Reactive Power Control for Wind Turbine using Exact Linearization Feedback

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Abstract

The quality of service and the respect of contractual characteristics of the voltage is a major issue of the transmission system operator. In this context, the code requires that the wind turbine system participate in the regulation of the voltage. Any variation in voltage must be compensated by producing or absorbing reactive power.
This article studies the modelling and control strategies of a wind energy conversion system based on a doubly fed induction generator. It presents a linear quadratic regulator with integrator (LQI) and an exact linearization feedback (ELF) controller for a doubly fed induction generator (DFIG). In the ELF technique, the nonlinear model of DFIG is linearized and the reference of active and reactive powers values are calculated by using reactive power management algorithm.
The simulation results show that the decoupling control strategy for DFIG is satisfactory and the predefined operating conditions are respected.

Keywords: Doubly fed induction generator, Wind turbine, Exact linearization feedback, LQI, MPPT.

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List of abbreviations

C_p	Power coefficients
ρ	Air density in (kg/m3)
R	Radius of the blade in (m)
v	Wind speed in (m/sec)
Ω_t	Turbine speed in (rad/sec)
ω_s	Synchronous angular velocity
M	Mutual inductance
V_{sd}, V_{sq}	Stator voltage in the d and q reference
i_{sd}, i_{sq}	Stator current in the d and q reference
ϕ_{sd}, ϕ_{sq}	Stator flux in the d and q reference
Rs, Rr	Stator and rotor resistances
P	Number of the pole pairs
L_s, L_r	Cyclic stator and rotor inductances

1. Introduction

Many countries have established a set of specific requirements for wind energy, among others the connection between wind turbines and the transmission network. This special requirement imposes new constraints on the production of all the parks. It must require the same applicable rules which are applied to conventional power stations connected to the transmission network. Indeed, the Transmission System Operators (GRT) gives a great importance to balancing reactive power [1].

Reactive energy on the transmission network has two consequences: the first one is an increase in the current which causes heating of the links and transformers with greater losses. This consequence can conduce to oversize the transmission network installations. The second consequence consists of the voltage variation during the winter months, when the consumption of reactive energy accentuates the voltage drops.

Therefore, the wind turbines connected to this level must also participate in the adjustment of the reactive power within the framework of certain constraints imposed by the GRT. These constraints are defined in the "Grid code" (technical connection rules) and depending on the structure of the network. GRTs can also apply various modifications to the production.

In this paper we use the exact Feedback linearization technique proposed by [2] to control the nonlinear model of the DFIG and LQI controller without linearization in the operating point. The first technique is based on differential geometry to transform the MIMO nonlinear system into SISO linear system under certain conditions. These control laws are applied to the rotor side converter and the grid side converter (GSC) in order to track the reference of the active and reactive power. In [3] proposes exact feedback linearization to control the DFIG. The same technique has been applied in [4], the authors did not consider the variation of rotor active power.

Another objective of this article is to modify the reference Power value in order to respect the constructive constraints of the DFIG. The Capability Curve of DFIG have been investigated in [5]. However, the authors did not use the results obtained to calculate the reference powers which consider other constraints such as the available power and the code requirements for wind power integration.

This paper investigates the DFIG, the exact feedback linearization technique applied to extracting the maximum power point MPPT. The reference power takes into account the recommendation of the transmission system operator but also the power available.

The performance of DFIG with the ELF controllers and power management algorithm is tested in various operating points. The overall structure of the study takes the form of six chapters: In the second section, we present the model of wind energy conversion system. Exact feedback linearization and LQI controller is discussed in the third and fourth part respectively. On the fifth one, we present active and reactive power management. The results of the simulation are provided on the sixth chapter. And Finally, the seventh section concludes the document.

2. Wind energy conversion systems

2.1. Turbine model

The mechanical power generated by wind turbine is given by [7]:

$$P_{aero}=\frac{1}{2}C_p(\lambda,\beta)\rho\pi R^2 v^3 \qquad (1)$$

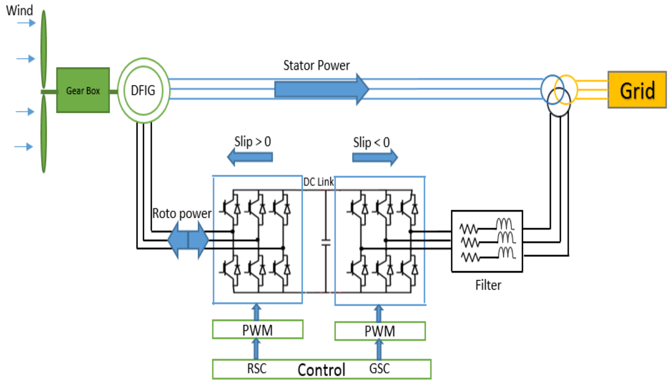

Figure 1. Diagram of the wind energy conversion system

In our study, the power coefficient is depend on the tip speed ratio and blade pitch angle, defined by [7]:

