A Linear Active Disturbance Rejection Control applied for DFIG based Wind Energy Conversion System

Ali Boukhriss¹, Tamou Nasser² and Ahmed Essadki ³

¹ Laboratoire de Génie électrique, ENSET, Université Mohamed 5
Rabat, Morocco

² Ecole Nationale Supérieure d'Informatique et d'Analyse des Systèmes, Université Mohamed 5
Rabat, Morocco

³ Laboratoire de Génie électrique, ENSET, Université Mohamed 5
Rabat, Morocco

Abstract

This paper proposes the control of a doubly fed induction generator DFIG used in wind turbine energy conversion. The control strategy is based on the linear active disturbance rejection control ADRC to generate the control voltages of the rotor side converter RSC and the grid side converter GSC, due to the changes in control inputs. The ADRC, based on the extended state observer ESO, estimate and compensate in real time all the internal and external disturbance of the physical plant, such as, the parameter uncertainties due to the temperature variation, the cross-coupling terms and the load current variation into the dc link voltage. Simulations results are carried out with MATLAB/SIMULINK.

Keywords: Doubly Fed Induction Generator, Active Disturbance Rejection Control, Extended State Observer, Wind Energy, Back To Back Converter.

1. Introduction

Now the global trend towards the use of renewable energy is increasing, in this case, wind energy begins to take a large part in the global market. Variable speed wind using DFIG have a major advantage, seen mainly in reducing of the size and cost of power converters, in fact the power transiting through the back to back converter is about 30–40% of its rated power [1], while allowing a variation of the rotor speed over a range of 0.7 to 1.3 of the synchronous speed. The control of DFIG using PI controller is widely used [2][3], however it has a major drawback when the internal DFIG parameters are subject to variations due to the effects of temperature, which consequently affect the performance of regulators [4][5]. ADRC method proposes a control law which is not based on the accurate mathematical model of the system [6][7], therefore all internal and external disturbances are estimated and rejected in real time, hence the name of the active disturbance rejection control ADRC. In this paper, ADRC is used to control the rotor side converter RSC and the grid side converter GSC.

2. Dynamic Model

The model system of converting wind power using DFIG is represented in Fig.1. The kinetic energy of wind is converted by the turbine connected via a gear box to the axis of the DFIG. The stator is connected to the network through a back to back converter through the filter (Rf, Lf), while the stator is directly connected to the network. Vector control techniques are used for decoupling of active and reactive power. Unity power factor is often set at GSC and reactive power is transited directly between the network and the stator depending on the command of the RSC.

Fig. 1 Schematic diagram of DFIG-based wind generation systems.

In this paper three commands will be developed to ensure the functioning of the wind turbine: Maximum power point tracking control MPPT, control of rotor current at RSC and control of the DC link voltage and power factor at GSC.
3. Mathematical Model

3.1 Turbine Model

The power and the torque on the shaft of the turbine are given by the expression:

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

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

Where \( \lambda \) is the Tip speed ratio of the rotor blade tip speed to wind speed defined as:

\[ \lambda = \frac{\Omega R}{v} \]  
(3)

\( \rho \) is the air density, \( S \) is the surface swept by the blades of the turbine, \( \Omega \) is the turbine speed, \( v \) the wind speed, \( \beta \) the pitch angle and \( C_p \) represents the wind turbine power coefficient given by the empirical expression:

\[ C_p(\lambda, \beta) = 0.22 \left( \frac{116}{\lambda} - 0.4 \beta - 5 \right) e^\frac{-52.5}{\lambda} + 0.0068 \lambda \]  
(4)

\[ \frac{1}{\lambda} = \frac{1}{\lambda_0} + 0.035 \left( \frac{0.08 \beta}{\beta^3 + 1} \right) \]  
(5)

Fig.2 shows the Cp curve for \( \beta = 0 \).

