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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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 conduct 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 technique 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]:
\[ P_{\text{mech}} = \frac{1}{2} C_p(\lambda, \beta) \rho \pi R^2 v^3 \] (1)

In our study, the power coefficient is depend on the tip speed ratio and blade pitch angle, defined by [7]:
\[ C_p(\lambda, \beta) = 0.48 \] (2)

The maximum value of \( C_p \) is given by: \( C_{p,\text{max}} = 0.48 \)
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:
\[ J \frac{d\Omega}{dt} = T_{\text{mech}} - T_{\text{load}} - D\Omega_{\text{mech}} \] (3)

2.2. Mathematical model for DFIG

The stator and rotor voltage in the d-q synchronous reference frames are expressed as follows [6]
\[ V_{q}\text{st} = R_{\text{st}} i_{q}\text{st} + \frac{d\phi_{q}\text{st}}{dt} + j\omega_{s} \phi_{d}\text{st} \] (4)
\[ V_{q}\text{rot} = R_{\text{rot}} i_{q}\text{rot} + \frac{d\phi_{q}\text{rot}}{dt} + j\omega_{r} \phi_{d}\text{rot} \]

The angular velocity of the rotor is given by:
\[ \omega_{r} = \omega_{s} - p\Omega_{\text{mech}} \] (5)

The stator flux and the rotor flux are:
\[ \phi_{q}\text{st} = L_{d} i_{q}\text{st} + M i_{q}\text{rot} \]
\[ \phi_{d}\text{rot} = M i_{d}\text{st} + L_{d} i_{d}\text{rot} \] (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]:
\[ V_{d}\text{rot} = 0 \quad V_{q}\text{rot} = V_{q}\text{st} \]
Reactive Power Control for Wind Turbine using Exact Linearization Feedback

\[ V_{sd} = R_{sd}i_{sd} + \sigma L_s \frac{di_{sd}}{dt} - \omega_L i_{sq} + \frac{L_d}{L_s} \phi_{sd} \]
\[ V_{sq} = R_{sq}i_{sq} + \sigma L_s \frac{di_{sq}}{dt} + \omega_L i_{sd} + \frac{L_d}{L_s} \phi_{sd} \]

The grid side converter can be expressed as follows:
\[ V_{sd} = \frac{3}{2} V_{dc} \]
\[ \frac{dW_{dc}}{dt} = -P_r - P_s \]
\[ W_{dc} = \frac{1}{2} C_{dc} V_{dc}^2 \]
\[ \frac{di_{sd}}{dt} = -\frac{R_s}{L_s} i_{sd} - \omega_L i_{sq} + \frac{1}{L_s} (V_{sd} - V_{g}) \]
\[ \frac{di_{sq}}{dt} = -\frac{R_s}{L_s} i_{sq} - \omega_L i_{sd} + \frac{1}{L_s} (V_{sd} - V_{g}) \]

Using coordinate:
\[ \begin{bmatrix} x_1 & x_2 & x_3 & x_4 & x_5 \end{bmatrix}^T = \begin{bmatrix} i_d & i_q & w & i_{dq} & V_{ds} \end{bmatrix}^T \]

The equation can be described by the following affine nonlinear form:
\[ \dot{x} = f(x) + g(x)u(t) \]

\[ f(x) = \begin{bmatrix} \frac{-R}{\sigma L_s} i_{sd} + \omega_L i_{sq} \\ -\omega_L i_{sd} - \frac{R}{\sigma L_s} i_{sq} - \frac{L_s}{\sigma L_s} \omega_L \phi_{sd} \\ -\frac{D}{L_s} \omega \\ \frac{R_s}{\sigma L_s} i_{sd} + \omega_L i_{sq} \\ \frac{R_s}{\sigma L_s} i_{sq} - \omega_L i_{sd} \\ \frac{3}{2CV_e} (V_{dc} - i_d/C) \end{bmatrix} \]

\[ g(x) = \begin{bmatrix} \frac{1}{\sigma L_s} & 0 & 0 & 0 & 0 & 0 \\ 0 & \frac{1}{\sigma L_s} & 0 & 0 & 0 & 0 \\ 0 & 0 & -\frac{1}{J} & 0 & 0 & 0 \\ 0 & 0 & 0 & -\frac{1}{L_s} & 0 & 0 \\ 0 & 0 & 0 & 0 & -\frac{1}{L_s} & 0 \\ 0 & 0 & 0 & 0 & 0 & -\frac{1}{L_s} \end{bmatrix} \]

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].

\[ \dot{z} = Az + Bw \\
\[ y = Cz \]

\[ u = -L^{-1}(x)(-p(x) + w) \]

\[ L(x) = \begin{bmatrix} L_{d1} & L_{d2} & \cdots & L_{d6} \\ L_{s1} & L_{s2} & \cdots & L_{s6} \end{bmatrix} \]

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 \[6\]:
\[ P_s = \frac{3}{2} (V_{sd} i_{sd} + V_{sq} i_{sq}) - \frac{3}{2} V_{dc} i_{rd} \]
\[ Q_s = \frac{3}{2} (V_{sd} i_{sq} - V_{sq} i_{sd}) - \frac{3}{2} V_{dc} i_{rq} \]
\[ \frac{d\theta}{dt} = \omega_e \]
\[ \phi_{sd} = \frac{3}{2} (V_{ad} i_{ad} - V_{aq} i_{aq}) - \frac{3}{2} V_{dc} i_{rd} \]

Therefore, we choose as output vector
\[ \begin{bmatrix} y_s = h_s(x) = \begin{bmatrix} P_s \\ Q_s \end{bmatrix} \\ y = h_r(x) = \begin{bmatrix} P_s \\ Q_s \end{bmatrix} \end{bmatrix} \]

