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Control by Back Stepping of the DFIG Used in the Wind Turbine

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***Abstract*— This paper presents the modeling and control back stepping of Double-Fed Induction Generator (DFIG) integrated into a wind energy system. The goal is to apply this technique to control independently the active and reactive power generated by DFIG. Finally, the system performance was tested and compared by simulation in terms of following instructions and robustness with respect to parametric variations of the DFIG.**

***Keywords*— Back stepping, Control, DFIG, Wind turbine**

I. INTRODUCTION

The development and use of renewable energy have experienced strong growth in recent years. Among these energy sources, the wind one has a fairly important potential; it is not powerful enough to replace the existing sources, but still can compensate for the increasing reduction of demand. There is a new solution using alternating machine operating in a rather unusual way; it is the double-fed induction machine (DFIG) [1].

DFIG is very popular because it has certain advantages over all the other variable speed; its use in electromechanical conversion chain as a wind turbine or engine has grown dramatically in recent years [2].Indeed, the energy converter used to straighten and curl alternating currents of the rotor has a fractional power rating of the generator [3], which reduces its cost relative to competing topologies.

In this context, several robust control methods of DFIG appeared; among them back stepping control is one of them. This technique is a relatively new control method for nonlinear systems. It allows sequentially and systematically, by the choice of a Lyapunov function, to determine the system's control law. Its principle is to establish in a constructive manner the control law of the nonlinear system by considering some state variables as virtual Drives and develop intermediate control laws [12].

II. BACKSTEPPING CONTROL

A. Historical

The back stepping was developed by Kanellakopoulos (1991) and inspired by the work of Feurer& Morse (1978) on one hand and Tsinias (1989) and Kokotovit& Sussmann (1989) on the other.

The arrival of this method gave a new life to the adaptive control of nonlinear systems .This, at despite the great progress made, lacked general approaches. The back stepping presents a promising alternative to methods based on certain equivalence. It is based on the second Lyapunov method, which combines the choice of the function with the control laws and adaptation. This enables it him, in addition to the task for which the controller is designed (continuation and / or regulation) to ensure, at all times, the overall stability of the compensated system [4].

B. Application of back stepping for machine control

Research on the development of the DFIG control technology has multiplied in recent decades. We currently find several techniques present in the literature, such as vector control, DTC, nonlinear controls such as back stepping and control sliding mode…

Application of back stepping technique to control the DFIG is to establish a machine control law via a Lyapunov function selected, ensuring the overall stability of the system. It has the advantage of being robust vis-à-vis the parametric variations of the machine and good continuation references [5]-[6].

C. Power control by back stepping of DFIG

In this section, we present a new approach to backstepping control applied to the asynchronous machine dual power supply. This approach is designed in such a way to keep the same general structure of a vector control power [7].

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D. Step 1: Computation of the reference rotor currents

We define the errors e_1 and e_2 representing the error between the actual power P_s and the reference power P_{ref} and the error between reactive power Q_s and its reference Q_{ref}.

$$\begin{cases} e_1 = P_{ref} - p_s \\ e_2 = Q_{ref} - Q_s \end{cases} \qquad (1)$$

The derivative of this equation gives:

$$\begin{cases} \dot{e}_1 = \dot{P}_{ref} - \dot{P}_s \\ \dot{e}_2 = \dot{Q}_{ref} - \dot{Q}_s \end{cases} \quad (2) \Rightarrow \begin{cases} \dot{e}_1 = \dot{P}_{ref} + V_s \dfrac{M}{L_s} \dot{I}_{qr} \\ \dot{e}_2 = \dot{Q}_{ref} + V_s \dfrac{M}{L_s} \dot{I}_{dr} \end{cases} \qquad (3)$$

The first Lyapunov function is chosen so such that:

$$v_1 = \frac{1}{2}(e_1^2 + e_2^2) \qquad (4)$$

Its derivative is:

$$\dot{v}_1 = e_1 \dot{e}_1 + e_2 \dot{e}_2 \qquad (5)$$

$$\dot{v}_1 = e_1(\dot{P}_{ref} - \dot{P}_s) + e_2(\dot{Q}_{ref} - \dot{Q}_s) \qquad (6)$$

$$\dot{v}_1 = e_1\left[\dot{P}_{ref} + \frac{MV_s}{L_s}\left(V_{qr} - R_r I_{qr} - g\omega_s \beta I_{dr} - g\frac{MV_s}{L_s}\right)\frac{1}{\alpha}\right] \qquad (7)$$
$$+ e_2\left[\dot{Q}_{ref} + \frac{MV_s}{L_s}\left(V_{dr} - R_r I_{dr} - g\omega_s \beta I_{qr}\right)\frac{1}{\alpha}\right]$$