![Fig. 2 Turbine power coefficient.](image)

The turbine shaft is connected to that of the DFIG through a speed multiplier \( k \). Fig.3 shows the mechanical model where \( J_t \) and \( J_m \) represent respectively the coefficient of inertia of the turbine and the generator and \( f_v \) is the viscosity coefficient. \( T_t \) and \( T_m \) represent respectively mechanical torque of turbine shaft and generator. \( \Omega_m \) is the rotational speed of the generator. Mechanical equation is written as:

\[ \left( \frac{J_t}{k^2} + J_m \right) \frac{d\Omega_m}{dt} + f_v \Omega_m = T_m - T_m \]  
(6)

3.2 DFIG Model

The model of DFIG is established in the synchronous reference \( dq \). Stator and rotor voltages are given by the following expressions, where \( R, L, L_m, \phi \) and \( I \) represent respectively resistance of windings, inductance, mutual inductance, flux and current. The subscripts \( s, r, d \) and \( q \) respectively indicate stator, rotor, d-axis and q-axis.

\[ V_{ds} = R I_{ds} + \frac{d\phi_{ds}}{dt} - \theta \phi_{ds} \]  
(7)

\[ V_{qr} = R I_{qr} + \frac{d\phi_{qr}}{dt} + \theta \phi_{ds} \]  
(8)

\[ V_{dr} = R I_{dr} + \frac{d\phi_{dr}}{dt} - \theta \phi_{ds} \]  
(9)

\[ V_{qs} = R I_{qs} + \frac{d\phi_{qs}}{dt} + \theta \phi_{ds} \]  
(10)

\[ \phi_{ds} = (L_m + L_{qdr}) I_{ds} + L_{qds} I_{dr} \]  
(11)

\[ \phi_{qr} = (L_m + L_{qdr}) I_{qr} + L_{qds} I_{ds} \]  
(12)

\[ \phi_{dr} = (L_m + L_{qqs}) I_{dr} + L_{qds} I_{qs} \]  
(13)

\[ \phi_{qs} = (L_m + L_{qqs}) I_{qs} + L_{qds} I_{ds} \]  
(14)

Electromagnetic torque \( T_e \) is written as:

\[ T_e = \frac{3}{2} p \frac{L_m}{L_m + L_{qds}} (\phi_{qs} I_{ds} - \phi_{ds} I_{qs}) \]  
(15)

Active and reactive stator power is given in synchronous reference \( dq \)-axis by the expression:

\[ P_s = \frac{3}{2} (V_{ds} I_{ds} + V_{qs} I_{qs}) \]  
(16)

\[ Q_s = \frac{3}{2} (V_{qs} I_{ds} - V_{ds} I_{qs}) \]  
(17)

3.3 Back to Back PWM Modeling

The back to back allows bidirectional transit of power between the rotor and the network [8]. Fig.4 represents the rectifier and inverter connected by the dc link voltage.
The basic idea is the estimation and compensation of \( f \). Eq. (24) can be written in an augmented state space form as:

\[
\begin{align*}
x_1 &= x_2 + b_0 u \\
x_2 &= h \quad \text{where} \quad h = f \\
y &= x_1
\end{align*}
\]

Or in the matrix form:

\[
\begin{bmatrix}
x \\
y
\end{bmatrix} = \begin{bmatrix}
A & B \\
0 & 1
\end{bmatrix} \begin{bmatrix}
x \\\ny
\end{bmatrix} + \begin{bmatrix}
C \\
E
\end{bmatrix} f
\]

Where

\[
A = \begin{bmatrix}
0 & 1 \\
0 & 0
\end{bmatrix} \quad B = \begin{bmatrix}
1 \\
0
\end{bmatrix} \quad C = \begin{bmatrix}
1
\end{bmatrix} \quad E = \begin{bmatrix}
0
\end{bmatrix}
\]

A state observer of Eq. (25) will estimate the derivatives of \( y \) and \( f \) since Eq. (25) is now a state in the extended state model.