$$C_p(\lambda i,\beta)=0.73\left(\frac{151}{\lambda i}-0.58\beta-0.002\beta^2-13.2\right)e^{\frac{-18.4}{\lambda i}} \qquad (2)$$

The maximum value of Cp is given by: $C_{p\max}=0.48$ when the speed of rotation of the turbine is slow, it is necessary to insert between the turbine and DFIG a speed multiplier. The friction losses are neglected.

The fundamental equation of dynamics has been defined by the following expression:

$$J\frac{d\Omega_{mec}}{dt}=T_{mec}-T_{em}-D\Omega_{mec} \qquad (3)$$

2.2. Mathematical model for DFIG

The stator and rotor voltage in the d-q synchronous reference frames are expressed as follows [6]

$$\overrightarrow{v_s^{dq}}=R_s\overrightarrow{i_s^{dq}}+\frac{d\overrightarrow{\phi_s^{dq}}}{dt}+j\omega_s\overrightarrow{\phi_s^{dq}} \qquad (4)$$

$$\overrightarrow{v_r^{dq}}=R_r\overrightarrow{i_r^{dq}}+\frac{d\overrightarrow{\phi_r^{dq}}}{dt}+j\omega_r\overrightarrow{\phi_r^{dq}}$$

The angular velocity of the rotor is given by:

$$\omega_r=\omega_s-p\Omega_{mec} \qquad (5)$$

The stator flux and the rotor flux are:

$$\overrightarrow{\phi_s^{dq}}=L_s\overrightarrow{i_s^{dq}}+M\overrightarrow{i_r^{dq}}$$

$$\overrightarrow{\phi_r^{dq}}=M\overrightarrow{i_s^{dq}}+L_r\overrightarrow{i_r^{dq}} \qquad (6)$$

In the study, the control strategy for the DFIGs is based on vector control, which is oriented to the stator voltage. Thus, the rotor voltage can be expressed as follows [7]:

$V_{sd}=0 \quad V_s=V_{sq}$

$$V_{rd} = R_r i_{rd} + \sigma L_r \frac{di_{rd}}{dt} - \omega_r \sigma L_r i_{rq} + \frac{L_m}{L_s}\frac{d\phi_{sd}}{dt}$$
$$V_{rq} = R_r i_{rq} + \sigma L_r \frac{di_{rq}}{dt} + \omega_r \sigma L_r i_{rd} + \omega_r \frac{L_m}{L_s}\phi_{sd} \quad (7)$$

The grid side converter can be expressed as follows:

$$\begin{cases} V_{dc}.i_d = \frac{3}{2}V_{gd}i_{gd} \\ \frac{dW_{dc}}{dt} = -P_f - P_r \\ W_{dc} = \frac{1}{2}C_{dc}V_{dc}^2 \\ \frac{di_{gd}}{dt} = -\frac{R_g}{L_g}i_{gd} - \omega_s i_{gq} + \frac{1}{L_g}(V_{sd} - V_{gd}) \\ \frac{di_{gq}}{dt} = -\frac{R_g}{L_g}i_{gq} - \omega_s i_{gd} + \frac{1}{L_g}(V_{sq} - V_{gq}) \end{cases} \quad (8)$$

Using coordinate:

$$\left[x1\ x2\ x3\ x4\ x5\right]^T = \left[id\ iq\ w\ igq\ Vds\right]^T$$

The equation can be described by the following affine nonlinear form:

$$\dot{x} = f(x) + g(x)u(t) \quad (9)$$

$$f(x) = \begin{bmatrix} -\frac{R_r}{\sigma L_r}i_{rd} + \omega_r i_{rq} \\ -\omega_r i_{rd} - \frac{R_r}{\sigma L_r}i_{rq} - \frac{L_m}{\sigma L_r L_s}\omega_r \phi_{sd} \\ -\frac{D}{J}\omega \\ -\frac{R_g}{\sigma L_g}i_{gd} + \omega_s i_{gq} \\ -\frac{R_g}{\sigma L_g}i_{gq} - \omega_s i_{gd} \\ \frac{3}{2CV_c}(V_{ds}i_{gq}) - i/C \end{bmatrix}$$

$$g(x) = \begin{bmatrix} \frac{1}{\sigma L_r} & 0 & 0 & 0 & 0 & 0 \\ 0 & \frac{1}{\sigma L_r} & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{-1}{J} & 0 & 0 & 0 \\ 0 & 0 & 0 & -\frac{1}{L_g} & 0 & 0 \\ 0 & 0 & 0 & 0 & -\frac{1}{L_g} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