The pursuits of goals are achieved by choosing the references of the current components representing the stabilizing functions as follows:

$$\begin{cases} I_{qrref} = X\left[k_1 e_1 + \dot{P}_{ref} + \dfrac{V_s M}{L_s \alpha}\left(V_{qr} - g\omega_s \beta I_{dr} - g\dfrac{MV_s}{L_s}\right)\right] \\ I_{drref} = X\left[k_2 e_2 + \dot{Q}_{ref} + \dfrac{V_s M}{L_s \alpha}\left(V_{dr} + g\omega_s \beta I_{qr}\right)\right] \end{cases} \qquad (8)$$

With: $X = \dfrac{L_s \alpha}{V_s M R_r}$, $\beta = L_s - \dfrac{M^2}{L_s}$, $\alpha = L_r - \dfrac{M^2}{L_s}$

Where: k_1, k_2 : positive constants.

The derivative of the Lyapunov function becomes:

$$\dot{v}_1 = -k_1 e_1^2 - k_2 e_2^2 \qquad (9)$$

So, I_{qrref} and I_{drref} in (8) are asymptotically stable.

E. Stepe2: computation of the control voltages.

We define the errors e_3 and e_4 respectively representing the error between the current quadrature rotor I_{qr} and the reference current I_{qrref} and the error between the direct rotor current I_{dr} and I_{drref} reference.

$$\begin{cases} e_3 = I_{qrref} - I_{qr} \\ e_4 = I_{drref} - I_{dr} \end{cases} \qquad (10)$$

The derivative of this equation gives:

$$\begin{cases} \dot{e}_3 = \dot{I}_{qrref} - \dot{I}_{qr} \\ \dot{e}_4 = \dot{I}_{drref} - \dot{I}_{dr} \end{cases} \quad (11) \Rightarrow \begin{cases} \dot{e}_3 = \dot{I}_{qrref} - \dfrac{1}{\alpha} V_{qr} - S_1 \\ \dot{e}_4 = \dot{I}_{drref} - \dfrac{1}{\alpha} V_{dr} - S_2 \end{cases} \qquad (12)$$

With:

$$S_1 = \frac{1}{\alpha}\left(R_r I_{qr} - g\omega_s \beta I_{dr} - g\frac{MV_s}{L_s}\right) \qquad (13)$$

$$S_2 = \frac{1}{\alpha}\left(-R_r I_{dr} + g\omega_s \beta I_{qr}\right) \qquad (14)$$

Actual control laws of the machine V_{qr} and V_{dr} shown in (12), then we can go to the final step.

The final Lyapunov function is given by:

$$v_2 = \frac{1}{2}(e_1^2 + e_2^2 + e_3^2 + e_4^2) \qquad (15)$$

The derivative of equation is given by:

$$\dot{v}_2 = e_1 \dot{e}_1 + e_2 \dot{e}_2 + e_3 \dot{e}_3 + e_4 \dot{e}_4 \qquad (16)$$

Which can be rewritten as follows:

$$\dot{v}_2 = -k_1 e_1^2 - k_2 e_2^2 - k_3 e_3^2 - k_4 e_4^2$$
$$+ e_3\left(k_3 e_3 + \dot{I}_{qrref} - \frac{1}{\alpha} V_{qr} - S_1\right) + e_4\left(k_4 \dot{e}_4 + I_{drref} - \frac{1}{\alpha} V_{dr} - S_2\right) \qquad (17)$$

Where: k_3, k_4 Positive constants.

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Control voltages V_{qr} and V_{dr} are selected as:

$$\begin{cases} V_{qr} = \alpha\left(k_3 e_3 + \dot{I}_{qrref} - S_1\right) \\ V_{dr} = \alpha\left(k_4 e_4 + \dot{I}_{drref} - S_2\right) \end{cases} \quad (18)$$

Which ensures: $\dot{v}_2 < 0$

The stability control is obtained by a good choice of gains: k_1, k_2, k_3 and k_4.

The general structure of control by the backstepping of DFIG is illustrated in Figure (1) the blocks computation I_{qrref} and I_{drref} represent the fictitious control, respectively provide current references obtained from the errors of active and reactive power.

