \tag{13}$$

3.1. The PW currents regulation

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

$$\begin{cases} V_{dp} = R_p.i_{dp} - \omega_p.L_p i_{qp} - \omega_p M_p i_{qr} \\ V_{qp} = R_p.i_{qp} + \omega_p.L_p i_{dp} + \omega_p M_p i_{dr} \end{cases} \tag{14}$$

$$\begin{cases} \dfrac{s_2}{s_1} V_{dc} = \dfrac{s_2}{s_1} R_c.i_{dc} - \omega_p L_c i_{qc} - \omega_p M_c i_{qr} \\ \dfrac{s_2}{s_1} V_{qc} = \dfrac{s_2}{s_1} R_c.i_{qc} + \omega_p L_c i_{dc} + \omega_p M_c i_{dr} \end{cases} \tag{15}$$

$$\begin{cases} 0 = \dfrac{1}{s_1} R_r.i_{dr} - \omega_p L_r i_{qr} - \omega_p M_c i_{qc} - \omega_p M_p i_{qp} \\ 0 = \dfrac{1}{s_1} R_r.i_{qr} + \omega_p L_r i_{dr} + \omega_p M_c i_{dc} + \omega_p M_p i_{dp} \end{cases} \tag{16}$$

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

$$s_1 = \frac{\omega_p - P_p \omega_p}{\omega_p}, s_2 = \frac{\omega_c - P_p \omega_p}{\omega_c} \tag{17}$$

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

$$i_{dc} = (\frac{L_r L_p - M_p}{M_p M_c}) i_{dp} - \frac{\psi_p L_r}{M_p \omega_p M_c} + \frac{R_r L_p}{M_p M_c \omega_p s_1} i_{qp} \tag{18}$$

$$i_{qc} = (\frac{L_r L_p - M_p}{M_p M_c}) i_{qp} + \frac{R_r \psi_p}{MpM_c \omega_p s_1} - \frac{R_r L_p}{MpM_c \omega_p s_1} i_{dp} \tag{19}$$

3.2. The CW currents regulation

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

$$V_{dc} = R_c.i_{dc} + (L_c - \frac{M_c^2}{L_r})\frac{di_{dc}}{dt} - \frac{M_c R_r L_p}{\omega_p L_r s_1 M_p}\frac{di_{qp}}{dt} - \frac{M_c M_p}{L_r}\frac{di_{dp}}{dt} + (\omega_p - (P_p + P_c)\omega_r)(L_c i_{qc} + M_c(-\frac{L_{qp}}{M_{p1}} i_{qp})) \tag{20}$$

$$V_{qc} = R_c.i_{qc} + (L_c - \frac{M_c^2}{L_r})\frac{di_{qc}}{dt} - \frac{M_c R_r L_p}{\omega_p L_r s_1 M_p}\frac{di_{dp}}{dt} - \frac{M_p M_c}{L_r}\frac{di_{qp}}{dt} - (\omega_p - (P_p + P_c)\omega_r)(L_c i_{dc} + M_c(\frac{\psi_P}{M_p} - \frac{L_{dp}}{M_p} i_{dp})) \tag{21}$$

The third term: $-(\omega_p - (P_p + P_c)\omega_r)(L_c i_{dc} + M_c(\frac{\psi_P}{M_p} - \frac{L_p}{M_p} i_{dp}))$ Shows another cross and the general block control diagram is shown in Figure 2.

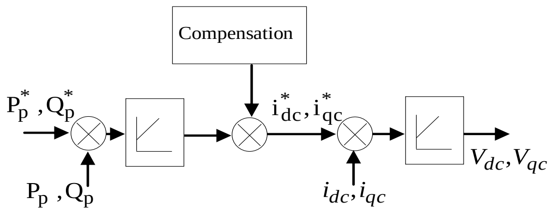

Figure 2. Control scheme for BDFM

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]:

$$\begin{cases} \dot{X} = AX + Bu \\ Y = CX \end{cases} \qquad u = \begin{bmatrix} V_{pd} & V_{pq} & V_{cd} & V_{cq} & 0 & 0 \end{bmatrix}^T \tag{22}$$

The state vector is

$$X = \begin{bmatrix} i_{pd} & i_{pq} & i_{cd} & i_{cq} & i_{rd} & i_{rq} \end{bmatrix}^T$$

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

$$C = \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}, \quad B = \begin{bmatrix} \text{inv(AL)} \end{bmatrix}, \quad A = \begin{bmatrix} \text{-inv(AL)} & \text{AR} \end{bmatrix}$$