3. Exact feedback linearization of DFIG

The method consists to transform the nonlinear system described by the equations in linear and controllable system [3][8].

$$\begin{cases} \dot{z} = Az + Bw \\ y = Cz \end{cases} \quad (10)$$

using input transformation to get a new input of the linearized system

$$u = -L^{-1}(x)(-p(x) + w)$$
with
$$L(x) = \begin{bmatrix} L_{g1}L_f^{r_1-1}h_1(x) & \ldots & L_{gm}L_f^{r_1-1}h_1(x) \\ \vdots & \vdots & \vdots \\ L_{g1}L_f^{r_m-1}h_m(x) & \ldots & L_{gm}L_f^{r_m-1}g_m(x) \end{bmatrix} \quad (11)$$
$$p(x) = \begin{bmatrix} L_f^{r_1}h_1(x) \\ \ldots \\ L_f^{r_m}h_m(x) \end{bmatrix}$$

We aim to order the DFIG to track the reference of the active and reactive power and also to keep the Voltage DC bus stable.

Neglecting stator resistance and the stator flux vector is aligned with d axe.

The active and reactive power equations are given by [6]:

$$\begin{cases} Ps = \frac{3}{2}(V_{sd}i_{sq} + V_{sq}i_{sq}) = \frac{3}{2}V_{sq}\frac{L_m}{L_s}i_{rq} \\ Qs = \frac{3}{2}(V_{sq}i_{sd} - V_{sd}i_{sq}) = \frac{3}{2}V_{sq}\frac{\phi_{sd}}{L_s} - \frac{3}{2}V_{sq}\frac{L_m}{L_s}i_{rd} \\ Qg = -\frac{3}{2}(V_{gq}i_{gd} - V_{gd}i_{gq}) = \frac{3}{2}V_{gd}i_{gq} \\ \frac{d\theta_r}{dt} = \omega_r \end{cases} \quad (12)$$

Therefore, we choose as output vector

$$\begin{cases} y_r = h_r(x) = [P_s \quad Q_s]^T \\ y_g = h_g(x) = \left[Q_g \quad V_{dc}\right]^T \end{cases} \quad (13)$$

The state variable and the input vector are:

$$x = \left[i_{rd} \quad i_{rq} \quad w_m \quad i_{gd} \quad i_{gq} \quad V_{dc}\right]^T$$
$$u = \left[V_{rd} \quad V_{rq} \quad \omega_r \quad V_{gd} \quad V_{gq}\right]$$

Differentiating (13) until an input appears:

$$\begin{cases} \dot{y}_{r1} = \dot{h}_{r1}(x) = \frac{3}{2}V_{sq}\frac{L_m}{L_s}(-\omega_r i_{rd} - \frac{R_r}{\sigma L_r}i_{rq} - \frac{L_m}{\sigma L_r L_s}\omega_r \phi_{sd}) + \frac{3}{2}V_{sq}\frac{L_m}{\sigma L_s L_r}V_{rq} \\ \dot{y}_{r2} = \dot{h}_{r2}(x) = -\frac{3}{2}V_{sq}\frac{L_m}{L_s}(-\frac{R_r}{\sigma L_r}i_{rd} + \omega_r i_{rq}) - \frac{3}{2}V_{sq}\frac{L_m}{\sigma L_s L_r}V_{rd} \\ \dot{y}_{g1} = \dot{h}_{g1}(x) = -\frac{R_g}{L_g}i_{gd} - \omega_s i_{gq} + \frac{1}{L_g}(V_{sd} - V_{gd}) \\ \dot{y}_{g2} = \dot{h}_{g2}(x) = \frac{3}{2CV_c}(V_{ds}i_{gq}) - P_r/(V_c C) \\ \ddot{y}_{g2} = \ddot{h}_{g2}(x) = L_f(L_f h_2) + L_{g1}(L_f h_2)V_{gd} + L_{g2}(L_f h_2)V_{gq} \\ \quad = \frac{3V_{ds}}{2CV_c}(-\frac{R_g}{\sigma L_g}i_{gq} - \omega_s i_{gd})) + (\frac{-3V_{ds}i_{gq}}{2CV_c^2} + P_r/V_c^2)(\frac{3V_{ds}i_{gq}}{2CV_c} - P_r/(V_c C))) \\ \quad -\frac{1}{V_c C}(\frac{\partial P_r}{\partial t}) - \frac{3V_{ds}}{2CV_c L_g}V_{gq} \end{cases} \tag{14}$$