The computation of commands voltages V_{qr} and V_{dr} are based on the error between the currents references and actual implanted by equation (18)

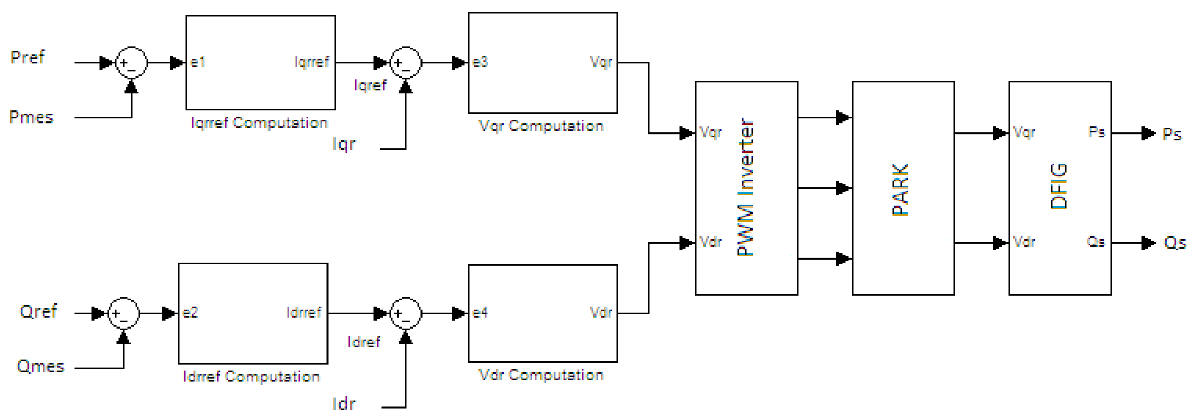

Fig.1: Block diagram of the control with power loop.

III. Modeling of the Wind Turbine

The total kinetic power available on a wind turbine is given by [8]:

$$P_{\max} = \frac{1}{2}\rho S v_v^3 = \frac{1}{2}\rho\pi R^2 v_v^3 \quad (19)$$

The aerodynamic power is given by:

$$P_{\max} = \frac{1}{2} C_p(\lambda)\rho.\pi.R^2.v_v^3 \quad (20)$$

$$C_p = f(\lambda,\beta) = C_1\left(\frac{C_2}{\lambda_i} - C_3\beta - C_4\right)e^{\left(\frac{C_5}{\lambda_i}\right)} + C_6\lambda \quad (21)$$

With:

$$C_{turbine} = \frac{p_m}{\Omega_1} = \frac{1}{2\Omega_1} C_p(\lambda)\rho\pi R^2 v_1^3 \quad (22)$$

$$P_{mg} = C_p P_m = \frac{1}{2} C_p \left(\frac{R\Omega_2}{KV_1}\right)\rho\pi R^2 v_1^3 \quad (23)$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \quad (24)$$

Multiplier model:

$$C_{mec} = \frac{C_{turbine}}{G} \quad (25)$$

A. Model of the shaft:

The fundamental equation of dynamics can be written:

$$J\frac{d\Omega_{mec}}{dt} = C_{turbine} - f\Omega_{mec} \quad (26)$$

With: $\Omega_{mec} = G\Omega_{turbine}$ (27)

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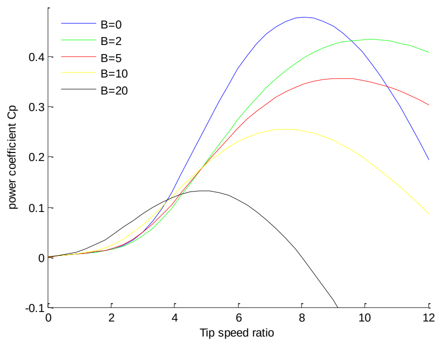

Fig.2: Power coefficient $C_p(\lambda, \beta)$

The figure (2) shows the C_p curves for multiple values of β. This curve is characterized by the optimum point; this value is called the Betz limit, and which is the point corresponding to maximum power coefficient.

B. *Modeling of the DFIG*

The model of DFIG is equivalent to the model of the induction machine cage. However, the rotor of the DFIG is not shorted.

