A NON LINEAR PREDICTIVE CONTROLLER FOR WIND ENERGY
CONVERSION SYSTEM

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ABSTRACT
This paper presents an application of the nonlinear model predictive controller (NMPC) to wind energy conversion systems based on variable speed doubly fed induction generators (DFIG). Induction machines present a highly nonlinear behavior, fast dynamics and complex control. The predictive control is a precious tool for control in various domains and is largely studied and well known in the case of linear systems. Recently, the extension of this technique to the control of nonlinear systems has been the subject of many researches. The kinetic optimal power of the wind to be transformed is determined by the maximum power point tracking (MPPT). The stator’s active and reactive powers transit are controlled by the rotor’s voltage. The prediction model is obtained using the Taylor series expansion. The presented simulation results show a very satisfying performance in trajectory tracking of the proposed NMPC controller. Robustness to parameters variations and rejection of disturbances are successfully achieved.

Keywords: Nonlinear model predictive control; doubly fed induction generator; maximum power point tracking;

1. INTRODUCTION
The functional objective of the wind energy conversion system (WECS) is converting the wind kinetic energy into electric power and injecting this power into an electrical grid. The WECS is composed of wind turbine blades, an electric generator, a power electronic converter and the strategy of the control system. At a given wind velocity, the mechanical power available from a wind turbine is a function of its shaft speed. In terms of energy capture, all studies come to the same result that variable speed turbines will produce more energy than constant speed turbines [1-2].

The Doubly-Fed Induction Generator (DFIG) is a kind of induction machine in which both the stator windings and the rotor windings are connected to the electrical grid. The rotating winding is connected to the stationary supply circuits via the back-to-back rectifier-inverter pair. The advantage of connecting the converter to the rotor is that variable-speed operation of the turbine is possible with a much smaller and therefore much cheaper converter. The power rating of the converter is often about 1/3 the generator rating [3]. The back-to-back rectified inverter consisting of two conventional Pulse-width modulated (PWM) voltage-source converters (VSC). The dc-link voltage will be maintained at a level higher than the amplitude of the grid line-to-line voltage, to achieve full control of the current injected into the grid. The rectifier and inverter are connected to the rotor generator (DFIG) and the electrical grid, respectively. The power flow is controlled by the grid-side converter in order to keep the dc-link voltage constant, while the generator-side converter is responsible for the control of the generator in order to allow for maximum wind power to be directed towards the dc bus [4].

The PID command (Proportional-Integral-Derivative) is the most technique of command used in industrial control systems. It is also one of more former, because it is very previous to the introduction of the digital control by computer, which established a real revolution for the Automatic [5]. The predictive control has become currently a precious tool for control in various domains. It is largely studied and well known in the case of linear systems. The extension of this technique for the control of nonlinear systems has recently been the subject of many researches, and several algorithms were proposed [6]. The objective of the non linear predictive control is to calculate the future command such that the output tracks its reference.

This paper focuses on the application of the nonlinear model predictive control to the wind energy conversion system, with a speed-variable based on a doubly-fed induction generator. The global plan of the system studies is represented by the face1. Results of simulation of the dynamic behaviour of the studied
The classical electrical equations of the DFIG in the PARK frame are written as follows:

\[
\begin{align*}
V_{ds} &= R_s I_{ds} + \frac{d\psi_{ds}}{dt} - \omega_s \psi_{qs} \\
V_{qs} &= R_s I_{qs} + \frac{d\psi_{qs}}{dt} + \omega_s \psi_{ds} \\
V_{dr} &= R_r I_{dr} + \frac{d\psi_{dr}}{dt} - (\alpha_s - \omega)\psi_{qr} \\
V_{qr} &= R_r I_{qr} + \frac{d\psi_{qr}}{dt} + (\alpha_s - \omega)\psi_{dr}
\end{align*}
\]  
(5)

By setting the quadratic component of the stator flux to the null value and by neglecting the stator resistance, the electrical equation can be written as follows:

\[
\begin{align*}
V_{ds} &= 0 \\
V_{qs} &= V_s \\
V_{dr} &= R_r I_{dr} + \alpha L_r \frac{dI_{dr}}{dt} - \omega_s \alpha L_r I_{qr} \\
V_{qr} &= R_r I_{qr} + \alpha L_r \frac{dI_{qr}}{dt} + \omega_s \alpha L_r I_{dr} + \frac{MV_s}{L_s}
\end{align*}
\]