This observer denoted as a Linear Extended State Observer (LESO) is constructed as:

\[
\begin{align*}
\dot{z} &= A \dot{z} + b_0 \dot{u} + L (y - \tilde{y}) \\
\tilde{y} &= C \dot{z} \quad \text{where} \quad L = \begin{bmatrix}
\beta_1 \\
\beta_2
\end{bmatrix}
\end{align*}
\]

\( L \) is the observer gain vector. To simplify the tuning process, the observer gains are parameterized as [15]:

\[
L = \begin{bmatrix}
2 \omega_b \\
\omega_b^2
\end{bmatrix}
\]

Where, \( \omega_b \) is the bandwidth of the observer determined by the pole placement technique [15]. The estimate is more precisely by increasing the bandwidth of the observer; however, a wide bandwidth increases the sensitivity to noise. In practice, a compromise is made between the speed at which the observer tracks the states and its sensitivity to sensor noise. With a properly designed ESO, \( z_1 \) and \( z_2 \) are tracking respectively \( y \) and \( f \).

The control law is given by:

\[
u = \frac{u_0 - z_2}{b_0}
\]

The original plant in Eq. (24) is reducing to a unit gain integrator:

\[
y = (f - z_2) + u_0 \approx u_0
\]

This can be controlled by a simple proportional controller.

\[
u_0 = k_p (r - z_1)
\]

Where, \( r \) is the input signal reference to track.

The controller tuning is chosen as \( k_p = \omega_k \), where \( \omega_k \) is the desired closed loop frequency [14].

The combination of linear ESO and the controller is the linear ADRC. Generally we choose \( \omega_k = 3 - 7 \omega_q \), and consequently, \( \omega_k \) is the only tuning parameter. Fig. 5 represents the implementation of the linear ADRC.
5. Rotor Side Control

The control strategy is based on the orientation of the stator flux on the d-axis. We recall that the voltage of a stator phase in $\alpha\beta$ reference is given by:

$$
\begin{align*}
V_a &= R_i i_a + \frac{d\phi_{a\alpha}}{dt} \\
V_\beta &= R_i i_\beta + \frac{d\phi_{a\beta}}{dt}
\end{align*}
$$

(31)

Angle $\theta$, required to the Park transformation can be calculated as:

$$
\begin{align*}
\phi_{a\alpha} &= \left( V_a - R_i i_a \right) dt \\
\phi_{a\beta} &= \left( V_\beta - R_i i_\beta \right) dt \\
\theta &= \arctan \left( \frac{\phi_{a\beta}}{\phi_{a\alpha}} \right)
\end{align*}
$$

(32)

Neglecting the effect of the stator resistance $R_s$, it follows that the voltage and the stator flux are rotating at the same speed with a shift angle of $90^\circ$. It follows:

$$
\begin{align*}
V_{ds} &= 0 \\
V_{qs} &= V_s
\end{align*}
$$

(34)

The electromagnetic torque and the stator reactive power are given by:

$$
\begin{align*}
T_e &= \frac{3}{2} P \frac{L_m}{L_s} \phi_{ds} I_{qs} \\
Q_s &= \frac{3}{2} V_s \left( \phi_{ds} - \frac{L_m}{L_s} I_{qs} \right)
\end{align*}
$$

(35)

(36)

where

$$
\begin{align*}
L_s &= L_m + L_i \\
L_p &= L_m + L_i
\end{align*}
$$

The electromagnetic torque $T_e$ and reactive power $Q_s$ are controlled respectively by the rotor currents $I_{qs}$ and $I_{ds}$.

To get the electromagnetic torque reference $T_{em}$, Maximum Power Point Tracking (MPPT) strategy is used to extract the maximum of power from the wind velocity. MPPT strategy applied in this paper only requires a rotation speed sensor. Maximum power extracted can be written as:

$$
P_{max} = \frac{1}{2} C_p \rho \frac{R^5}{\lambda_{opt}^2} \Omega^3
$$

(37)

$$
T_m = \frac{1}{2} C_p \rho \frac{R^5}{k^2 \lambda_{opt}^2} \Omega_m^2
$$

(38)

Where, $\lambda_{opt}$ is the optimal tip speed ratio corresponding to maximum power coefficient $C_{p_{max}}$.