With this output vector, the calculation of relative degrees gives:

$$r = r_{r1} + r_{r2} + r_{g1} + r_{g2} = 5 \tag{15}$$

Now the feedback linearization method is applied to the model of DFIG the control input to the DFIG in function of virtual control input is as follows:

$$w_r = \begin{bmatrix} \dot{y}_{r1} & \ddot{y}_{r2} \end{bmatrix} \text{ and } \quad w_g = \begin{bmatrix} \dot{y}_{g1} & \ddot{y}_{g2} \end{bmatrix}$$

$$u_r = L^{-1}(x)(-p(x) + w_r)$$

$$\text{where} \tag{16}$$

$$L(x) = \begin{bmatrix} L_{g1}h_{r1}(x) & L_{g2}h_{r1}(x) \\ L_{g1}L_f h_{r2}(x) & L_{g2}L_f h_{r2}(x) \end{bmatrix}$$

$$p(x) = \begin{pmatrix} L_f h_{r1}(x) \\ L_f h_{r2}(x) \end{pmatrix}$$

$$u_g = L_g^{-1}(x)(-p_g(x) + w_g)$$

$$\text{where} \tag{17}$$

$$L_g(x) = \begin{bmatrix} L_{g1}h_{g1}(x) & L_{g2}h_{g1}(x) \\ L_{g1}L_f h_{g2}(x) & L_{g2}L_f h_{g2}(x) \end{bmatrix}$$

$$p_g(x) = \begin{pmatrix} L_f h_{g1}(x) \\ L_f^2 h_{g2}(x) \end{pmatrix}$$

Finally, the new state vector that transforms the nonlinear DFIG model into linear model is:

$$z_r = \begin{bmatrix} h_{r1}(x) & h_{r2}(x) \end{bmatrix} \text{ and } \quad z_g = \begin{bmatrix} h_{g1}(x) & L_f h_{g2}(x) \end{bmatrix}$$

$$\begin{bmatrix} \dot{z}_{r1} \\ \dot{z}_{r2} \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}\begin{bmatrix} z_{r1} \\ z_{r2} \end{bmatrix} + \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}\begin{bmatrix} w_{r1} \\ w_{r2} \end{bmatrix}$$

$$\begin{bmatrix} \dot{z}_{g1} \\ \dot{z}_{g2} \\ \dot{z}_{g3} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix}\begin{bmatrix} z_{g1} \\ z_{g2} \\ z_{g3} \end{bmatrix} + \begin{bmatrix} 1 & 0 \\ 0 & 0 \\ 0 & 1 \end{bmatrix}\begin{bmatrix} w_{g1} \\ w_{g2} \end{bmatrix} \tag{18}$$

For this system a simple Proportional controller can be designed

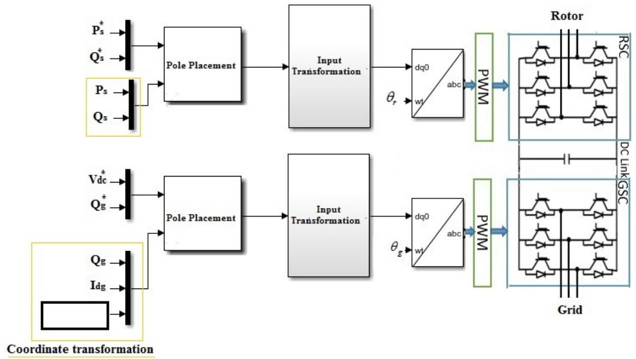

Figure 2. Block Diagram of the proposed ELF approach control design

4. LQI controller of DFIG

The nonlinear system can be described by the following linear form with disturbance [11]:

$$\begin{aligned} \dot{x} &= A(t)x + Bu + Ed(t) \\ y &= h(x) = Cx + Du \end{aligned} \tag{19}$$