(6)

where:

\[
\alpha = 1 - \frac{M^2}{L_s L_r}, \quad s = \frac{(\alpha_s - \omega)}{\omega_s}
\]

The electromagnetic torque is given:

\[T_g = P \frac{M}{L_s} \psi_s I_{qr}\]  
(7)

The stator active and reactive powers are:

\[
\begin{align*}
P_{s-max} &= -\frac{M}{L_s} V_s I_{qr} \\
Q_{s-max} &= \frac{V_s^2}{\omega_s L_s} - \frac{M}{L_s} V_s I_{dr}
\end{align*}
\]

(8)

In order to convert the maximum of the wind power, it is desirable for the generator to have a power characteristic that will follow the maximum $C_{p,max}$ line. If the wind speed is measured and the mechanical characteristics of the wind turbine are known, it is possible to deduce in real time the optimal mechanical power which can be generated using the maximum power point tracking (MPPT) [9]. The expression of the optimal mechanical power is obtained as follows:

\[
P_{mec-opt} = \frac{1}{2} \frac{C_{p,max} \cdot \rho \cdot \pi R^5}{\lambda_{p,max}^2} \cdot \Omega_t^3
\]

(9)

The reference of grid active power is determined by the following expression:

\[P_{grid-ref} = \eta \cdot P_{mec-opt}\]  
(10)
The system of equation (11) is written under matrix shape
\[ \dot{x} = F(x) + B(x) \cdot V(t) \] (12)

Vector function \( F(x) \) is defined as follows
\[ F(x) = \begin{pmatrix} -\frac{R_r}{\sigma L_r} l_{dr} + s \omega_s l_{qr} \\ -\frac{R_r}{\sigma L_r} l_{qr} - s \omega_s l_{dr} + s \frac{M V_s}{\sigma L_r L_s} \end{pmatrix} \]

Vector function \( B(x) \) is defined as follows
\[ B(x) = \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} \begin{pmatrix} 1 \\ 0 \end{pmatrix} \]
\[ B_d(x) = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \] and \[ B_i(x) = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \]

The variables to be controlled in the DFIG are the d and q axis component of the rotor current.
\[ x(t) = \begin{pmatrix} l_{dr} \\ l_{qr} \end{pmatrix} \]

The command is the d and q axis component of the rotor voltage.
\[ V(t) = \begin{pmatrix} V_{dr} \\ V_{qr} \end{pmatrix} \]

The outputs of the system are the stator reactive and active powers.
\[ y(t) = \begin{pmatrix} y_1(t) \\ y_2(t) \end{pmatrix} \]
\[ y_1 = Q_{s-mes} \]
\[ y_2 = P_{s-mes} \]

Their references are:
\[ y_r(t) = \begin{pmatrix} y_{r1}(t) \\ y_{r2}(t) \end{pmatrix} \]
\[ y_{r1} = Q_{s-ref} \]
\[ y_{r2} = P_{s-ref} \]
\[
\begin{align*}
h_2(x) &= -\frac{MV_s}{L_s}I_{qr} \\
L_f h_2(x) &= \frac{\partial h_2(x)}{\partial x} F(x) \\
L_Bh_2(x) &= \frac{\partial h_2(x)}{\partial x} B_d(x) = 0 \\
L_Bq h_2(x) &= \frac{\partial h_2(x)}{\partial x} B_q(x) = -\frac{MV_s}{\sigma L_r L_s} 
\end{align*}
\]

The relative degrees of the system output \(y_1\) and \(y_2\) are \(r = 1\) and \(r = 2\) respectively.

\[
\dot{y}(t) = L_f h(x) + G(x).V(t)
\]

Where:

\[
\dot{y}(t) = \begin{bmatrix} \dot{y}_1(t) \\ \dot{y}_2(t) \end{bmatrix}, \quad L_f h(x) = \begin{bmatrix} L_f h_1(x) \\ L_f h_2(x) \end{bmatrix}
\]

\[
G(x) = \begin{bmatrix} -\frac{MV_s}{\sigma L_r L_s} & 0 \\ 0 & -\frac{MV_s}{\sigma L_r L_s} \end{bmatrix}
\]

Relative degree of the system is defined as \(r = r_1 + r_2 = 2\). The relative degree of the system is equal to the system order. Consequently, there is no zero dynamics. After replacing (21) in (14), we obtain the predicted output \(y(t+\tau)\) as follows:

\[
y(t + \tau) = y(t) + \tau \dot{y}(t)
\]

where:

\[
h(x) = \begin{bmatrix} h_1(x) \\ h_2(x) \end{bmatrix}
\]