In a steady state and neglecting the effect of viscosity, Eq.(6) leads to $T_m = T_{em}$. It follows that the electromagnetic torque reference is given by:

$$
T_{em} = k_{opt} \Omega_m^2
$$

(39)

Where

$$
k_{opt} = \frac{1}{2} C_p \rho \frac{R^5}{k^2 \lambda_{opt}^2}
$$

(40)

The reference rotor currents are then deduced from Eqs.(35) and (36):

$$
\begin{align*}
I_{dr}^{ref} &= \frac{1}{L_m} \left( \phi_{dr} - \frac{2}{3} L_m Q_s^{ref} \right) \\
I_{qr}^{ref} &= -\frac{2}{3 p \phi_{dr}} L_m T_{em}^{ref}
\end{align*}
$$

(41)

(42)

The expressions of the rotor currents can be put into the form:

$$
\begin{align*}
\frac{dl_{dr}}{dt} &= \frac{V_{dr}}{\phi_{dr}} - \frac{R_s}{\phi_{dr}} I_{dr} + \omega_r I_{qs} + \omega_r \frac{L_m}{L_s} \phi_{qs} - \frac{L_m}{L_s} \frac{d\phi_{dr}}{dt} \\
\frac{dl_{qr}}{dt} &= \frac{V_{qr}}{\phi_{dr}} - \frac{R_s}{\phi_{dr}} I_{qr} - \omega_r I_{qs} - \omega_r \frac{L_m}{L_s} \phi_{qs} - \frac{L_m}{L_s} \frac{d\phi_{dr}}{dt}
\end{align*}
$$

(43)

(44)

This, leads for the $I_{dr}$ current, and the same study is used for $I_{qr}$ current, to:

$$
\frac{dl_{dr}}{dt} = f(I_{dr}, d, t) + b_0 u(t)
$$

(45)

Where

$$
\begin{align*}
f &= -\frac{R_s}{\phi_{dr}} I_{dr} + \omega_r I_{qs} + \frac{L_m}{\phi_{dr}} \left( \omega_r \phi_{qs} \frac{d\phi_{dr}}{dt} \right) + \frac{1}{\phi_{dr}} b_0 V_{dr}
\end{align*}
$$

(46)

$f$ represents the generalized disturbance, $I_{dr}$ and $u$ denote respectively the output and the control input of the plant, $b_0$ is the parameter gain to approximate. A linear active rejection control LADRC is easy to implement to control the rotor currents. Fig.6 shows a schematic block diagram for the rotor side control.
6. Grid Side Control

This converter has two roles: to maintain the DC bus voltage constant regardless of the magnitude and direction of the rotor power flow and maintain a unity power factor at the connection point with the grid. A voltage oriented control VOC is used to control the grid side converter GSC.

6.1 Regulation of the Voltage Loop

If we neglected losses in three phase PWM rectifier, the input active power \( P_f \) is equal to the DC link power \( P_{dc} \), that is:

\[
P_f = P_{dc}
\]

A phase locked loop PLL is used to orient the voltage on the q-axis and so the voltage on the d-axis is equal to zero. The input active \( P_f \) and reactive power \( Q_f \) is writing in dq-axis as:

\[
P_f = \frac{3}{2} V_{qf} I_{qf}
\]

\[
Q_f = \frac{3}{2} V_{qf} I_{qf}
\]

\[
P_{dc} = u_{dc} I_{sec} = \frac{3}{2} V_{qf} I_{qf}
\]

Thus let to

\[
cu_{dc} \frac{du_{dc}}{dt} = \frac{3}{2} V_{qf} I_{qf} - u_{dc} i_{dv}
\]

Letting \( w=\frac{c}{u_{dc}} \), then Eq. (50) can be expressed as:

\[
\frac{dw}{dt} = \frac{3}{c} V_{qf} I_{qf} - \frac{2}{c} w^{3/2} i_{dv}
\]

Eq. (51) can be written in the form:

\[
\frac{dw}{dt} = f + b_w u
\]

Where

\[
f = -\frac{2}{c} w^{3/2} i_{dv} + \left( \frac{3}{c} V_{qf} - b_0 \right) I_{qf}
\]

\[
u = I_{qf}
\]

Where, \( f \) represents the generalized disturbance, \( w \) and \( I_{qf} \) are respectively the output and the control input of the plant. \( b_0 \) the parameter to approximate. So the linear ADRC can be used in the voltage loop.