The state variable and the input vector are:
\[ x = \begin{bmatrix} i_{ad} \\ i_{aq} \\ w_a \\ i_{rd} \\ i_{rq} \\ V_{dc} \end{bmatrix} \]
\[ u = \begin{bmatrix} V_{ad} \\ V_{aq} \\ \omega_e \\ V_{gd} \\ V_{qs} \end{bmatrix} \]

Differentiating (13) until an input appears:
With this output vector, the calculation of relative degrees gives:

\[ r = r_1 + r_2 + r_3 + r_4 = 5 \]  

(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:

\[
\begin{aligned}
\dot{y}_1 &= \frac{3}{2V_C} \left( \frac{L}{L_i} \left( -\frac{R}{\sigma L_i} i_d - \frac{L_m}{\sigma L_i} \omega_0 \phi_d \right) + \frac{3}{2} V_s \frac{L_m}{\sigma L_i} V_{se} \right) \\
\dot{y}_2 &= \frac{3}{2V_C} \left( \frac{L}{L_i} \left( -\frac{R}{\sigma L_i} i_q + \omega_0 i_d \right) - \frac{3}{2} V_s \frac{L_m}{\sigma L_i} V_{se} \right) \\
y_1 &= h_1(x) = \left( \frac{R}{L_i} i_d - \frac{L_m}{L_i} \omega_0 \phi_d \right) \frac{1}{L_i} (V_{se} - V_{qe}) \\
y_2 &= h_2(x) = \left( 3 \frac{V_s}{2V_C} \frac{L_m}{\sigma L_i} V_0 \right) - \frac{1}{V_C} \left( \frac{\partial P}{\partial i_d} \right) \frac{1}{2C_V} V_{se} P
\end{aligned}
\]

(14)

4. LQI controller of DFIG

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

\[
\begin{aligned}
\dot{x} &= Ax + Bu + Ed(t) \\
y &= Cx + Du
\end{aligned}
\]

(19)

\[ E_i = \begin{bmatrix} 0 & 0 \\ 0 & -\frac{L_m}{\sigma L_i} \end{bmatrix} d_i(t) = \begin{bmatrix} 0 \\ \omega_0 \phi_d \end{bmatrix} \]

The augmented system is:

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

(20)

\[ \xi = \int (\tau - y(t)) d\tau \]

(21)

where

\[ \hat{A} = \begin{bmatrix} A & 0 \\ 0 & 0 \end{bmatrix}, \quad \hat{B} = \begin{bmatrix} B \\ 0 \end{bmatrix} \]

and \( X_{obs} = [i_d, i_q, \dot{\xi}]^T \)

The optimal controller gain is [9-10]:

\[ K = -R^{-1} \hat{B}^T P \]

(22)
Reactive Power Control for Wind Turbine using Exact Linearization Feedback

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

\[ P\dot{\bar{A}} + \bar{A}^T P - PBB^T P + Q = 0 \]  \hspace{1cm} (23)

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

\[ u = -Kx \]

Where: \(x = [x, \dot{x}]\) and \(K = [K_x, K_i]\)

\[ u = -Kx \]

Where: \(x = [x, \dot{x}]\) and \(K = [K_x, K_i]\)

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:

\[ P_s^2 + Q_s^2 = (3\hat{V}s\hat{I}s)^2 \]  \hspace{1cm} (25)

Rotor current limitation:

\[ P_s^2 + Q_s^2 = (3\hat{V}s\hat{I}s)^2 \]  \hspace{1cm} (26)

Rotor voltage limitation:

\[ P_s^2 + Q_s^2 = (3\hat{V}s\hat{I}s)^2 \]  \hspace{1cm} (27)

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

\[ P_{\text{ref}} = P_s + P_d \]

\[ Q_{\text{ref}} = Q_s + Q_d = Q_s \]

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 \( P_s \) with \( \alpha Q_s \) we obtain:

\[ Q_s^2 - (3\hat{V}s\hat{I}s)^2/(\alpha^2 + 1) = 0 \]  \hspace{1cm} (29)

\[ (1 + \alpha^2)Q_s^2 + \frac{6V_s^2}{X_s}Q_s + \frac{9V_s^2(V_s^2 - X_s^2I_s^2)}{X_s^2} = 0 \]  \hspace{1cm} (30)

\[ (1 + \alpha^2)Q_s^2 + \frac{6V_s^2}{\sigma X_s}Q_s + \frac{9V_s^4}{(\sigma X_s)^2} - \frac{3V_s^2X_s}{(\sigma sX_s X_s)}V_s = 0 \]  \hspace{1cm} (31)

\( Q_{\text{max},1}, Q_{\text{max},2} \) and \( Q_{\text{max},1}^- \) are solutions to equations (29), (30) and (31) respectively

\[ Q_{\text{max}}^- = \min(Q_{\text{max},1}, Q_{\text{max},2}^-) \quad \text{and} \quad Q_{\text{max}}^+ = \max(Q_{\text{max},1}+, Q_{\text{max},2}+)\]

When the power factor is positive \( Q_{\text{max}} = Q_{\text{max}}^- \) else \( Q_{\text{max}} = Q_{\text{max}}^+ \).
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 Table 1 and Table 2.

5.1. Performance Comparison between EFL and LQI Controllers

The EFL controller parameters: \( P_1 = 1000 \), \( P_2 = 1000 \) 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](image-url)
5.2. The proposed Reactive Power management

**Figure 7b.** Reactive Power

**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
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             | G=20    | Maximal power coefficient | 0.087mH |
| Gain multiplier     |         |                      |         |

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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