Exploiting the equation (27), we shall have:

\[
V(t + \tau) = -G(x)^{-1} \begin{bmatrix} I_{3,1}^{-1} \quad I_{2,2} \end{bmatrix} M
\]

5. SIMULATION RESULTS

The non-linear predictive control is applied for a DFIG 1.5MW, 690V, 50Hz, two pole pairs. We present the results of dynamic simulation of the behavior of the studied wind generator. The control of powers exchanged between the wind turbine and the grid is realized by the predictive control and \(Q_{grid-set} = 0\).

In order to test the tracking reference functioning of DFIG in subsynchronous and subsynchronous mode of the generator, we introduce an blot of the wind speed shown in fig 3. The slip and the angular speed random of the DFIG follow the wind speed variation to see fig 4 and fig 5. The active power exchanged between the rotor and the grid is plotted in fig 6. The sense of drainage depends on the sign of the DFIG slip. From the fig 7 and fig 8, the stator and the grid power active tracks perfectly their references. The sense of passes in transit of the reactive power in the stator and in the rotor depends the slip to see fig 9.
reactive power exchanged between the DFIG and the grid tends to nullify. See figure 10. The frequency and the amplitude of the rotor currents and the voltage depends of the wind speed. See fig 11.

In order to test the robustness of the non linear model predictive control, the electric and mechanical parameters are varied in the DFIG model see fig 12-a. The grid active power tracks it’s the reference after the variation of the rotor resistance to see figure 12-b. The tracking of the reference is also assured after the variation of the moment of inertia. In that case, it is the reference which changes because the optimal mechanical power depends on mechanical parameters of the wind generator. See face 12-c.

6. CONCLUSION

The presented simulation results show that the DFIG works in both quadrants of the torque-speed plan that are sub-synchronous and super-synchronous modes. The active power supplied to the network varies according to the wind speed and follows perfectly the predicted reference. This justifies the efficiency and the reliability of this command in tracking the predicted references. The robustness of the proposed predictive control is demonstrated insensible against the rotor’s resistance variations and the variation of inertia moment.

Fig 3. Wind speed

Fig 4. DFIG slip

Fig 5. Angular speed random of the DFIG.

Fig 6. Rotor active power

Fig 7. Stator active power

Fig 8. Grid active power and its reference

Fig 9. Stator and rotor reactive power
THE PARAMETERS OF THE WIND GENERATOR:

\[ L_s = L_r = 0.0137 \, \text{H} \quad M = 0.0135 \, \text{H} \quad R_s = 0.012 \, \Omega \]

\[ R_r = 0.021 \, \Omega \quad P = 2 \quad f = 0.0071 \quad J = 500 \, \text{Kg.m}^2 \]

\[ V_s = 690\, \text{v} \quad R = 36.5\, \text{m} \quad G = 124. \]

**Nomenclature**

- \( v \): The wind speed
- \( \Omega_t \): Turbine speed
- \( \Omega_g \): Mechanical speed of the generator
- \( T_{aero} \): Aerodynamic torque
- \( T_g \): Generator torque
- \( s \): Slip of the generator
- \( C_p \): Power coefficient
The tip speed ratio is 

\[ \lambda \]

Air density is

\[ \rho \]

turbine radius is

\[ R \]

gear ratio is

\[ G \]

two-phase stator and rotor voltages are

\[ V_{ds}, V_{qs}, V_{dr}, V_{qr} \]

two-phase stator and rotor fluxes are

\[ \psi_{ds}, \psi_{qs}, \psi_{dr}, \psi_{qr} \]

two-phase stator and rotor currents are

\[ i_{ds}, i_{qs}, i_{dr}, i_{qr} \]

two-phase stator and rotor Resistances are

\[ R_s, R_r \]

total cyclic stator and rotor inductance is

\[ L_s, L_r \]

the number of pole pairs is

\[ P \]

ingravity is

\[ J \]

viscous friction is

\[ F \]

Stator active and reactive power is

\[ P_s, Q_s \]

Rotor active and reactive power is

\[ P_r, Q_r \]

Active and reactive grid power is

\[ P_{grid}, Q_{grid} \]

Optimal mechanical power is

\[ P_{mec-opt} \]

couple électromagnétique de la DFIG

\[ \tau_r \]

Predictive time.

REFERENCES