Park transformation:

The classical electrical equations of the DFIG in the Park frame are written as follows [9]:

$$\begin{cases} V_{sd} = R_s I_{sd} + \dfrac{d\phi_{sd}}{dt} - \dot{\theta}_s \phi_{sq} \\ V_{sq} = R_s I_{sq} + \dfrac{d\phi_{sq}}{dt} - \dot{\theta}_s \phi_{sd} \end{cases} \tag{28}$$

$$\begin{cases} V_{rd} = R_r I_{rd} + \dfrac{d\phi_{rd}}{dt} - \dot{\theta}_s \phi_{rq} \\ V_{rq} = R_s I_{rq} + \dfrac{d\phi_{rq}}{dt} - \dot{\theta}_s \phi_{rd} \end{cases} \tag{29}$$

The stator and rotor flux can be expressed as:

$$\begin{cases} \phi_{ds} = L_s i_{ds} + M I_{dr} \\ \phi_{qs} = L_s i_{qs} + M I_{qr} \end{cases} \tag{30}$$

$$\begin{cases} \phi_{dr} = L_r i_{dr} + M I_{ds} \\ \phi_{qr} = L_s i_{qr} + M I_{qs} \end{cases} \tag{31}$$

The electromagnetic torque is given by the following expression:

$$C_{em} = P\frac{M}{L_s}(\phi_{ds} I_{qr} - \phi_{qs} I_{dr}) \tag{32}$$

Mechanical Equation:

$$\frac{d\Omega}{dt} = \frac{1}{J}(C_{em} - C_r - f_r \Omega) \tag{33}$$

$$C_{em} = P[I_s]^T + \frac{d}{d\theta}([M_{sr}][I_r]) \tag{34}$$

For medium and high power machines used in wind turbines, we can neglect the stator resistance [8]. Under this hypothesis, the equation (30) becomes:

$$\begin{cases} \phi_{ds} = \phi_s = L_s i_{ds} + M I_{dr} \\ \phi_{qs} = 0 = L_s i_{qs} + M I_{qr} \end{cases} \tag{35}$$

Equation (32) allows us to write.

$$\begin{cases} i_{ds} = \dfrac{\phi_s}{L_s} - \dfrac{M}{L_s} i_{dr} \\ I_{qs} = -\dfrac{M}{L_s} i_{qr} \end{cases} \tag{36}$$

$$\begin{cases} V_{ds} = 0, R_s = 0 \\ V_{qs} = V_s = \omega_s \phi_{ds} \end{cases} \tag{37}$$

$$\begin{cases} \phi_{dr} = (L_r - \dfrac{M^2}{L_s} i_{dr}) + M\dfrac{V_s}{L_s \omega_s} \\ \phi_{qr} = (L_r - \dfrac{M^2}{L_s}) i_{qr} \end{cases} \tag{38}$$

Active and reactive power equations then become:

$$\begin{cases} P = V_{ds} i_{ds} + V_{qs} i_{qs} \\ Q = V_{qs} i_{ds} + V_{ds} i_{qs} \end{cases} \tag{39}$$

$$\begin{cases} P_s = -V_s \dfrac{M}{L_s} i_{qr} \\ Q_s = -V_s \dfrac{M}{L_s} i_{dr} + V_s \dfrac{\phi_s}{L_s} \end{cases} \tag{40}$$

Replaces equations (31) into (29) we obtain:

$$\begin{cases} V_{dr} = R_r i_{dr} + (L_r - \dfrac{M^2}{L_s})\dfrac{di_{dr}}{dt} - g\omega_s (L_s - \dfrac{M^2}{L_s}) i_{qr} \\ V_{qr} = R_r i_{qr} + (L_r - \dfrac{M^2}{L_s})\dfrac{di_{qr}}{dt} + g\omega_s (L_s - \dfrac{M^2}{L_s}) i_{dr} + g\dfrac{MV_s}{L_s} \end{cases} \tag{41}$$

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In steady state, so we can write:

$$\begin{cases} V_{dr} = R_r i_{dr} - g\omega_s (L_s - \dfrac{M^2}{L_s}) i_{qr} \\ V_{qr} = R_r i_{qr} + g\omega_s (L_s - \dfrac{M^2}{L_s}) i_{dr} + g\dfrac{MV_s}{L_s} \end{cases} \qquad (42)$$

The electromagnetic torque is then written:

$$C_{em} = P\frac{M}{L_s}\phi_{ds} I_{qr} \qquad (43)$$

The previous equations used to establish a block diagram of the electrical system to regulate:

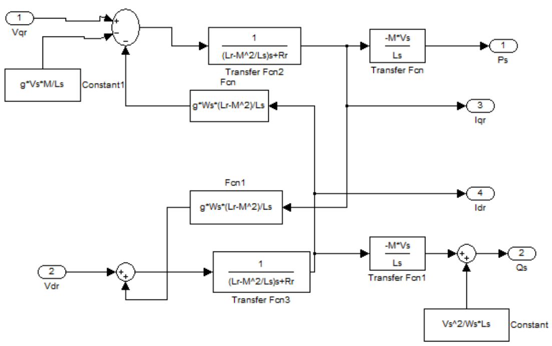

Fig.3: Block diagram of the DFIG regulate.