Where

$$A_r(t) = \begin{bmatrix} -\frac{R_r}{\sigma L_r} & \omega_r \\ -\omega_r & -\frac{R_r}{\sigma L_r} \end{bmatrix} \quad B_r = \begin{bmatrix} \frac{1}{\sigma L_r} & 0 \\ 0 & \frac{1}{\sigma L_r} \end{bmatrix}$$

$$E_r = \begin{bmatrix} 0 & 0 \\ 0 & -\frac{L_m}{\sigma L_r L_s} \end{bmatrix} \quad d_r(t) = \begin{bmatrix} 0 \\ \omega_r \phi_{sd} \end{bmatrix}$$

$$\text{with } \omega_r = \omega_{r0} + \delta\omega_r$$

The augmented system is:

$$\begin{bmatrix} \dot{x} \\ \dot{\xi} \end{bmatrix} = \begin{bmatrix} A & 0 \\ -C & 0 \end{bmatrix}\begin{bmatrix} x \\ \xi \end{bmatrix} + \begin{bmatrix} B \\ 0 \end{bmatrix}u + \begin{bmatrix} Ed(t) \\ r \end{bmatrix} \tag{20}$$

Where

$$\xi = \int_0^t (r - y(\tau))d\tau \tag{21}$$

we pose

$$\hat{A} = \begin{bmatrix} A & 0 \\ -C & 0 \end{bmatrix}, \quad \hat{B} = \begin{bmatrix} B \\ 0 \end{bmatrix}$$

$$\text{and } X_{aug} = [i_{rd} \quad i_{rq} \quad \xi]^T$$

The optimal controller gain is [9-10]:

$$K = -R^{-1}\hat{B}^T P \tag{22}$$

$P = P^T \geq 0$ is solution to the Riccati equation :

$$P\hat{A}+\hat{A}^T P - P\hat{B}R^{-1}\hat{B}^T P + Q = 0 \quad (23)$$

The controller performance using LQI method depends on the choice of Q and R weighting matrices.

$$u = -Kx \quad (24)$$

$$Where: x = [x, xi] \; and \; K = [Kx, Ki]$$

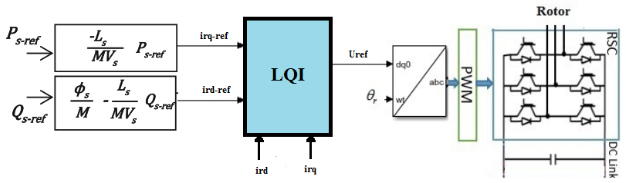

Figure 3. Block Diagram of the proposed LQI control design

5. Active and reactive power management

The P-Q curves of wind turbine generator depends not only on wind speed but also on the constructive constraints of the DFIG namely stator current, rotor current, rotor voltage and the stability limit [12].

Stator current limitation:

$$Ps^2 + Qs^2 = (3VsIs)^2 \quad (25)$$

Rotor current limitation:

$$Ps^2 + (Qs + \frac{3Vs^2}{Xs})^2 = (\frac{3VsXm}{Xs} Ir)^2 \quad (26)$$

Rotor voltage limitation:

$$Ps^2 + (Qs + \frac{3Vs^2}{\sigma Xs})^2 = (\frac{3VsXm}{\sigma XsXr\, s} Vr)^2 \quad (27)$$

The GSC is used to control the active power to maintain the dc link voltage constant and the unity power factor.

$$P_{total} = P_S + P_R \quad (28)$$

$$Q_{total} = Q_S + Q_R = Q_S$$

2.1. Active Power Control

In order to extracting maximum available power from wind turbine generator, the mechanical speed of the DFIG must be adjusted according to the variation of the wind speed.

The active power capability of a wind turbine generator can be presented by a figure 4.

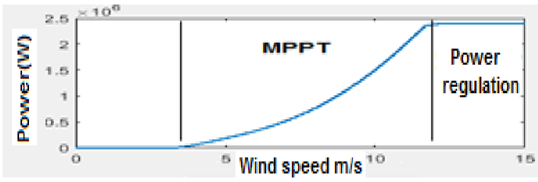

Figure 4. Available Power

The active power reference is obtained from a Maximum Power Point Tracking (MPPT) algorithm in region I and equal to the nominal power in the region II.
if reactive power generation has priority and it goes beyond the constructive constraints of the DFIG, the generator cannot operate at the maximum power.