Where:

$$AL = [L_p \quad 0 \quad 0 \quad 0 \quad M_p \quad 0$$
$$0 \quad L_p \quad 0 \quad 0 \quad 0 \quad M_p$$
$$0 \quad 0 \quad L_c \quad 0 \quad M_c \quad 0$$
$$0 \quad 0 \quad 0 \quad L_c \quad 0 \quad M_c$$
$$M_p \quad 0 \quad M_c \quad 0 \quad L_r \quad 0,$$
$$0 \quad M_p \quad 0 \quad M_c \quad 0 \quad L_r]$$

$$AR = [\quad R_p \quad -\omega_p L_p \quad 0 \quad 0 \quad 0 \quad -\omega_p M_p$$
$$\omega_p L_p \quad R_p \quad 0 \quad 0 \quad \omega_p M_p \quad 0$$
$$0 \quad 0 \quad R_c \quad -\omega_2 Lc \quad 0 \quad -\omega_2 M_c$$
$$0 \quad 0 \quad \omega_2 L_c \quad R_c \quad \omega_2 M_c \quad 0$$
$$0 \quad -\omega_3 M_p \quad 0 \quad -\omega_3 M_c \quad R_r \quad -\omega_3 L_r$$
$$\omega_3 M_p \quad 0 \quad \omega_3 M_c \quad 0 \quad \omega_3 L_r \quad R_r\ ]$$

Where:

$$\omega_2 = \omega_p - (P_p + P_c)\omega_r$$
$$\omega_3 = \omega_p - P_p \omega_r$$

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

$$\dot{\hat{X}} = A\hat{X} + BU + L(Y - C\hat{X}) \quad (23)$$

L: is the observer gain matrix

$$\dot{\hat{X}} = \left(A - LC\right)\hat{X} + BU + LY \quad (24)$$

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 MATLB.

4.1. Estimation of the rotor speed

The estimation error of the state variable giving by:

$$\dot{E} = (A - LC)E + \Delta A\hat{X} \quad (25)$$

ΔA is the error between the two matrices as being exclusively caused by the error between the real and the estimated speed

$$\Delta A = (A - \hat{A}) \quad (26)$$

Assuming that $\Delta\omega r = \omega r - \hat{\omega} r$

$$\Delta A = \Delta\omega r\begin{bmatrix} 0 & -a1 & 0 & a2 & 0 & a3 \\ a1 & 0 & -a2 & 0 & -a3 & 0 \\ 0 & -a4 & 0 & a5 & 0 & a6 \\ a4 & 0 & -a5 & 0 & -a6 & 0 \\ 0 & a7 & 0 & -a8 & 0 & a9 \\ -a7 & 0 & a8 & 0 & -a9 & 0 \end{bmatrix}$$

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:

$$V = E^T E + \frac{1}{kL}\Delta\omega r^2 \tag{27}$$

Where:

$$E = \begin{bmatrix} i_{pd} - i_{pd} \\ i_{dpd} - i_{pd} \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix},$$

Where kL is a positive constant, Assuming that $\Delta\omega r = \omega r - \hat{\omega r}$
The application of the general adaptation mechanism

$$\hat{\omega r} = k\int E^T \Delta A\, \hat{X}\, dt \tag{28}$$

Where:

$$\hat{\omega r} = k\int e_{pd}(-a1\,\hat{i}_{pq} + a2\,\hat{i}_{cq} + a3\,\hat{i}_{rq}) + e_{pq}(a1\,\hat{i}_{pd} - a2\,\hat{i}_{cd} - a3\,\hat{i}_{rd})\, dt \tag{29}$$

Which means:

$$\hat{\omega r} = k\int a2(e_{pd}\,\hat{i}_{cq} - e_{pq}\,\hat{i}_{cd}) + a1(e_{pq}\,\hat{i}_{pd} - e_{pd}\,\hat{i}_{pq}) + a3(e_{pd}\,\hat{i}_{rq} - e_{pq}\,\hat{i}_{rd})dt \tag{30}$$

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

$$\hat{\omega r} = k\int a2(e_{pd}\,\hat{i}_{cq} - e_{pq}\,\hat{i}_{cd})dt \tag{31}$$

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.

$$\hat{\omega r} = Kp(e_{pd}\,\hat{i}_{cq} - e_{cq}\,\hat{i}_{cd}) + Ki\int(e_{pd}\,\hat{i}_{cq} - e_{cq}\,\hat{i}_{cd}) \tag{32}$$

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:

$$P = \frac{\pi}{2} C_p R^2 \rho v^3 \tag{33}$$

Where ρ =air density, R=radius of Blades, ν =wind speed and C_p=power coefficient which can be derived as:

$$C_p(\lambda,\beta) = 0.5176\,(\frac{116}{\lambda_i} - 0.4\beta - 5)e^{-\frac{21}{\lambda_i}} + 0.0068\,\lambda \tag{34}$$

Where:

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \tag{35}$$

The power conversion coefficient defined as:

$$\lambda = \frac{\omega_t R}{\nu} \tag{36}$$

Where ω_t =the turbine rotor speed.