IV. SIMULATIONS RESULTS.

The Control of The DFIG proposed was simulated using (Matlab / Simulink). The parameters of the DFIG are attached. The parameters k_1, k_2, k_3 and k_4 of backstepping control are chosen as follows: $k_1 = 80600$, $k_2 = 900600$, $k_3 = 5000$, $k_4 = 6000$, to meet the convergence condition.

In the first case, we present the response of the DFIG under the backstepping control. The following figures illustrate the active power, reactive, the rotor currents in quadrature and direct the rotor voltages in quadrature and direct.

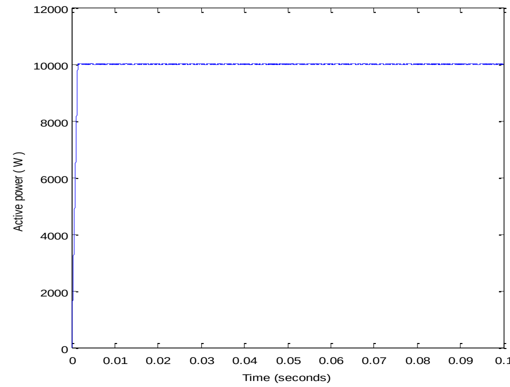

Fig.4: Active power (W).

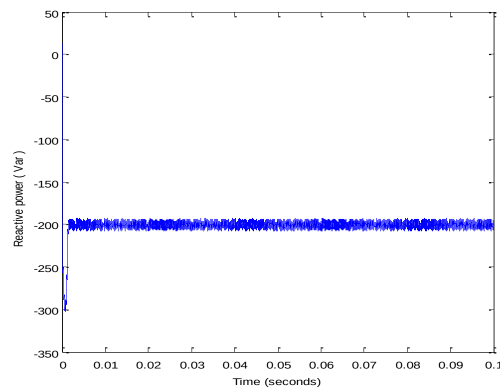

Fig.5: Reactive power (Var)

The negative sign of the reactive power shows that the generator functions in capacitive mode.

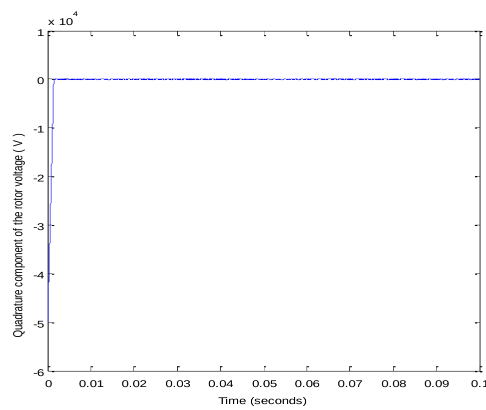

Fig.6: Quadrature component of the rotor voltage (V).

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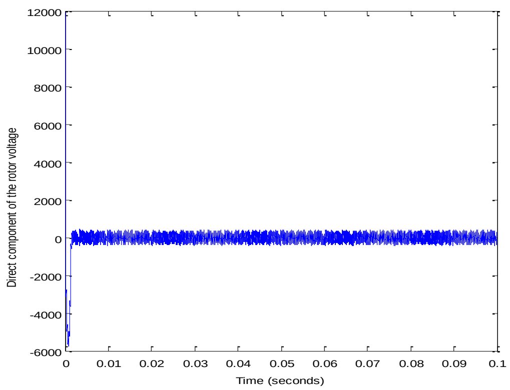

Fig.7: Direct component of the rotor voltage (V).

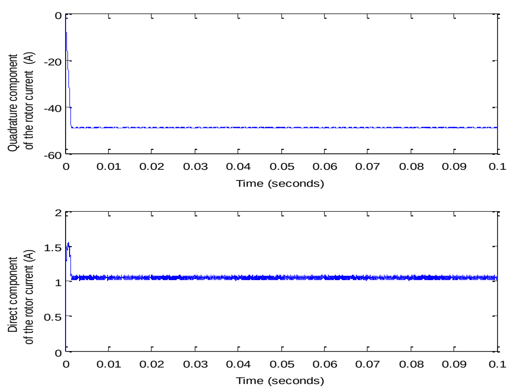

Fig.8: Rotor current Idr and Iqr (A)

To demonstrate the performance of the order by Backstepping, the DFIG is subject to robustness tests for the operating conditions, set point change and the parameters of the machine.