2.2. Reactive Power Control

The reactive power reference is calculated from the power factor imposed by the transmission system operator.

we replace Ps with αQs we obtain:

$$\begin{cases} Qs^2 - (3VsIs)^2/(\alpha^2+1) = 0 & (29) \\ (1+\alpha^2)Q_s^2 + \frac{6V_s^2}{X_s}Q_s + \frac{9V_s^2(V_s^2 - X_m^2 I_r^2)}{X_m^2} = 0 & (30) \\ (1+\alpha^2)Q_s^2 + \frac{6V_s^2}{\sigma X_s}Q_s + \frac{9V_s^4}{(\sigma X_s)^2} - \frac{3V_s X_m}{(\sigma s X_s X_r)}V_r = 0 & (31) \end{cases}$$

$Q^{+-}_{\phi \max 1}, Q^{+-}_{\phi \max 2}$ *and* $Q^{+-}_{\phi \max 3}$ *are solutions to equations* (29), (30) *and* (31) respectively

$$\begin{cases} Q^{+}_{\phi \max} = \min(Q^{+}_{\phi \max 1}, Q^{+}_{\phi \max 2} \; and \; Q^{+}_{\phi \max 3}) \\ Q^{-}_{\phi \max} = \max(Q^{-}_{\phi \max 1}, Q^{-}_{\phi \max 2} \; and \; Q^{-}_{\phi \max 3}) \end{cases} \quad (32)$$

When the power factor is *positive* $Q_{\phi \max} = Q^{+}_{\phi \max}$ *else* $Q_{\phi \max} = Q^{-}_{\phi \max}$

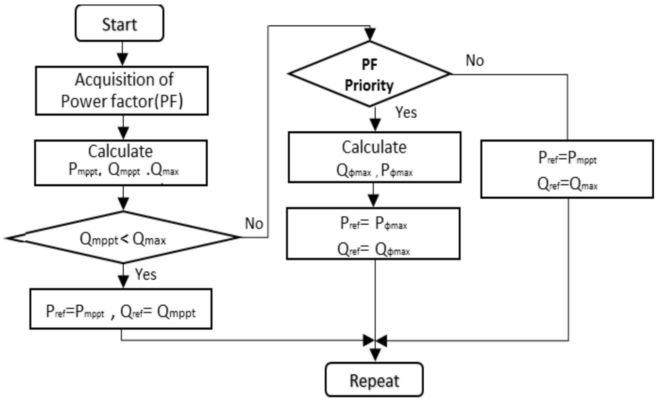

Figure 5. The proposed Reactive Power management

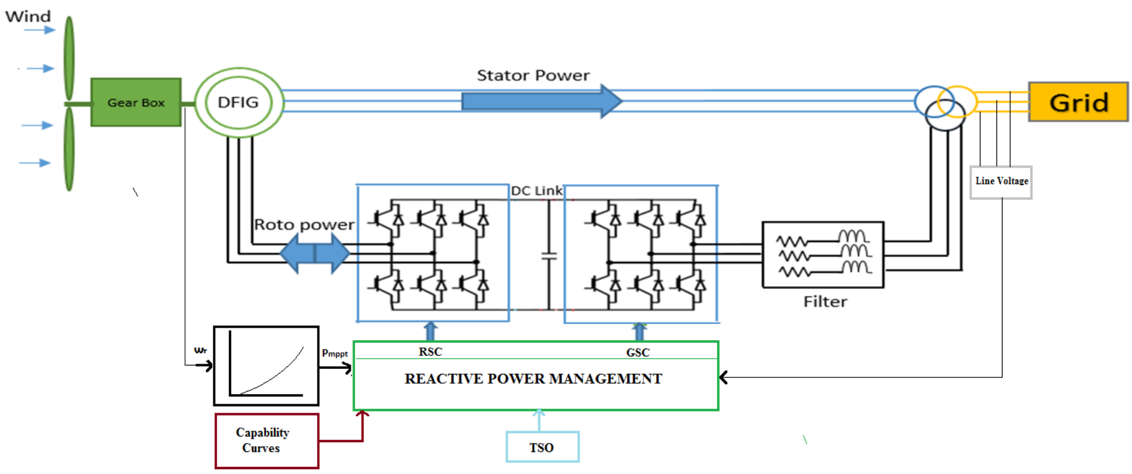

Figure 6. The proposed Diagram of the wind energy conversion system

6. Results and Discussion

All simulations were carried out using SIMULINK environment of MATLAB. The parameters of the Wind turbine and the DFIG are given in the Table1 and Table2.