The wind turbine is normally characterized between Cp and γ for the given values of pitch angle (β°) is as illustrated in Figure 3.

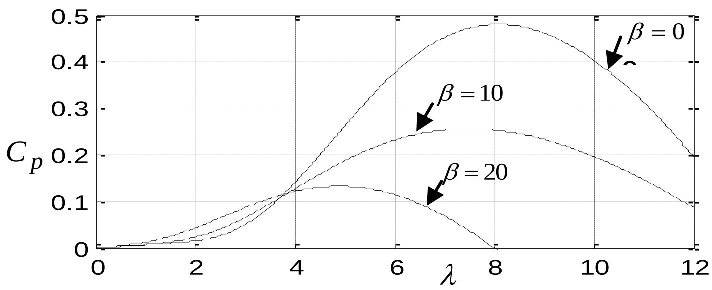

Figure 3. Wind turbine generator $C_p - \lambda$ characteristics

5.1. Pitch angle controller design

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

Used the wind velocity υ, the reference rotor speed for extracting the MPPT is obtained by:

$$\omega_m = \frac{G\lambda_{opt}\nu}{R} \tag{37}$$

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

$$\omega_m = G\omega_t \tag{38}$$

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.

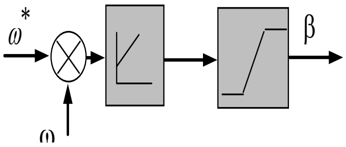

Figure 4. Pitch angle controller

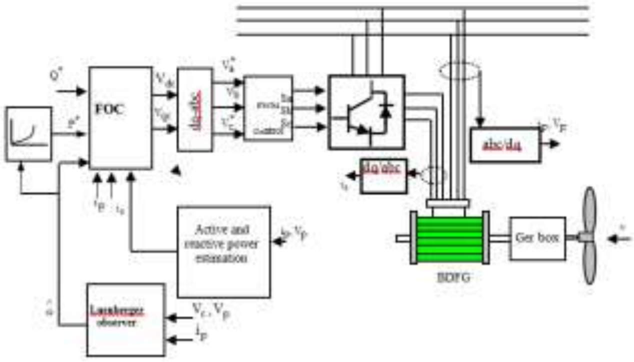

Figure 5. Sensorless vector control of the BDFM using Luenberger observer

6. SIMULATION RESULTS

The senseless control developed has been implemented in a MATLB 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 sensouless 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.