6.2 Regulation of the Current Loop

Eqs. (20) and (21) that represent the currents in the filter can be written as:

\[
\frac{dl_f}{dt} = \frac{1}{L_f} \left( V_{ds} - R_f I_{df} - L_f \omega I_{qf} \right) - \frac{1}{L_f} V_{dl}
\]

\[
\frac{dq_f}{dt} = \frac{1}{L_f} \left( V_{qs} - R_f I_{df} + L_f \omega I_{qf} \right) - \frac{1}{L_f} V_{ql}
\]

This led to put the current \( I_{df} \) and the same studies can be used for \( I_{qf} \), into the form:

\[
\frac{dl_f}{dt} = f(I_{df}, d, t) + b_w u(t)
\]

Where

\[
f = \frac{1}{L_f} \left( V_{ds} - R_f I_{df} - L_f \omega I_{qf} \right) - \left( \frac{1}{L_f} + b_0 \right) V_{dl}
\]

As above a linear ADRC can be applied.

7. Simulation and Results

Simulation of the DFIG wind turbine and the applied control strategies have been carried out with the Matlab/Simulink. The parameters of the DFIG coupled to the turbine are given in Appendix. Simulations are made in three tests:
3.1 Test A

A constant wind speed \( v=12 m/s \) is applied to the turbine, which leads to a torque electromagnetic reference \( T_{em,ref}=7911 mN \) and a machine rotor speed equal to \( n=1740 \text{rpm} \). A stator reactive power reference is set at 0 MVAR, which will be changed to 1 MVAR at \( t=1 s \) and then to 0 Mvar at \( t=1.5 s \). Rotor currents \( I_{dr} \) and \( I_{qr} \) and their references \( I_{dr,ref} \) and \( I_{qr,ref} \) are plotted in Fig. 8. It is clear that the rotor currents follow well their references depending on response time imposed by the desired closed loop frequency \( \omega_c=60 \text{rd/s} \) which correspond to \( tr=50 \text{ms} \). Fig. 9 and Fig. 10 show the general disturbance \( f_{I_{dr}} \) and \( f_{I_{qr}} \) with their estimates by a linear ESO \( Z_{I_{dr}} \) and \( Z_{I_{qr}} \); we can see that the ESO estimates in real time the total disturbances which will then be rejected by the linear ADRC. Rotor currents \( I_{dr} \) and \( I_{qr} \) and their estimates \( Z_{I_{dr}} \) and \( Z_{I_{qr}} \) are illustrated in Fig. 11; here also the ADRC proves again its performances. The decoupling effect between the direct and quadratic stator flux is illustrated in Fig. 12. Reactive stator power and their reference are shown in Fig. 13. The stator voltage \( v_s \) and the stator current \( i_s \) are in phase before \( t=1 s \) and they are no longer in phase after \( t=1 s \); indeed, the reactive power is a step change from 0 to 1 MVAR as shown in Fig. 14. Fig. 15 illustrates the regulation of DC bus voltage \( U_{dc} \), which follows its reference after a transitional regime.

3.2 Test B

A second test is performed linearly varying wind speed from 10 m/s at \( t=1s \) to 10.7 m/s at \( t=1.5s \). The corresponding rotor speed varies between \( n=1450 \text{rpm} \) (hypo synchronous mode) to \( n=1550 \text{rpm} \) (hyper synchronous mode) as shown in Fig. 16. Rotor power \( P_r \) transiting through the back to back converter is negative in hypo synchronous mode and positive in hyper synchronous mode indeed the slip changes the sign as illustrated in Fig. 17.