5.1. Performance Comparison between EFL and LQI Controllers

The EFL controller parameters: P1=1000, P2=1000 and The LQI parameters:

$$K = \begin{bmatrix} 0.3301 & 0.0027 & -31.5933 & -1.3647 \\ 0.0027 & 0.4561 & 1.3647 & -31.5933 \end{bmatrix}$$

The simulations presented are performed with full order DFIG model, the results shown illustrate the performance of the EFL and LQI controllers under different operating zones.

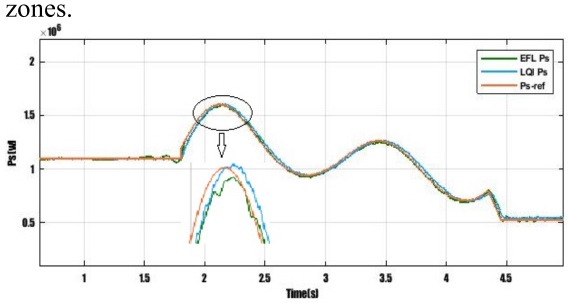

Figure 7a. Active Power

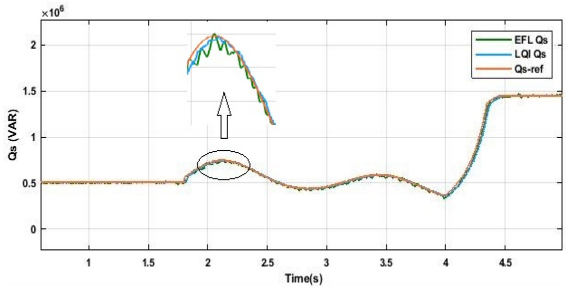

Figure 7b. Reactive Power

5.2. The proposed Reactive Power management

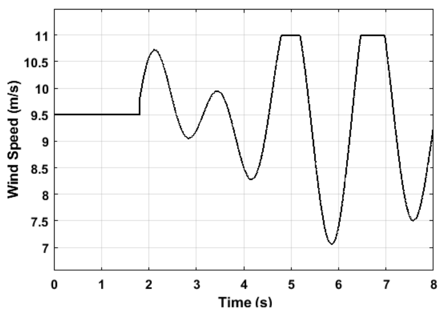

Figure 8a. Wind Speed

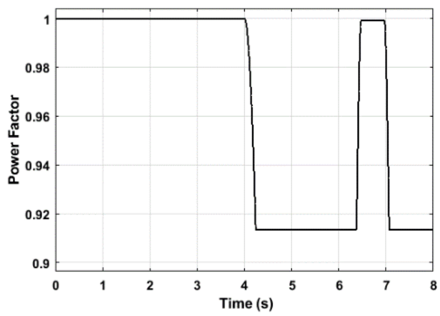

Figure 8b. Power Factor

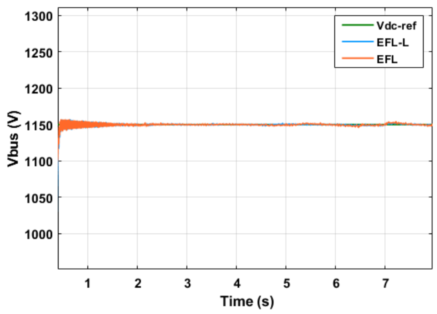

Figure 8c. DC link voltage

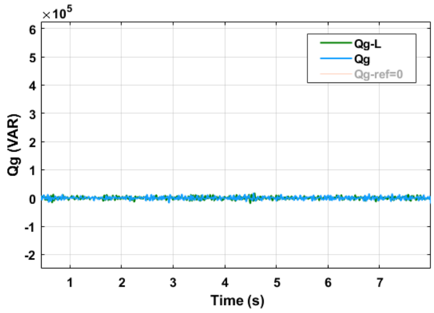

Figure 8d. Grid Reactive power

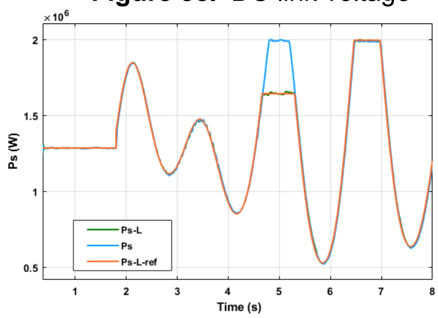

Figure 8e. Active power

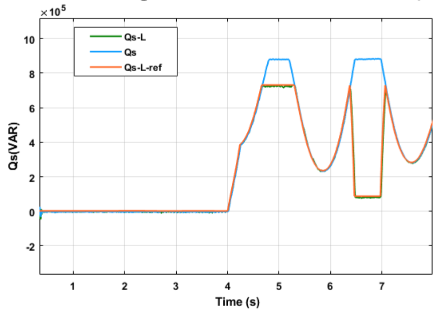

Figure 8f. Reactive power

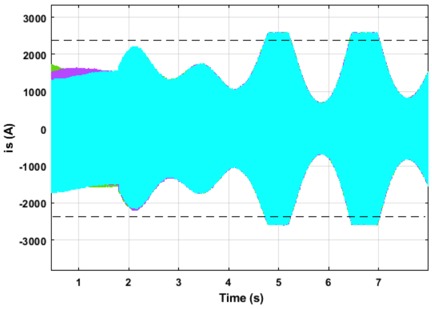

Figure 8g. Stator Current without Power management

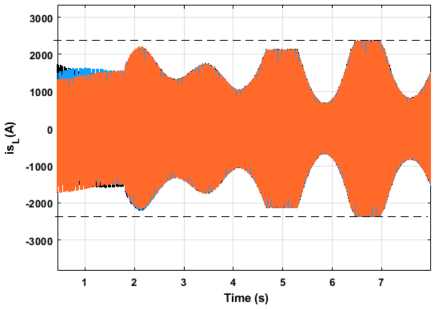

Figure 8h. Stator Current with Power management

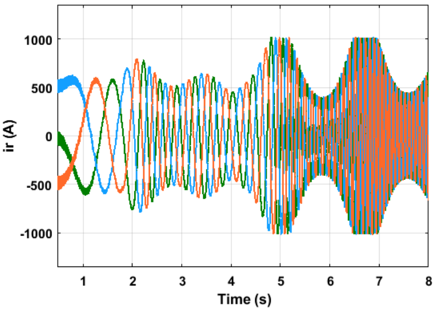

Figure 8i. Rotor Current without Power management

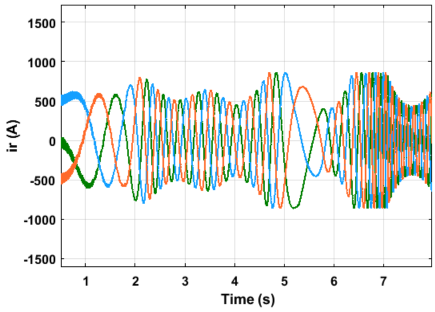

Figure 8j. Rotor Current with Power management

The Figure 8 shows that the strategy of EFL developed to achieve decoupled tracking is checked and the response time is satisfied despite the variation of wind speed and the power factor.
Figure 8g to Figure 8j shows the stator current, rotor current respect constraint limit.