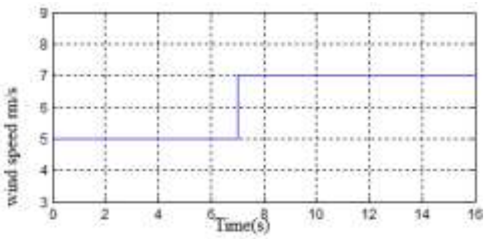

Figure 6. Wind speed

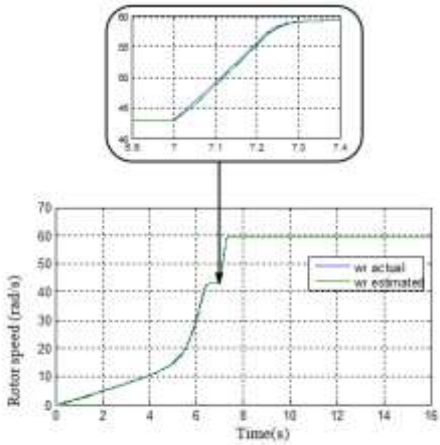

Figure 7. Zoom of actual and estimated rotor speed

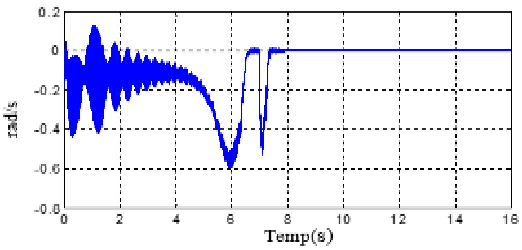

Figure 8. Error of rotor speed

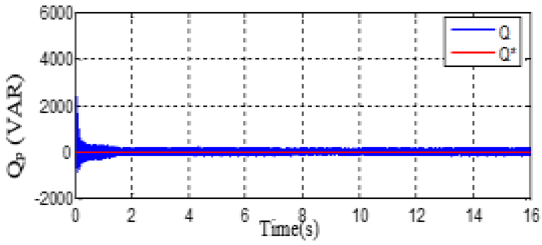

Figure 9. Power winding reactive power

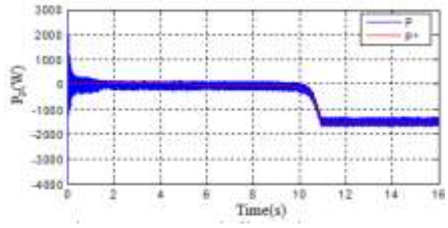

Figure 10. Power winding active power

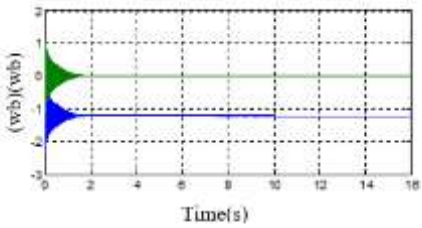

Figure 11. Phase power winding current

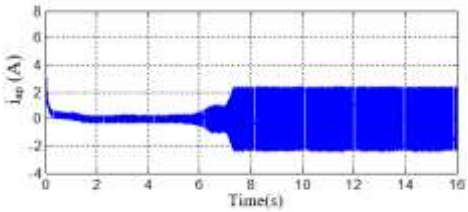

Figure 12. Phase power winding current

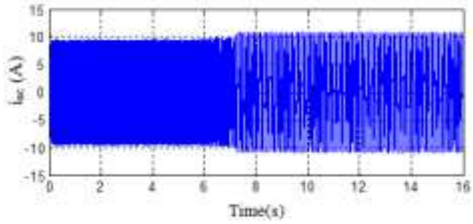

Figure13. Phase control winding current

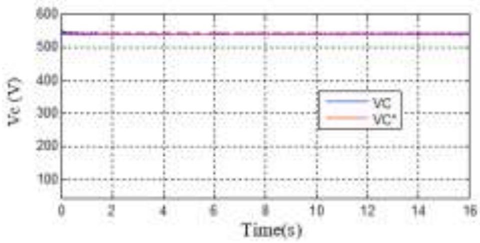

Figure 14. DC voltage

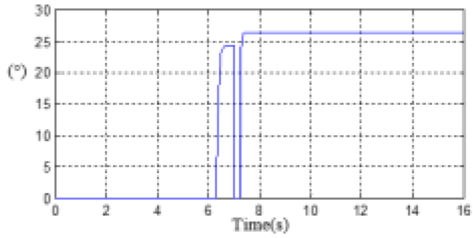

Figure 15. Blade pitch angle

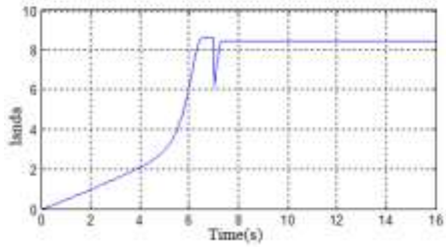

Figure 16. Power coefficient Cp variation

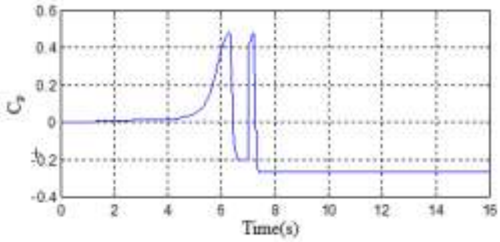

Figure 17. Power coefficient Cp variation

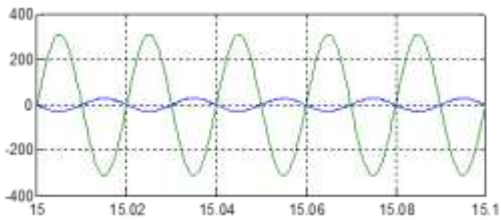

Figure 18. Zoom of phase PW current and voltage

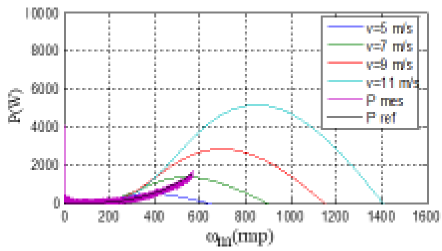

Figure 19. Power coefficient Cp variation

7. CONCLUSION

In this study we presented in detail sensorless control strategy for (BDFG) in variable speed 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

	PW	CW	Rotor
Resistance (Ω)	R_p =1.732	R_c =1.079	R_r = 0.473
self-inductance (mH)	L_p =714.8	L_c =121.7	L_r =132.6
Mutual inductance (mH)	M_p =242.1	M_c =59.8	

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