3.3 Test C

A third test is performed under the conditions of the first trial to reveal the robustness of the controller. Rotor resistance was varied by taking the values of 0.5\( R_r \), \( R_r \) and finally 1.4\( R_r \) to highlight the possible variations in the rotor resistance which can be due to a temperature rise. Fig. 18 demonstrates robust control based on linear active disturbance rejection control. The global uncertainties are estimated and compensated in real time.
Fig. 11  rotor current $I_{dr}$ & $I_{qr}$ and their estimate $\tilde{I}_{dr}$ & $\tilde{I}_{qr}$.

Fig. 12  direct and quadratic stator flux $\phi_{ds}$ & $\phi_{qs}$.

Fig. 13  stator reactive power $Q_s$ and their reference $Q_{s\_ref}$.

Fig. 14  stator voltage $V_s$ and stator current $I_s$.

Fig. 15  DC link voltage $U_{dc}$ and $U_{dc\_ref}$.

Fig. 16  rotor speed.
the ADRC based on linear ESO is easy to implement. It does not require exact knowledge of the internal dynamics of physical plant, which is the main reason that makes it robust against changes in internal parameters that affect the time constants of the DFIG current loops as in the traditional PI controller.

Appendix

Doubly fed induction generator parameters:

- Rated power: 1.5MW
- Grid voltage line to line rms: $U=690V$, $f=50Hz$
- Stator and rotor resistance: $R_s=10.3m\Omega$, $R_r=8.28m\Omega$
- Stator and rotor inductance: $L_s=280.1\mu H$, $L_r=117.7\mu H$
- Mutual inductance: $L_m=26.96mH$
- Number of pole pairs: $p=2$

Turbine parameters

- Rotor diameter: $D=60m$
- Total moment of inertia: $J_t=303.96kgm^2$
- Optimal tip speed ratio: $\lambda_{opt}=6.5$
- Maximal power coefficient: $C_{pmax}=0.48$

DC link parameters

- DC link voltage: $U_{dc}=1400V$
- Filter: $L_f=0.25mH$, $R_f=0.785m\Omega$
- DC link capacitor: $C=50mA$

Rotor current controller parameters

- Desired closed loop frequency: $\omega_{cr}=60rd/s$
- Observer bandwidth: $\omega_{r0}=5\omega_{cr}=300rd/s$
- Parameter gain: $b_{r0}=2432$

Filter current controller parameters

- Desired closed loop frequency: $\omega_{cf}=300rd/s$
- Observer bandwidth: $\omega_{f0}=5\omega_{cf}=1500rd/s$
- Parameter gain: $b_{f0}=-4000$

Voltage loop parameters

- Desired closed loop frequency: $\omega_{cv}=30rd/s$
- Observer bandwidth: $\omega_{v0}=5\omega_{cv}=150rd/s$
- Parameter gain: $b_{v0}=33941$

7. Conclusion

In this paper, we presented a new strategy for control of DFIG based wind energy system. The implementation of
References


Ali Boukhriss was born in Agadir, Morocco. He received a License degree from ENSET School, Mohamed 5 Souissi University Rabat, and a master degree from ENSA School, Ibn Zohr University Agadir in 2011. He is currently working toward the PhD degree in electrical engineering research at ENSET, Mohamed 5 Souissi University Rabat, Morocco.

Tamou NASSER is currently an Associate Professor (Profeesseur Assistant) at the communication networks department of National High School for Computer Science and Systems (ENSIAS), Mohamed V Souissi University, Morocco, since 2009. She received her PhD degree in 2005 and her research MS degree, in 2000, respectively, all in electrical engineering from Mohammadia Engineering School (EMI), Morocco. Her research interests renewable energy, motor drives, power system, and Smart Grid. Doctor Tamou NASSER is a member of Al Jazari research group.

AHMED ESSADKI is currently a Professor and university research professor at the electrical engineering department of ENSET, Mohamed V Souissi University, Morocco. In 2000, He received his PhD degree from Mohammadia Engineering School (EMI), Morocco. From 1990 to 1993, he pursued his Master program at UQTR University, Quebec Canada, respectively, all in electrical engineering. His current research interests include renewable energy, motor drives and power system. Doctor Ahmed ESSADKI is a member of RGE Lab in research group leader.