7. Conclusion

In this paper, a model of doubly fed induction generator (DFIG) wind turbine has been developed to control active and reactive power injection on the grid.
It was proven that the exact linearization feedback (ELF) method can transform the DFIG system and the grid side converter (GSC) into a linear canonical form. therefore, Proportional controllers gives good results.
Compared to ELK approach, the linear quadratic regulator with integrator (LQI) applied on the rotor side converter (RSC) has smaller oscillation around the setpoint.
The LQI controller developed in this paper can't be applied on the GSC.
At a second stage, an algorithm aimed at estimating the maximum production capacity of the active and reactive powers in order to generate the reference power is proposed and verified by the simulation results.
The advantage of this algorithm is to improves reactive power compensation and protects the DFIG against maximum temperature limit (rotor current and stator current) and limit isolation (rotor voltage limit).

Appendix.

Table 1. Wind Turbine parameters

Parameters	Value	Parameters	Value
Inertia	Ps=2MW	Radius of the turbine	0.087mH
Damping	Ps=2MW	Maximal power coefficient	0.087mH
Gain multiplier	G=20		

Table 2. Double Fed Induction Generator parameters

Parameters	Value	Parameters	Value
Rated Power	Ps=2MW	Stator Inductance	0.087mH
Frequency	50Hz	Rotor Inductance	0.087mH
Number of poles	2	Mutual Inductance	2.5mH
Stator Resistance	2.6mΩ	Rated Stator current	1760Arms
Rotor Resistance	2.9mΩ	Rated Rotor current	1800Arms
Rated Power	Ps=2MW	Stator Inductance	0.087mH

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