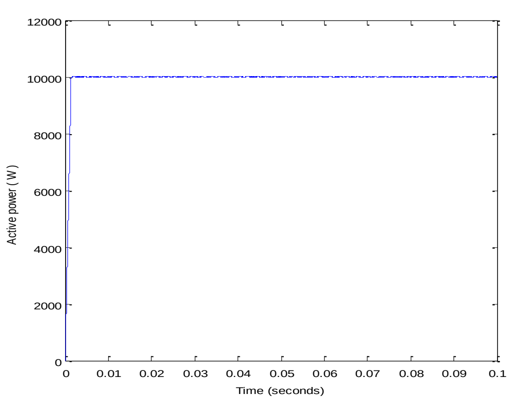

Fig.9: Active power (W) with change of Rr (-50%)

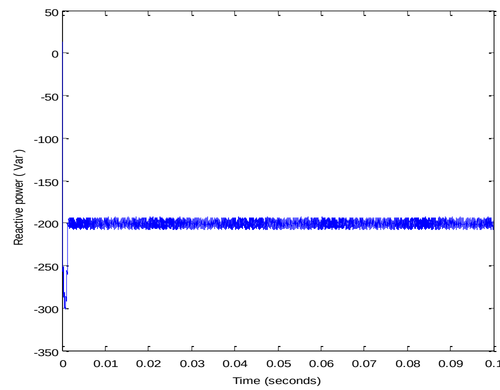

Fig.10: Reactive power (Var) with change of Rr (-50%)

The two figures (9) and (10) show a good behavior of the machine despite the change in the rotor resistance, active and reactive power exhibit a good track their orders

V. CONCLUSION

The first part of this article is devoted to the design of a backstepping control law for DFIG. This law is established step by step while ensuring the stability of the loop machine closed by a suitable choice of the function of Lyapunov.

The second part presents the modeling of the turbine and controlling of the machine based on the physical equations, followed by simulation of operation.

A simulation result allows us to show the proposed algorithm capabilities, in terms of regulation, tracking and disturbance rejection, and demonstrating the robustness of this technique can advantageously replace conventional PI control.

From a conceptual point of view, we can notice that the backstepping control is simpler is easier to implement and has very interesting global stability properties

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APPENDIX:

Appendix: Wind turbine data

Blade Radius	R=3.5 m
Power coefficient	0.48
Optimal relative wind speed	8
Moment of inertia	J=0.0017 kg/m²

Appendix: DFIG parameters

Rated power	10kw
Rated stator voltage	Vs=220V
Nominal frequency	Ws=2π50
Number of pole pairs	P=2
Rotor resistance	Rr=0.62Ω
Stator resistance	Rs=0.455Ω
Stator inductance	Ls=0.084 H
Rotor inductance	Lr=0.085 H
Mutual inductance	M=0.078 H
Sliding	g=0.03

Appendix: Power coefficient constants:

$c_1 = 0.5176, c_2 = 116, c_3 = 0.4, c_4 = 5, c_5 = 21,$
$c_6 = 0.0068$

Backstepping parameters:

$k_1 = 80600$, $k_2 = 900600, k_3 = 5000$, $k_4 = 6000$

$P_{ref} = 10Kw$

$Q_{ref} = -200VAr$

List of symbols:

ρ : Air density

R :Blade radius.

v_v : Wind speed (m/s)

$P_{\max}$: Wind maximum power.

C_p : Power coefficient:

$\lambda = \frac{\Omega_1 R}{V_1}$: Relative wind speed

Ω_1 : Wind turbine speed(Shaft speed).

C_{mec} : Wind turbine torque (Nm).

G : Mechanical speed multiplier.

Ω_{mec} : Mechanical speed (rad/s).

P_{mg} : Mechanical power (watts).

Ω_2 : Rotation speed multiplier (rad/s).

f : Damping cofficient.

C_{em} : Electromagnetic torque(Nm).

J : Moment of inertia(Kg.m²)

V_{dr}, V_{qr} : Direct and quadrature rotor voltages

$C_{turbine}$: Wind turbine torque (Nm).